
EXPOSED
AQUACULTURE OPERATIONS
CENTRE FOR RESEARCH-BASED INNOVATION
FINAL
REPORT
2015-2023
Norwegian Centre
for Research-based
Innovation

FINAL REPORT 2015-2023

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This is the final report from EXPOSED: Exposed aquaculture operations, a Centre for Research-based Innovation (CRI). The centre has been funded by the Norwegian research Council and partners for eight years in the period 2015-2023.

For more in-depth insight into activities and results, please visit https://exposedaquaculture.no/.

Norwegian Centre for Research-based Innovation

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Foreword

Over the past eight years, the EXPOSED Aquaculture Operations Centre for Research-Based Innovation, (EXPOSED) has united global salmon farmers, essential service and technology providers, and leading research groups. Their shared objective has been to develop knowledge and technology to bolster robust, safe and efficient fish farming operations in exposed locations. The Research Council of Norway has financially supported this collaboration, aiding research across diverse scientific disciplines and promoting innovations in various application areas.

As the project period concludes, this report compiles the research and innovation efforts conducted by the centre and its associated projects. It also illustrates the impact of these initiatives on the centre partners, the aquaculture industry, and society. For a deeper understanding of the activities and results of the centre, we invite you to read our annual reports and published scientific papers, all of which are referenced in this report. A review of state-of-the-art research results in the field of exposed aquaculture operations, particularly Norwegian fish farming, as well as a catalogue of one-page summaries of individual results is also made available at https://exposedaquaculture.no/.

As you explore this report and other traces of our work, we hope you gain a deeper understanding of exposed aquaculture operations, our work and our achievements. What is harder to convey is the experience of working together. We extend our deepest gratitude to our industry and research partners, whose invaluable contributions have not only brought the various results that we see today, but also been part of an exciting and fruitful community. We also acknowledge the Research Council of Norway, whose grant number 237790 has been instrumental in driving the innovations realized.

Even though we mark the end of the project period, numerous challenges remain, and new solutions must be discovered. The knowledge and methodologies we have acquired will be precious for future collaborations, where research and innovation for exposed aquaculture operations will be crucial. Collectively, we have embarked on a journey of innovation and discovery, and we will continue to shape the future of aquaculture together.

Centre Director,

Hans Bjelland

SINTEF Ocean

SAMMENDRAG

Over en periode på åtte år har EXPOSED bidratt til å frembringe **kunnskap** og **teknologi** som setter sitt preg på utviklingen innen eksponert havbruk. Dette har vært mulig gjennom et **langvarig samarbeid** med ledende oppdrettere, leverandørbedrifter og undervisnings- og forskningsmiljø.

Krevende kyst med muligheter

Store deler av Norges kystlinje er avsidesliggende og utsatt for utfordrende forhold som vind, bølger og sterk strøm. Fiskeoppdrett under slike forhold byr på mange utfordringer. EXPOSED har hatt som mål å bidra til robuste, sikre og effektive operasjoner for eksponert havbruk.

Samarbeid for løsninger

EXPOSED var finansiert av partnerne og Norges forskningsråd i 2015-2023. Statusen som Senter for Forskningsdrevet Innovasjon (SFI) har bidratt til et langsiktig og produktivt samarbeid mellom ulike aktører. Åtte års partnerskap har resultert i både felles forståelse av retning og behov og felles løsninger.

Tid til modning har vært særlig viktig i havbruksbransjen, som har vært i rivende utvikling i denne perioden. Et bredt konsortium var gjennom hele senterperioden viktig for å kunne identifisere og løse utfordringer og begrensninger ved dagens havbruks-operasjoner. Vi har derfor lagt stor vekt på felles aktiviteter som årlige samlinger, tematiske workshops og ukentlige videomøter for kunnskapsdeling og faglige diskusjoner, med bedriftsrepresentanter, forskere, stipendiater, studenter og andre inviterte, som myndighetsrepresentanter.

Forskningsområder og resultater

EXPOSED har vært inndelt i seks overordnede forskningsområder, som har gitt rammen for ulike prosjekt fra grunnleggende forskning til mer anvendte prosjekter. Forskningsområdene har grepet inn i hverandre og noen av resultatene er:

- **Sikkerhet**: Risikovurderingsmetode for helhetlig fareforståelse og ansatte-involvering; Sikkerhetsindikatorer; Operasjonsgrenser og avbruddskriterier; Beredskapsbehov for anleggs-, område- og bransjenivå.
- **Fiskevelferd**: Kunnskap om laksens og rensefiskens svømmekapasitet under ulike forhold er viktig for å velge lokaliteter, tilpasse rutiner og teknologi. Laksen takler vannstrøm og faste; Ved store bølger trekker laks unna not og går dypere; Metoder og forståelse av stress, restitusjon, energi, adferdsmodus og hastighet; Ny fisketag/-måling og kommunikasjonsplattform.
- **Robuste konstruksjoner og not**: Økt kunnskap om bølger og strøm; Presise lastmodeller for nøter, tekniske standarder og modellforsøk for å optimalisere anleggsdesign; Ett tall på eksponeringsgrad for en lokalitet, til bedre forvaltning og planlegging av lokaliteter.
- **Sikre fartøysoperasjoner**: Analysemetodikk for bevegelse mellom fartøy og merd, og virkning på anlegg og operasjonsgrenser; Logistikkoptimering; Optimalisering av skroglinjer og fartøysdesignmetodikk spesifikt for eksponert havbruk.
- **Overvåking og beslutningsstøtte**: Beslutningsstøtteverktøy for fartøyoperasjoner; Forståelse av komplekse sensorsystem for mer presis miljøbeskrivelse; Modellering av havbruksanlegg, inkludert fartøy-/merd-samspill og numerisk simulering forberedt for sanntids slitasje- og vedlikeholdsplanlegging.

- **Autonome systemer**: Teknologi og simuleringsverktøy for kontaktfrie løfteoperasjoner; Automatisert merdinspeksjon - design av autonome ROV-operasjoner for hulldeteksjon og vedlikehold Navigering og lokalisering av ROV og AUV relativt til not og fleksible strukturer.

Samla sett har altså EXPOSED resultert i mer robuste, sikre og effektive operasjoner. Resultater med direkte betydning er bedre teknologi og forståelse av operasjonene, inkludert hensyn til fisken og personellet. Dette har ført til endringer hos leverandører, oppdrettere og rederi. I tillegg har resultatene påvirket myndigheter og regelverksarbeid. EXPOSED har videre bidratt til utvikling og revisjon av standarder og veiledninger, og det er gitt innspill til regelverksgrupper, næring og myndigheter om forsknings- og utviklingsbehov for eksponerte lokaliteter og for havbruk til havs.

Konsortiet har hatt et utstrakt samarbeid med andre aktører og myndigheter som har tatt i bruk forskningsresultatene.

Internasjonalt potensial og veien videre

Selv om senteret har dreid seg om norske forhold, har det vært verdifullt å ha et internasjonalt blikk på forskninga. EXPOSED har finansiert samarbeid med forskere i Norge, Færøyene og Australia. Resultatene har også blitt gjort kjent internasjonalt, særlig gjennom samarbeidende forskere og nettverk.

Etter avslutning av EXPOSED videreføres mye av samarbeidet og arbeidet. Partnerne og resultatene har gitt grobunn for nye prosjekter, som både er i gang og er i støpeskjeen. Mange av studentene og stipendiatene har begynt å jobbe i partnerorganisasjonene, og noen videreutvikler sine prosjekt der.

Challenging environmental conditions

SUMMARY

For eight years, EXPOSED has brought forward **knowledge** and **technology** that has developed exposed aquaculture. The credit goes to a **long-term partnership** of world-leading fish farmers, supplier companies and educational and research institutions.

Challenging coast with opportunities

The Norwegian coast, with its remoteness and harsh wind, wave and current conditions, poses many challenges to fish farming. EXPOSED has focused on developing knowledge and technologies to enable robust, safe, and effective operations for exposed aquaculture.

Collaboration to develop solutions

Our initiative, funded from 2015 to 2023 by partners and the Research Council of Norway, utilized the Centre for Research-based Innovation (CRI) status to cultivate productive, long-term collaboration. The eight-years partnership has fostered joint problem-solving and helped shape a unified direction and vision.

During these fast-paced times in the aquaculture industry, this partnership was essential to identify and overcome challenges. Our approach included joint activities like annual gatherings, thematic workshops, and weekly video meetings. A broad range of stakeholders have been involved, with company representatives, researchers, PhD candidates, students, and other invitees, such as government representatives.

Research areas and outcomes

The EXPOSED Centre has been divided into six major research areas, which have provided the framework for various projects that range from basic research to more applied projects. The research areas influence each other and some of the results are:

- **Safety**: We've implemented a risk assessment method that provides a comprehensive understanding and encourages employee involvement. This includes safety indicators, operational limits, interruption criteria, and an emergency preparedness plan tailored for construction, area, and industry-level needs.
- **Fish welfare**: We prioritize the welfare of fish by gaining extensive knowledge about the swimming capacities of salmon and cleaner fish under various conditions. This information guides our site selection, routine operations, and technology use. In rough conditions, salmon have proven to cope well, moving deeper and away from nets when waves are large. We've developed methods to understand stress, recovery, and energy levels, as well as behavior and speed. Additionally, we've introduced a new fish tagging system and communication platform.
- **Robust structures and nets**: Our understanding of waves and currents has increased, allowing us to create precise load models for nets and to develop technical standards for optimizing aquaculture farm design. We've implemented a rating system to measure a site's exposure level, which improves management and site planning.
- **Safe vessel operations**: We've established an analysis methodology to study movement between vessels and cages and to understand the impact on facilities and operational limits. Additionally, we've optimized logistics and developed a method for optimizing hull lines and vessel designs, specifically for exposed aquaculture.
- **Monitoring and decision support**: We have decision support tools for vessel operations and have gained an understanding of complex sensor systems to provide more precise environmental descriptions.

Our modelling of aquaculture facilities includes vessel and cage interaction and prepares numerical simulations for tasks such as real-time wear and maintenance planning.

- **Autonomous systems**: Our technology and simulation tools allow for contact-free lifting operations. We've automated cage inspection with the design of autonomous ROV operations for hole detection and maintenance. Also, we've made advancements in navigation and localization of ROVs and AUVs relative to nets and flexible structures.

The results have directly improved technology and operational understanding, influencing suppliers, fish farmers, and shipowners alike, and have been shared with authorities and policymakers. EXPOSED has contributed to the development and revision of standards and guidelines.

International Collaboration and Future Direction

Although our focus was primarily on Norwegian conditions, international collaborations, including those with researchers from Norway, the Faroe Islands, and Australia, proved valuable. Our results have gained international recognition, particularly through researcher networks.

Looking ahead, much of our collaborative work will persist beyond EXPOSED. New projects are in progress, thanks to the fertile ground provided by our partners and previous achievements. Many students and PhD candidates are now part of our partner organizations, contributing to the industry's ongoing restructuring and the search for robust, safe, and efficient operations.

Salmon swimming in current

VISION AND OBJECTIVES

EXPOSED aims to develop knowledge and technology to support **robust**, **safe,** and **efficient** operations on exposed fish farms.

Major parts of the Norwegian waters have been 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 was 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 of autonomous systems, offshore structures and vessels to sustain aquaculture production under all conditions, and to enable more robust, safe, controlled, and continuous operations.

EXPOSED brought 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).

There has been a significant industrial and political interest in the centre's research and innovation activities. This interest, driven in part by societal and regulatory developments, has promoted changes in the focus of partner innovation.

This interest has also generated enthusiasm among students, allowing the centre to recruit large numbers of MSc candidates and well-qualified PhD students.

Main objective

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

Industry objectives

The first objectives that was defined were:

- 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.

During the Centre period, two new objectives were identified:

- 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. These indicators have been expanded through the centre period.

Harsh conditions. Photo by Marius Dahle Olsen

BASIC FACTS ABOUT THE CENTRE

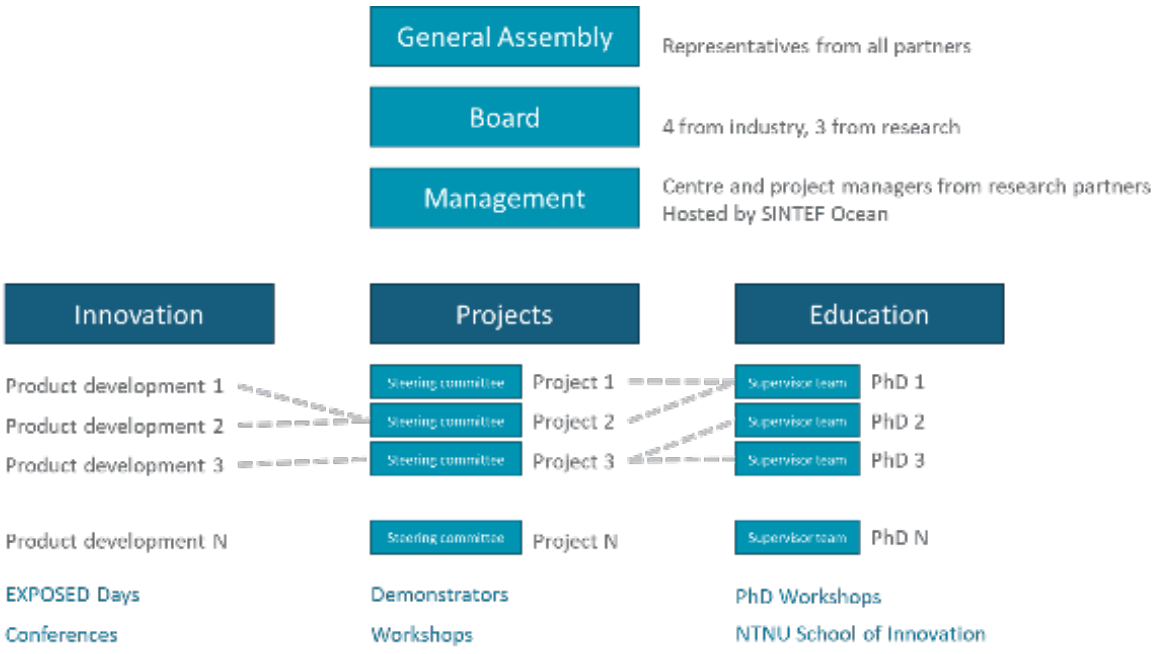
Organisational structure

The organisation and operation of the centre was 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 was the operative decision-making body for the centre.

Hans V. Bjelland was the **Centre Director**, with responsibility for managing the centre on behalf of the host institution, SINTEF Ocean. Bjelland was reporting to the Board. The Centre Director, together with the **Management Group**, was managing centre activities related to **projects**, **education** and **innovation**.

In 2023, the Board members were as follows:

Board member	Affiliation
Alf Jostein Skjærvik (Chair)	SalMar
Hanne Digre	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



Organisational structure of the EXPOSED centre.

The projects were organised with a **Project Manager** and a **Steering Committee**. The Project Manager was responsible for carrying out the project, while the Steering Committee, headed by a representative of one of the industrial partners, focused on the supervision of project progress and adherence to its objectives. The Management Group was consisting of a Research Manager for each of the six core research areas:

Management Group member	Role and responsibility	Period
Hans V. Bjelland SINTEF Ocean	Centre Director	2015-2023
Esten Ingar Grøtli SINTEF Digital	Area 1	2015-2023
Gunnar Senneset SINTEF Ocean	Area 2	2015-2018
Jan Tore Fagertun SINTEF Ocean	Area 2	2019-2023
Pål Lader SINTEF Ocean	Area 3	2015-2016
David Kristiansen SINTEF Ocean	Area 3	2017-2020
Heidi Moe Føre SINTEF Ocean	Area 3	2020-2023
Dariusz Eirik Fathi SINTEF Ocean	Area 4	2015-2016
Ørjan Selvik SINTEF Ocean	Area 4	2016-2023
Ingunn M. Holmen SINTEF Ocean	Area 5	2015-2021
Trine Thorvaldsen SINTEF Ocean	Area 5	2021-2023
Frode Oppedal Institute of Marine Research	Area 6	2015-2016
Ole Folkedal Institute of Marine Research	Area 6	2016-2023
Kristine Størkersen SINTEF Ocean	The effect project/ Scientific Coordinator	2021-2023
Kaja Kristine Haug SINTEF Ocean	Scientific Coordinator	2020-2023

Key results	2015	2016	2017	2018	2019	2020	2021	2022	2023	Total
Scientific peer-reviewed publications	2	4	13	8	13	7	7	9	4	**67**
Dissemination measures for users – presentations, interviews, etc.	28	51	23	41	28	4	12	45	21	**253**
Popular scientific articles		1	1		1			6	2	**11**
PhD degrees completed				1	3	2	3	1	2	**12**
Master degrees		3	20	5	3		9	1		**40**

Research facilities

The centre was having 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 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, was 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 is utilised as a resource for 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. Transport, food and energy production represent the backbone of ocean-based industries, and are also core areas for SINTEF Ocean. In addition, we focus on environmental technology, with one of the world's leading professional environments in marine environmental technology.	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, 4
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 has had key role within the EXPOSED centre.	1, 3, 4, 5
NTNU's Department of Computer and Information Science (IDI). Conducts research in 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 has brought together several leading global salmon farmers, key service and technology providers, and leading research groups.

Industry partners	Contribution/role
Mowi. The world's largest salmon and trout farmer with major operations in Norway, Scotland, Canada and Chile.	End user of technology and solutions
Cermaq. The world's third largest salmon and trout farmer, with operations in harsh environments.	End user of technology and solutions
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 Seatex, Kongsberg Maritime Subsea and Kongsberg Maritime. A supplier of technology to the global maritime and offshore sector. Provider of knowledge and communication, control, navigation, decision support, AUVs, etc.	Technology/solution provider
Aqualine (ScaleAQ). A major international supplier of aquaculture equipment and complete fish farms.	Technology/solution provider
Møre Maritime. A provider of maritime consulting, engineering and 3D modelling services.	Technology/solution provider
Anteo. Operates and develops technical solutions and decision support systems for fish farming companies.	Technology/solution provider
Argus Remote Systems. Carries out R&D on, and is a manufacturer of, electrical ROVs.	Technology/solution provider
AQS. Service provider of fish farm inspection and maintenance services, as well as other operations, including delousing.	Service provider
Marin Design. A provider of vessel designs and maritime consulting services.	Technology/solution provider
DNV. A leading classification society and certification body, and a recognized advisor to a wide range of industries.	Certification, classification and advisory services
MacGregor Norway. A leading provider of maritime system handling solutions and services to the offshore, fisheries, research and mooring sectors.	Technology/solution provider
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
ÅF (previously Reinertsen/ÅF Reinertsen) is a leading engineering and design company within energy, industry, infrastructure and digital solutions, with focus on customized robust and sustainable solutions, on land and in sea. (2015-2021)	Technology/solution provider
Lerow was a service provider for inspection and cleaning of net cages and moorings by advanced use of ROV. (2015-2020)	Service provider

COOPERATION WITHIN THE CENTRE

The partners of EXPOSED have contributed in all research activities, together with researchers and other partners, and further developing own innovations.

The centre has organized two yearly events for all partners, 'the EXPOSED-days', one in the spring and one in the autumn. PhD and post-doctorate researchers were invited to all events. These events have been described as fruitful in finding a common ground of knowledge and understanding among partners, and for scientific approaches and use of results.

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

In 2021, a new line of PhD and postdoc workshops were initiated. In earlier years, an annual seminar for PhD students and postdocs have been productive in bridging knowledge across research areas.

The centre has also continued with video meeting series that was initiated in the first phase of the Covid-19 pandemic, with great success.

All these events were serving as arenas for cooperation, innovation, presentation of research results, exchanges of ideas and the generation of new projects.

Depending on the level of covid measures (2020), meetings have been arranged face to face, digitally, or as hybrid solutions. In the last years of the EXPOSED centre, and when the society slowly opened in the aftermath of the covid pandemic, the centre focused on providing new and old recruitments with arenas for discussion, learning and dissemination.

See more about the cooperation in the sections about communication as well as effects for the partners.

EXPOSED Days in May 2017.

Third year students from the Department for Product Design are working with EXPOSED on "Future Concepts" and where on a field trip to learn more about the Aquaculture industry.

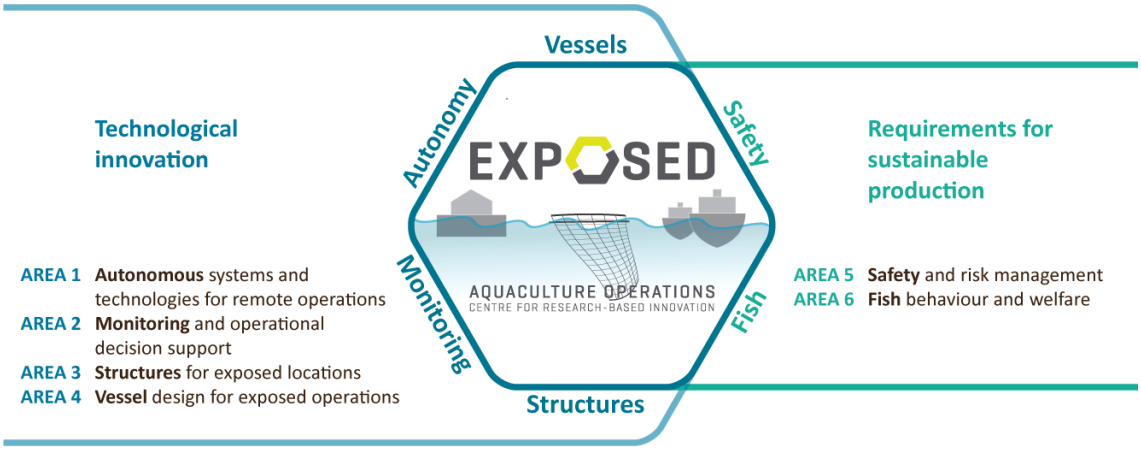
Centre Director Hans Bjelland holding a presentation at the EXPOSED days in October 2022.

RESEARCH

Research plan

At the beginning of the Centre period the activities in EXPOSED were organised in projects combining research areas, partners, and methods. As a part of the midway evaluation, the centre management team decided that the projects should be carried out with shorter length to help them become more adjustable to changes and needs from the industry. The projects were covering fundamental research, industrial research, as well as increased focus on developing demonstrators to promote future innovations.

EXPOSED included 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 robust monitoring and assessing of structures, systems, and fish welfare to support operational decisions.

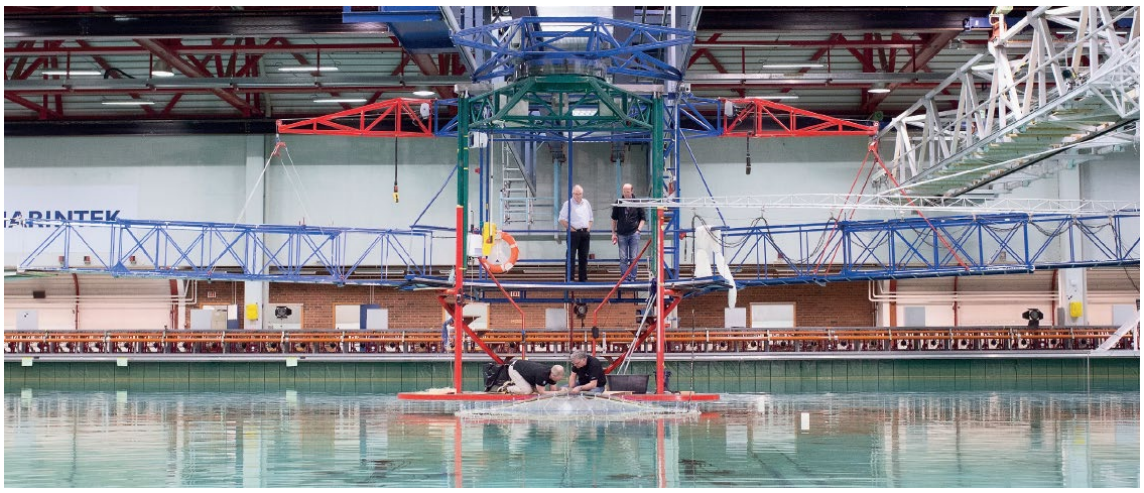
Area 3: Structures for exposed locations

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.

One of the full-scale test sites at SINTEF ACE



Testing of aquaculture structures in the Ocean Basin at Tyholt in Trondheim.

AQS Loke will be monitored with Kongsberg Seatex's MRUs to study vessel motion during operations.

Two of the centre's research areas focused 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.

The research activities have combined research areas, partners, and methods. Industry partners, researchers, and PhD candidates were included in the project teams.

During the two last years of the centre period, an overarching project was implemented. The goal was to bring together the knowledge and results from all research areas, and to understand and communicate the overall findings and effects of EXPOSED. As a part of this work, the partners were interviewed, and both partners and researchers from all research areas collaborated in analysis and dissemination.

EXPOSED has initiated and encouraged **associated projects**.

The associated projects typically involved one or more existing centre partners, and in some cases in addition other external companies or research partners. The partners in those projects varied depending on the main funding source (the Research Council of Norway/RCN, EU, or innovation-driven).

The centre also explored the potential in collaborating with other centres and groups. EXPOSED shared PhD students with NTNU AMOS and collaborated on PhD training with two maritime SFIs; the SFI Move (supporting the marine operations value chain) and the SFI Smart Maritime (supporting improved energy efficiency and harmful emissions reductions from the maritime sector). A number of EXPOSED partners are also partners in and collaborate with the SFIs Blues (Floating structures for the next generation of ocean industries) and CtrlAqua (Centre for Closed-Containment Aquaculture).

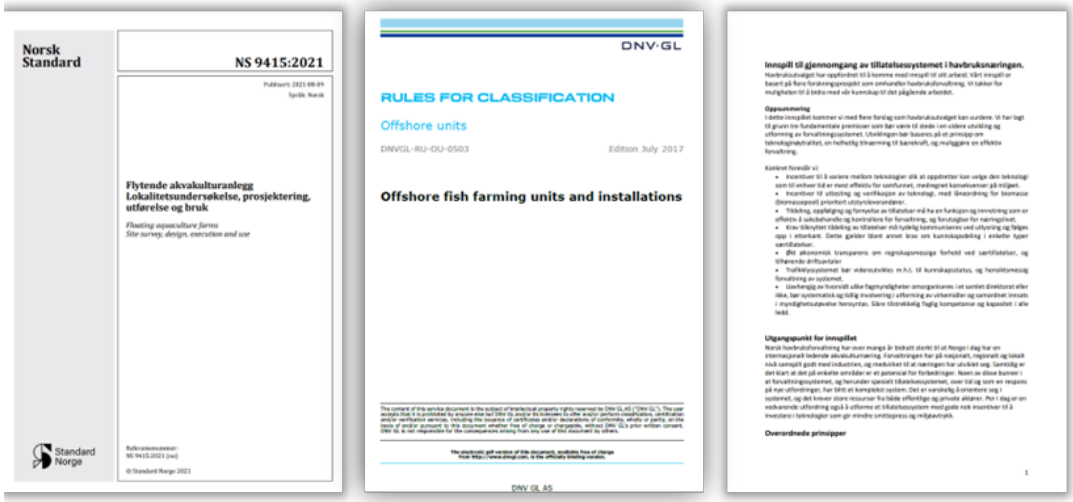
SFI BLUES

MOVE SFI Marine Operations

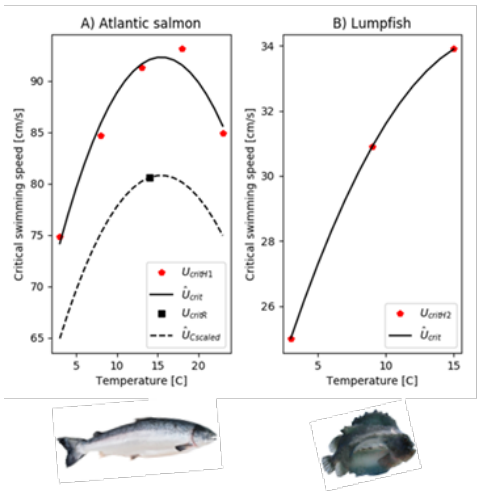
SMART MARITIME

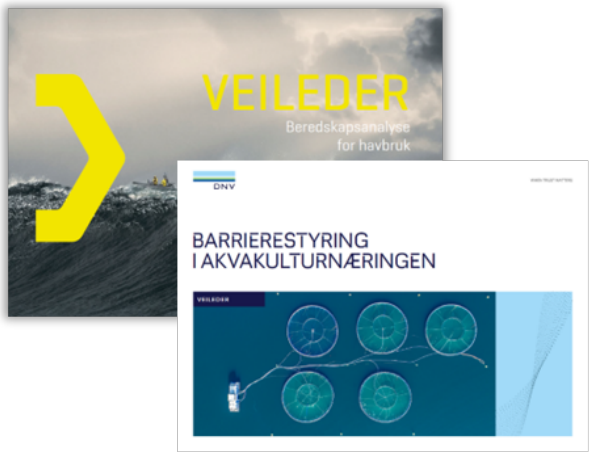
AMOS

A new type of well boat made by Møre Maritime



Developing and contributing to standards and regulations





Making guidelines for operations at exposed sites and leading to changed practices and new assessment of existing and new sites by fish farmers, government and technology/knowledge/service providers

Research achievements

The challenges for exposed aquaculture operations are intertwined and have been addressed using several research approaches. In the recent years, research and innovation in EXPOSED have developed solutions for some of the challenges:

Supporting equipment

Technology for contact free lifting operations, and design of autonomous ROV operations for hole detection and maintenance.

- Navigation/localization of ROV/AUVs, relative to nets and flexible structures enables more precise and autonomous operations.
- Machine vision-based hole detection and integrity control, used to improve inspection operations.

Monitoring and decision-support

Measuring site conditions and combining data into monitoring systems for decision-support in design and operations.

- Environmental descriptions of coastal sites, to improve precision and relevance of the basis for design and operations planning.

Structures and nets

- Understanding environmental conditions and load.
- A new formula for net drag coefficient.
- Methods for structural analysis, precise model testing.
- A new technical standard.

Vessel operations

- A design methodology for vessels
- Logistics optimization.
- Modelling of aquaculture systems, including vessel-structure interaction, as a future tool to study the systems, inform design and monitor conditions.
- Methods to analyse and predict operational limits, supporting technology development in design decisions and operational planning.

Safety

- Working environment and competence requirements are studied to improve procedures and inform design and technology development.
- A model for holistic risk assessment of aquaculture operations.
- Realistic safety management and accident investigations.
- Safety indicator methods.
- A guide for emergency preparedness.

Fish welfare

- Salmon and cleaner fish swimming capacity, which is important to assess new locations and new farming technology.
- Measuring tail-beat frequency, swimming speed, metabolic rate and heart rate.
- Measuring of fish distribution in the cage.

The scientific results are closely linked with the industry's products and innovations. EXPOSED thus uses the words *innovation* and *result* interchangeably. Innovations were in this centre defined as new or improved products, services, processes, organization, regulation, or concepts developed to achieve positive impact in a company or society. Not all innovations from this center are materialized as commercially available products or services, but they are part of the present knowledge base for the continuous maturing of technology and decision-support for operations.

Examples of other achievements among the EXPOSED partners:

Improved design of technologies and vessels

- The technology providers have improved their design of net pen constructions, ROV's, and sensor technology.
- The naval architect partner Møre Maritime has developed new vessel concepts based on dialogue and activities in the research centre. Examples of vessel concepts are more stable service vessels for the fish farmers and larger live fish carriers/well boats.

New standards and guidelines

- The partners Safetec, DNV, and SINTEF Ocean have developed guidelines for emergency preparedness in aquaculture (https://www.sintef.no/globalassets/sintef-ocean/veileder-beredskapsanalyse-for-havbruk-sfi-exposed.pdf).
- Knowledge from the centre is included in the 2021 revision of Standard Norway's NS9415 *Marine fish farms — Requirements for site survey, risk analyses, design, dimensioning, production, installation and operation*. Many of the researchers and industry partners have been a part of the standard committee or contributed with research results and submitted comments.
- Partner DNV has developed guidelines for the safety of aquaculture rafts and barrier control in aquaculture (in Norwegian: https://www.dnv.no/feature/understanding-managing-aquaculture-risk.html).

Improved decision support

- Fish farmers have been able to understand, including start or stop operations on fish farm sites based on new knowledge. The gathered weather information from sensor buoys etc. in sites is even more valuable combined with research results about how the fish reacts to waves, wind and water current.
- Partner Anteo has developed a tool for decision support on vessel logistics, employing information from the fish farm partners and live fish carriers/well boats (https://anteo.webflow.io/produkter#logistikk).

INTERNATIONAL COOPERATION

EXPOSED has opened several international opportunities, including invitations to be part of global centres and projects that will further enhance our footprint in aquaculture technology research and innovation.

Our work on exposed fish farming has raised the interest of numerous countries, such as Scotland, the Faroe Islands, Chile, Australia, China, South Korea, and Japan. This international recognition signifies the global relevance of our research.

Key Partnerships and Collaborations

The centre has continued existing successful collaboration with the Fiskaaling research organization in the Faroe Islands, conducting joint analyses of fish welfare data from Norway and the Faroe Islands.

In Australia, the University of Melbourne partnered with EXPOSED in Research Area 6: Fish Behavior and Welfare. Additionally, our host institution, SINTEF Ocean, and its partner DNV, engaged in studies as part of the Blue Economy Cooperative Research Centre in Australia (cooperation started in 2019).

Projects with International Partners

Our portfolio also includes projects involving international partners and funding:

- Echofeeding: Investigates echo sounder technology for appetite-led feeding and welfare-monitoring of caged salmon.
- FlexAqua: Addresses reliable flexible shielding technologies for infestation prevention in offshore seas and coastal areas.
- SalmonInsight: Uncovers connections between salmon physiology and online monitored behavior.

Exchange and International Bodies

EXPOSED engaged in exchange activities with Memorial University in St. John's, Newfoundland, fostering collaboration between Norway and Canada.

Our researchers worked closely with partners from the International Council for the Exploration of the Sea (ICES), particularly contributing to the working group on Open Ocean Aquaculture (WGOOA).

Conferences and Webinars

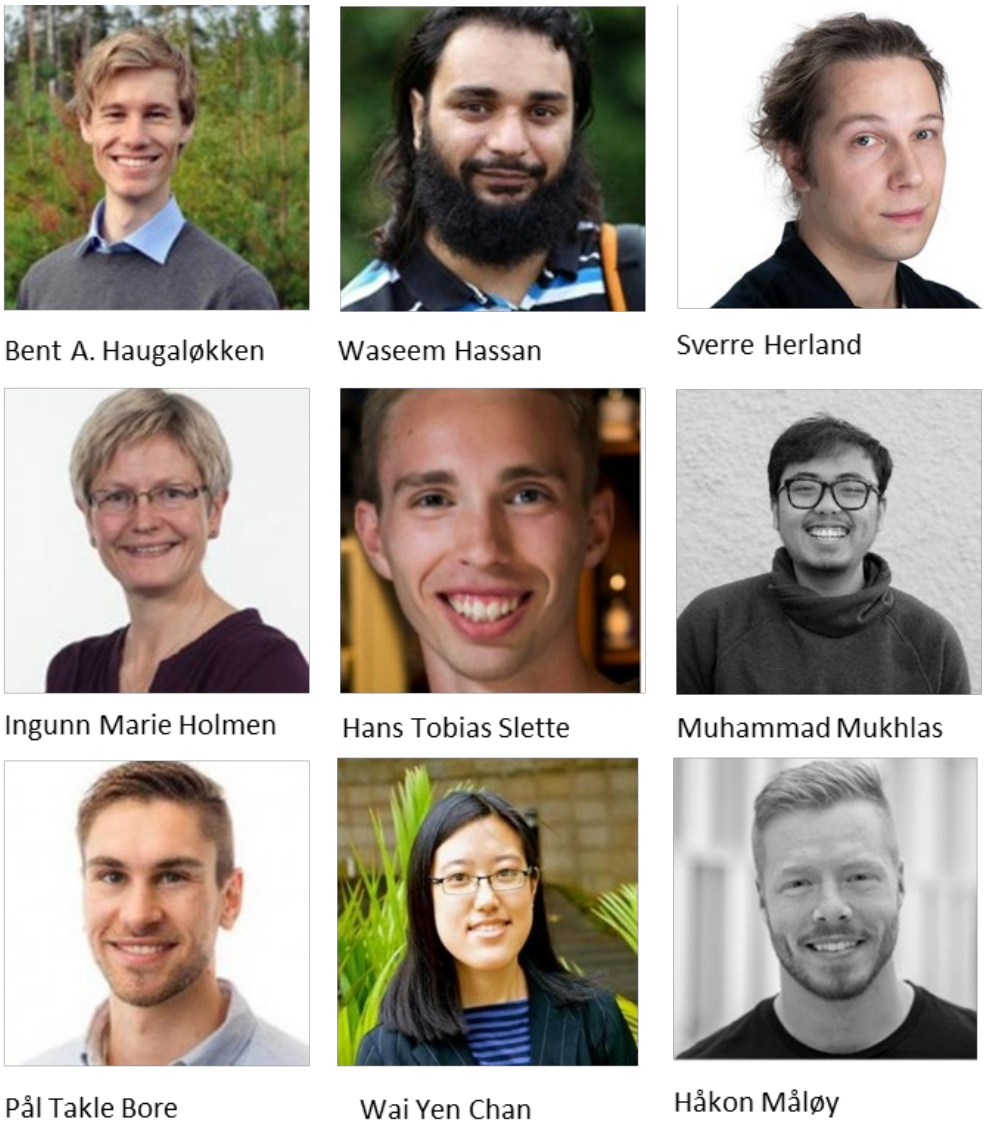
Over the years, EXPOSED researchers have chaired and contributed to various international conferences, such as the Aquaculture Europe Conference. They have also made presentations on webinars hosted by international organizations like the European Aquaculture Technology and Innovation Platform (EATIP).

TRAINING OF RESEARCHERS

14 PhD candidates and postdocs have been funded by EXPOSED, in addition to several candidates from associated projects.

Education was implemented primarily via three departments at NTNU; Marine Technology, Computer and Information Science, and Engineering Cybernetics. In addition, some PhD and MSc students were educated at the University of Bergen, facilitated by a collaborative agreement with the Norwegian Institute of Marine Research.

Several other NTNU departments have been involved in MSc and bachelor's degree studies related to projects carried out at the centre. EXPOSED partners have supervised and provided projects for both national and international master student.



Nine of the 11 PhD candidates financed by EXPOSED.

Two candidates have performed both their PhD and their postdoc through EXPOSED (see below). Malthe Hvas has been at UiB and the Marine Research Institute, and Bjørn Magnus Mathiesen has been at NTNU and SINTEF Digital. Both have earned permanent employment at their research institute.

Malthe Hvas

Bjørn Magnus Mathisen

Ása Johannesen

Both PhD candidates and postdocs in EXPOSED, Hvas and Mathiesen. Postdoc Johannesen from Fiskaaling.

EXPOSED has aimed for close collaboration between the students, the organised research activities, and the industry partners, whether they were financed by EXPOSED or not. Alle active students and postdoc researchers were invited to all events in EXPOSED, and we established a student network to advance collaboration, knowledge sharing and industrial insights. Most PhD project research results have been presented and discussed as part of EXPOSED-days, EXPOSED video meeting series forum for exposed operations), and the EXPOSED conference.

Kristbjörg Edda Jónsdóttir

Stian Sandøy

Stefan A. Vilsen

Eirik Svendsen

Yugao Shen

Siri Holen

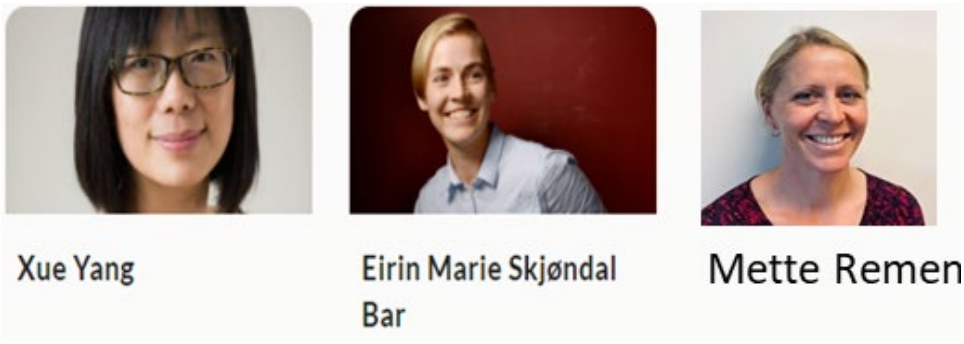
Martin Slagstad

Some PhD candidates associated with EXPOSED.

EXPOSED has been involved in NTNU School of Innovation. Together with international and national companies and research partners, NTNU and SINTEF have centre status for several leading research environments within ocean space technology. The challenge is to also excel in creating new products and solutions. In order to overcome this challenge, researchers will also need competence within innovation and entrepreneurship.

The main goals of the NTNU School of innovation is to

- Create a culture for innovation
- Strengthen the awareness and competence on innovation
- Contribute to increased commercialization of research results



Associated postdocs, employed at SINTEF Ocean and the Marine Research Institute.

After PhD

As EXPOSED ended in 2023, most PhD candidates and research activities are finished, but the two students recruited last will graduate after the centre termination.

One of the PhD-student of EXPOSED, Hans Tobias Slette, has described why he chose to join the centre, and how his experience was working with EXPOSED:

> *"I decided to join EXPOSED when I heard about the vacant PhD position in research area 4. The topic of vessel design and vessel operations was already a strong interest of mine. Exposed aquaculture is an interesting area of application for the topic, and knowing that the main supervisor would be Bjørn Egil Asbjørnslett this seemed like an opportunity too good to let pass.*
>
> *Doing a PhD should always be a challenge, but being a part of EXPOSED was helpful in several ways. It provided me with a network and contact with industry, researchers and other students that would otherwise have been difficult to obtain. Regular meetings in the centre contributed to broaden the perspective of my work and was an arena for valuable insight and discussions.*
>
> *Now I work as a research scientist at SINTEF Ocean with several of the researchers I got to know in EXPOSED. I am also lucky to continue to work with several of the industry partners from the centre. My plan is to continue pursuing a career as a research scientist within the topics of the aquaculture industry and maritime."*

Several of the EXPOSED candidates were employed by EXPOSED partners after completing their respective degrees. For instance, Malthe Hvas was taking his PhD and postdoc at EXPOSED and is now employed at Institute of marine research.

An overview of employment of candidates by number are shown in the table below.

Number of employments of PhD candidates (both financed by EXPOSED and financial support from sources outside the centre) by centre termination in 2023.

By centre company (including research institutes)	By other companies	By university (EXPOSED partner)	Outside Norway	Still phd student at the end of the centre period	Total
9	4	3	3	3	22

COMMUNICATION OF KNOWLEDGE

EXPOSED has placed significant importance on robust communication – with the public, other stakeholders, and within the centre's partners. To foster cross-disciplinary innovation and efficient communication, we have organised a range of meetings and events. For instance, the EXPOSED Days have served as a platform for fostering innovation, presenting research findings, exchanging ideas, and initiating new projects.

The EXPOSED Catalogue, popular among the partners, serves as a living document to enhance access to the centre's accumulated knowledge and stimulate future innovation. It offers a comprehensive overview of completed projects and provides links to relevant articles, memos, associated projects, and personnel. The catalogue has been made publicly accessible on the EXPOSED website.

The EXPOSED Catalogue can be found at exposedaquaculture.no.

Both scientific and industry partners have been active in the communication of EXPOSED. At the annual EXPOSED days and the last EXPOSED conference, presentations and sessions were co-organized by industry and scientific personnel. There are for example a number of occasions where different partner groups jointly have organized conferences and sessions. The partners have been collaborating in multiple ways, like participation in a standard committee and authoring the revision of NS 9415 Floating aquaculture farms. Communication of results from demonstrations and tests have been shared, like when the magazine *Norsk fiskeoppdrett* reported from a test in spring 2023 and interviewed both Eivind Lona (SINTEF Ocean) and Martin Søreide (Scale AQ). The industry partners have mainly acted as quality assurers in scientific reporting and publications. In 2023 the partners Safetec, DNV and SINTEF Ocean together made two publications: The guidelines for emergency preparedness in aquaculture (in Norwegian) and a scientific publication in the level 2 journal Aquaculture: Prepared for the worst? Emergency preparedness in Norwegian fish farming – Status and further improvements.

In 2019, EXPOSED made a strategic decision to enhance its visibility and set an international agenda. Consequently, researchers affiliated with the centre led a session about aquaculture constructions at the international conference OMAE. In 2022, the EXPOSED Director chaired a

session on open-offshore aquaculture at the Aquaculture Europe conference.

In the final period of the centre, partners shifted their focus from promoting individual research results to communicating overarching findings to a wider audience. Thus, the centre placed greater emphasis on popular science dissemination beyond the research community.

The primary communication channels utilised by the centre included:

- Research activities and partner meetings within the Research Areas.
- Participation in Norwegian and international conferences and forums. For instance, we hosted a dedicated session at the Norwegian industry conference Aqua Nor.
- Publication of articles in relevant scientific, trade and popular science media.
- Video meetings for partners and invited stakeholders to present results, discuss industry challenges, changes in regulation, etc.
- The EXPOSED website (http://exposedaquaculture.no/)
- Several podcasts about exposed aquaculture (https://www.sintef.no/smart-forklart, https://podcast.app/hekta-pa-havbruk-p1870796/ and https://podcasts.apple.com/no/podcast/technoport-podcast-5-hans-bjelland/id1536483142?i=1000506006213)

Communication with a line of different stakeholders has been central in EXPOSED. For example, the researchers have been the voice of safety, fish welfare, and technological robustness in the public debate.

Over the last two years, the centre management has prioritized reaching out to society, the public, and government officials. A plan for popular dissemination was developed, utilizing research findings from each research area, along with the overarching results. We targeted national newspapers and business magazines with audiences interested in aquaculture or policies. We also produced a podcast. Some of our news articles and media links received extensive online shares, making them hard to track. Please see Appendix 3 for a list of the popular communication pieces we were able to compile.

EFFECTS OF CENTRE FOR THE HOST INSTITUTION AND RESEARCH PARTNERS

EXPOSED has given its researchers and partners a leading position in a time of important innovations in the aquaculture industry. By fostering **long-term research collaborations** between essential industrial and academic partners, the centre has been instrumental in the growth and development of expertise, knowledge, and infrastructure.

EXPOSED has been structured to make the most of the involved disciplines, organizations, and research groups. Our six research areas form an integrated unit that serve to all required aquaculture operations. The centre has actively encouraged and nurtured interdisciplinary collaboration on multiple levels:

- Within the host institution, SINTEF Ocean's departments.
- Among institutes within the SINTEF Group.
- Among the three research organization partners: SINTEF, NTNU, and IMR.
- Between partners and the broader research system.

Effects for host institution

SINTEF Ocean, by hosting EXPOSED, has had the privilege of partnering with competent organizations to address large-scale research questions. As a platform for discussions and collaborations, EXPOSED provides unique insights into current issues and future challenges. It supports SINTEF Ocean's aspiration to maintain Norway's leadership in marine technology and biomarine research.

EXPOSED has significantly contributed to the evolution and achievement of SINTEF Ocean's research strategy, and the wider SINTEF Group. Central to this strategy is aquaculture technology, which encompasses a spectrum of research areas such as safety, general marine technology, and monitoring and decision support. EXPOSED has fostered collaboration across SINTEF Ocean and the SINTEF Group, contributing to the development of knowledge, software, and services to meet rising demands in the R&D market. The SINTEF Group's vision of 'Technology for a better society' aligns well with the Centre's goals, emphasizing the development of knowledge and technology for safe, sustainable seafood production in exposed coastal and ocean areas.

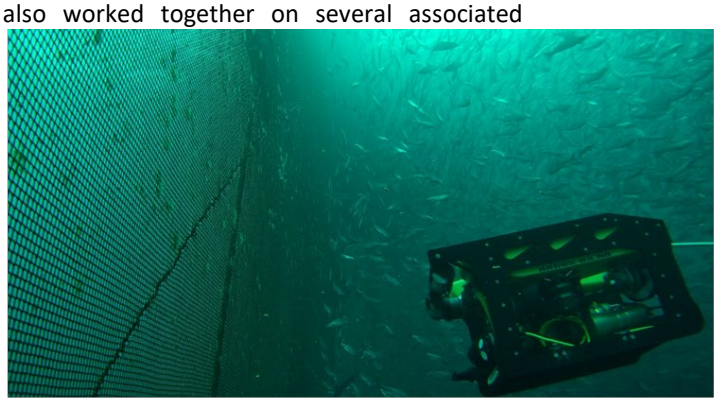
The merger of SINTEF Fisheries and Aquaculture, the original host of EXPOSED, with research partner MARINTEK to form SINTEF Ocean, was a response to the evolving R&D needs of the ocean industries. Global economic shifts, reduced oil prices, and rising salmon prices have all increased focus on aquaculture. EXPOSED has engaged researchers across SINTEF Ocean's departments, encouraging internal interaction and mobility. A strategic focus on aquaculture at the Ships and Ocean Structures department has resulted in numerous model tests in the Ocean Basin Laboratory focusing on innovative fish farm concepts, which will facilitate more exposed aquaculture operations. Cooperation between SINTEF Ocean and SINTEF Digital, which have overlapping research activities in autonomy, robotics, and machine learning/vision, has become regular through the Centre's work.

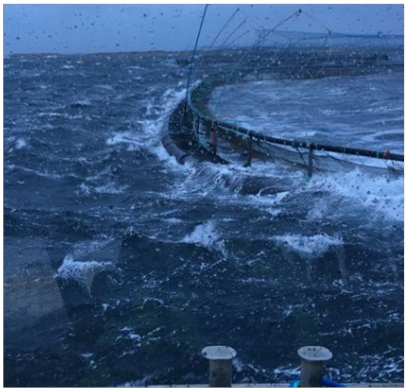
Effects for research partners

Most of EXPOSED's activities represent a collaborative effort from all research partners - IMR, NTNU, SINTEF Ocean, and SINTEF Digital. For these research groups, the Centre has expanded knowledge, networks, and the extent of research activities and topics. The value of

this collaboration has been highlighted during meetings and EXPOSED-themed discussions about the practical challenges faced by fish farmers. This emphasizes the importance of a multidisciplinary approach and close collaboration among research groups and partners.

Several of EXPOSED's research partners have also worked together on several associated projects, such as SFI Smart Maritime, SFI MOVE, SFI Blues, SFI Autoship, SFI Harvest and NTNU AMOS (Centre for Autonomous Marine Operations and Systems). These collaborations have involved research activities, model development, knowledge exchange, and joint publications.





Effects for the research system

The joint activities of the partners in EXPOSED have increased knowledge and resulted in a shared understanding across technological, biological, and societal research disciplines. This new knowledge and collaboration have increased quality and coherence in the Norwegian research system.

In 2022, NTNU, NTNU Societal Research and SINTEF established a Gemini centre for sustainable aquaculture in order to coordinate these strong research groups.

EXPOSED has also collaborated with other NTNU and SINTEF research centres to evaluate the critical factors for innovation in large partnerships and the CRI/SFI system. The goal of this SFI Task Force is to strengthen and enhance the Norwegian innovation ecosystem. They are striving to better understand, measure, and highlight all types of innovations emerging from the SFIs. Their report, due for release in the fall of 2023, aims to shape the research system in the coming years.

Moreover, the research partner NTNU has made structural advancements in their research and educational system. They introduced a minor in aquaculture for technology and engineering students, now available to all students pursuing a 5-year master's degree at NTNU. As stated on the NTNU webpage, "minor students form an interdisciplinary group from various technology programs, sharing a common interest in Norway's second largest economy - the aquaculture sector. Through a combination of specialized subjects, industry-led meetings, and company visits, students are well prepared to join an industry increasingly focused on technology. The seminar themes are derived from practical knowledge, research, and societal needs:

- Aquaculture as a system and technology
- Fish welfare
- Technology development on biology's terms
- Sustainable aquacultur

EFFECTS OF CENTRE FOR THE INDUSTRY PARTNERS AND SOCIETY AT LARGE

The aquaculture industry has experienced a period of **significant development** and disruption concurrent with the timeline of EXPOSED. Technologies and regulations have been updated, with EXPOSED making considerable contributions.

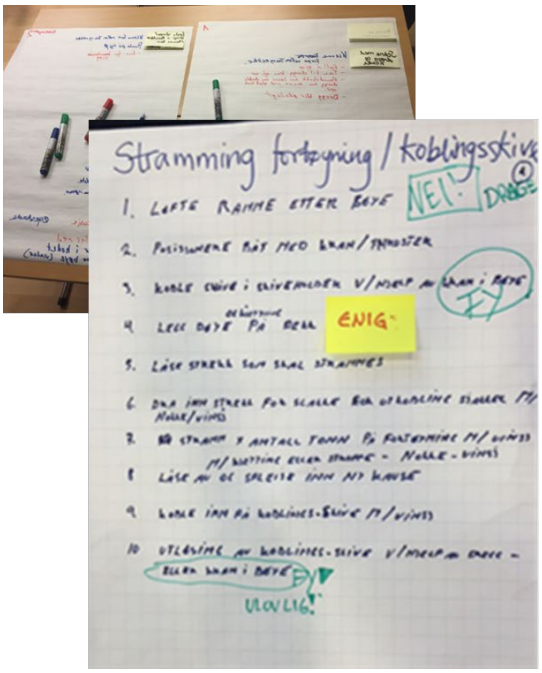
Effects for industry partners

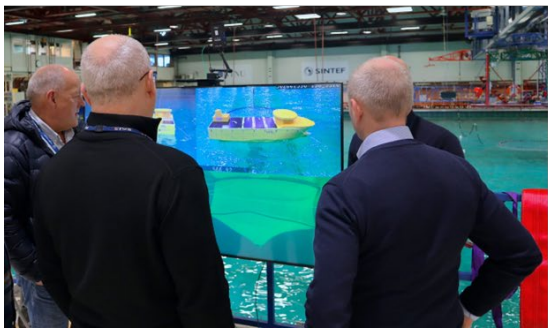
EXPOSED's industry partners have been connected to the research activities and collaborations previously described. They've been involved in various stages of the R&D activities and projects. They were also invited to share how the Centre influenced their R&D activity, its primary effects, and opportunities created.

One of EXPOSED's greatest accomplishments has been the establishment of a robust network comprising various disciplines and organizations. All partners have emphasized this benefit, noting that it has broadened their perspective and offered new insights into the evolving aquaculture industry. The mutual understanding fostered among the partners has reduced uncertainties and guided decisions on innovation directions.

EXPOSED has been a platform for the larger industry partners to discuss and contribute to topics related to exposed aquaculture. It has been instrumental in identifying critical areas that warrant research. The Centre has also pinpointed specific areas in aquaculture that present challenges and opportunities for improvement, particularly with existing and future technologies. This insight has informed the partners' decisions on which R&D activities to pursue or abandon.

EXPOSED has created opportunities for partners to collaborate with both industry and research partners, thereby fostering a shared understanding of the specific needs of exposed aquaculture. Openness is a common strategy in the aquaculture industry, and while patents have not been the focus of EXPOSED activities, numerous innovations have been developed.





The partners have valued the long-term dialogue and meeting arenas in EXPOSED.

Early on, a patent landscape analysis was conducted, assisted by the Norwegian Industrial Property Office. EXPOSED has not tracked individual patents held or developed by each partner. Most of the industry partners' innovations are incremental changes developed across the centre period. For example, aquaculture company partners have employed exposed sites because of the knowledge created in EXPOSED. Improved vessel design and floating collars have been developed as collaboration between researchers and companies. New standard NS9415 and guidelines for rafts and emergency preparedness have been developed by some partners because other companies or authorities urged for it. See findings section for more examples.

Internal report documenting the state of knowledge and discussing the innovation potential of salmon farming at more exposed sites (b) Patent landscaping report.

Effects for the public and society at large

For the EXPOSED consortium, communicating research results has been essential to facilitate innovation, acquire more research funding, and elevate the knowledge level in aquaculture discussions. It has influenced media and societal debates about coastal and offshore aquaculture.

Throughout its existence, EXPOSED has focused on external dialogue, supporting projects like "Brohode 2020" led by NTNU and funded by the Norwegian Research Council. These projects aim to foster closer collaboration between the aquaculture industry, universities, and research institutes. Networks and industry clusters such as NCE Aquatech, NCE Aquaculture, NCE Seafood Innovation and Stiim Aqua have been useful platforms for dissemination and dialogue beyond the consortium.

In 2021, Centre Director Hans Bjelland was appointed to a public committee for a comprehensive review of the permit system in the aquaculture industry – the Havbruksutvalget. This appointment is a

recognition of his and EXPOSED's history of close cooperation between research and the aquaculture industry. The committee will submit their recommendations in September 2023.

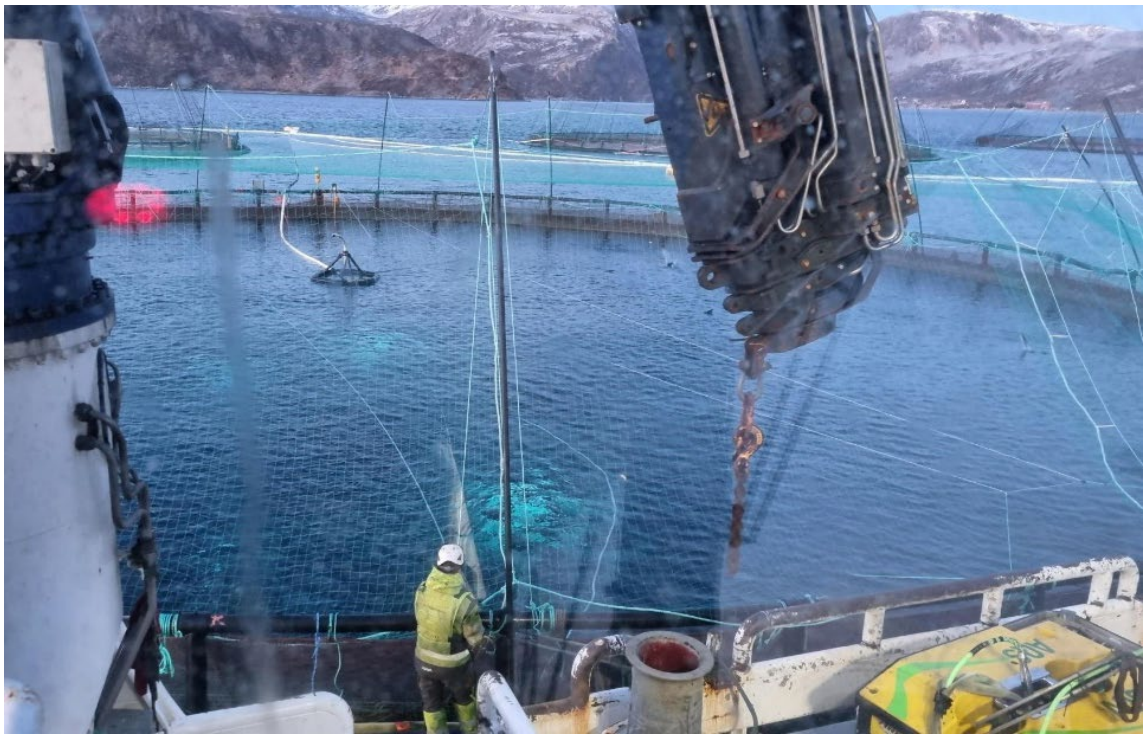
From 2022, EXPOSED activities focused on understanding and improving the Centre's contributions by analyzing research outcomes, communicating specific and general results, and discussing the industry and societal needs. This resulted in collaborations with more companies, authorities, and governmental bodies on the further development of the aquaculture industry and governance.

EXPOSED has given and is still developing directions for further development of the aquaculture industry.

Exchange of personnel between the partners

Over the years, several members of EXPOSED have changed employment among the partners. This exchange has fostered more knowledge and understanding across companies and groups, potentially increasing research in the industry and improving industry competence in research and education.

A former EXPOSED PhD student, now employed by SINTEF Ocean, participates in the "Researcher in Industry" scheme, an activity of the previously mentioned associated Brohode project. This initiative allows a researcher to intern in a company for a few weeks, boosting the company's competence in a selected area while strengthening the relevance of research and education.



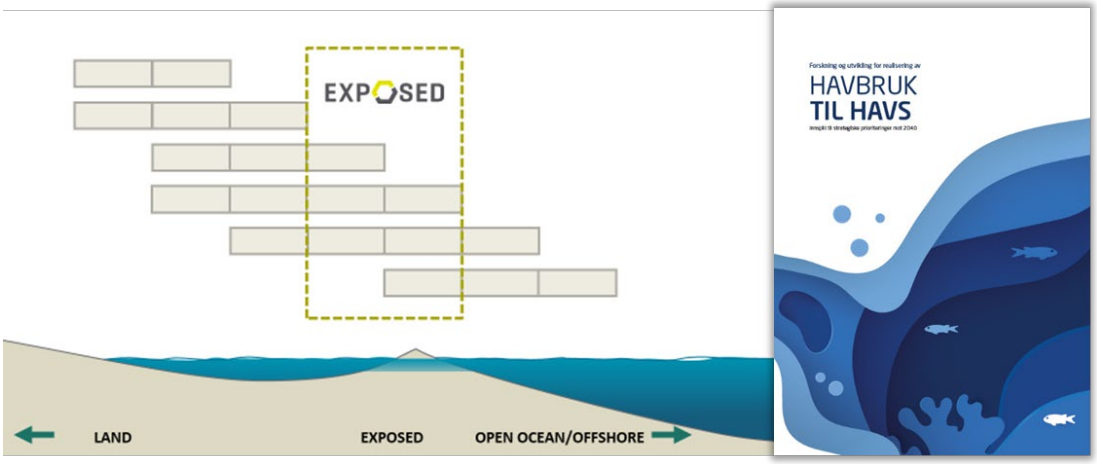
The researcher did not take any pictures of himself while being a "Researcher in Industry", but this is a photo he shot of a coworker in an operation.

FUTURE PROSPECTS

The partners of the EXPOSED Centre anticipate a lasting, positive impact stemming from its work. With significant challenges still present and considerable potential for enhanced solutions, the outcomes of EXPOSED are expected to inspire a variety of innovations and further research. In fact, the partners are continually refining their products based on these results.

As outlined in the impact sections, the aquaculture industry's concepts and regulations are currently undergoing substantial transformation. The results of EXPOSED are helping shape these technological and policy advancements.

From a research perspective, the Centre's activities have inspired several new projects. EXPOSED has underscored that exposed and offshore aquaculture represent unique realities, each demanding different approaches and solutions. The EXPOSED partners have developed specialist competence in these areas.



XPOSED has not emphasized on offshore aquaculture as this is still not in operation, but has gained useful knowledge when offshore aquaculture is being planned.

SFI Blues aspires to empower the Norwegian industry to create innovative floating stationary structures. These structures will meet diverse needs and requirements in the renewable energy, aquaculture, and coastal infrastructure sectors. The knowledge and expertise nurtured through EXPOSED play a crucial role in achieving this goal.

SFI Blues will further explore research questions about maritime environment and aquaculture technology.

Moreover, infrastructure elements like buoys, fish tags, swimming tunnels, and models, provided by EXPOSED and owned by the partners, will continue to be used in research projects to expand knowledge about fish or aquaculture sites.

Looking ahead, SINTEF Ocean plans to incorporate the research outcomes from EXPOSED into the forthcoming Norwegian Centre for Ocean Technology. This represents the most substantial single investment in maritime research infrastructure in recent Norwegian history.

The evolving aquaculture industry will demand scientific design and verifications.

CONCLUSION

As the journey of EXPOSED draws to a close, it's a moment to pause and reflect on the intricate tapestry we've woven together as a Research Centre. At the heart of our model was an emphasis on collaboration between research groups and users, creating an arena for ideas and solutions designed to address real-world challenges in aquaculture.

As a Centre for Research-Based Innovation, we are measured both by our delivery of scientific excellence and by our contributions towards fostering change and innovations in the industry. The former can be quantified through academic indicators, but innovation is both a more intrinsic process among the various partners and a process that sometimes take time to materialize. This report documents how EXPOSED has delivered on both.

A successful centre is not merely a vessel of knowledge and innovation but also a crucible of interdisciplinary cooperation. This has been deeply embodied in our model, where we prioritized cross-pollination of ideas, integrating academic insights with practical industry perspectives. We have seen first-hand how this collaborative approach fuels discovery, yields applicative solutions, and fosters a broader understanding of the multifaceted nature of our field.

During our period, the aquaculture industry has undergone substantial changes, with the evolution of new production systems designed for both sheltered and increasingly exposed locations. Our understanding of the challenges and potential solutions for exposed aquaculture operations has deepened significantly. Our research has dynamically adapted to these changes, while the original choice of our six research areas and how to organise our activities has been proven successful throughout. As we press on with technological advancements, our core focus remains on addressing key challenges associated with fish welfare and risk management.

APPENDIX 1: PERSONNEL, INCLUDING POSTDOCS AND PHD CANDIDATES

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
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
Ørjan Selvik	SINTEF Ocean	Vessel design
Martin Gutsch	SINTEF Ocean	Marine operations
Eivind Lona	SINTEF Ocean	Aquaculture structures
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
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	Gender	Nationality	Period	Thesis title
Bjørn Magnus Mathisen	M	Norwegian	Q3 2015 – Q2 2020	Monitoring and operational decision support
Pål Takle Bore	M	Norwegian	Q3 2015 – Q4 2018	Intelligent aquaculture structures
Ingunn Marie Holmen	F	Norwegian	Q1 2016 – Q2 2021	Safety and risk management
Bent Arnesen Haugaløkken	M	Norwegian	Q3 2016 – Q3 2019	Remotely-controlled and automated underwater vehicles
Malthe Hvas	M	Danish	Q2 2016 – Q2 2019	Physiology and behaviour of salmon in strong water currents
Waseem Hassan	M	Pakistani	Q4 2016 – Q4 2020	Acoustic fish telemetry for real-time fish performance monitoring in aquaculture
Håkon Måløy	M	Norwegian	Q2 2018 – Q1 2022	Recognizing ecological behaviour patterns using deep learning
Hans Tobias Slette	M	Norwegian	Q3 2018 – Q3 2021	Methods and models for marine system design of vessels and vessel operations in exposed aquaculture
Muhammad Mukhlas	M	Indonesian	Q4 2018 – Q4 2022	Closed cage aquaculture structures in waves and currents
Sverre Herland	M	Norwegian	Q3 2020 – Q3 2023	Reinforcement learning for contact-free operations
Wai Yen Chan	F	Chinese	Q4 2021 – Q3 2024	Computer vision for maritime situational awareness purposes

PhD students with financial support from sources outside the EXPOSED centre

Name	Gender	Nationality	Funding	Period	Thesis title
Siri Holen	F	Norwegian	Sustainfarmex (RCN)	Q1 2012- Q1 2019	Safety in Norwegian Fish Farming - Concepts and methods for improvement
Kristbjörg Edda Jónsdóttir	F	Norwegian	Strategic research project at SINTEF Ocean	Q3 2016 - Q3 2019	Dynamics of water flow and turbulence in large-scale aquaculture sea cages
Stian Sandøy	M	Norwegian	Reducing risk in aquaculture – improving operational efficiency, safety and sustainability (HAVBRUK2, RCN)	Q3 2016 - Q3 2019	Sensor fusion for autonomous underwater inspection of aquaculture structures
Yugao Shen	M	Chinese	NTNU AMOS – Centre for Autonomous Marine Operations and Systems	Q3 2013 - Q3 2016	Limiting operational conditions for a well boat
Stefan A. Vilsen	M	Danish	NTNU AMOS – Centre for Autonomous Marine Operations and Systems	Q1 2014 - Q1 2018	Hybrid model testing of marine systems
Eirik Svendsen	M	Norwegian	SalmonInsight (HAVBRUK2, RCN)	Q3 2018 - Q3 2022	Links between salmon physiology and online monitored behaviour
Martin Slagstad	M	Norwegian	NTNU AMOS – Centre for Autonomous Marine Operations and Systems	Q4 2019-	Advanced and rational analysis of steel fish farms in exposed waters

Postdoctoral researchers with financial support from the centre budget

Name	Gender	Nationality	Period	Scientific topic
Ása Johannesen	F	Faroese	Q3 2018 – Q3 2020	Fish behaviour and welfare in waves
Malthe Hvas	M	Danish	Q2 2019 – Q3 2022	Physiology and behaviour of salmon in strong water currents
Bjørn Magnus Mathiesen	M	Norwegian	Q4 2021- Q1 2023	Monitoring and operational decision support

Postdoctoral researchers with financial support from sources outside the centre

Name	Gender	Nationality	Period	Scientific topic	Funding
Mette Remen	F	Norwegian	Q1 2012-Q1 2015	Tolerance limits for oxygen fluctuations and water current speed	SFI Create (RCN) and Akvaplan NIVA
Xue Yang	F	Chinese	Q2 2017 - Q1 2019	Operational risk assessment	Reducing risk in aquaculture – improving operational efficiency, safety and sustainability (HAVBRUK2, RCN)
Eirin Marie Bardal	F	Norwegian	Q4 2016 - Q4 2016	Environmental risk assessment in aquaculture	Reducing risk in aquaculture – improving operational efficiency, safety and sustainability (HAVBRUK2, RCN)

Master's students

Name	Gender	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

Name	Gender	Period	Affiliation	Topic
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)
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)

Name	Gender	Period	Affiliation	Topic
David Williams	M	Q3 2016 – Q2 2017	Department of Marine Technology, NTNU	Extreme loads on a feeding barge
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)
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 2021	Department of Marine Technology, NTNU	Simulation-based analysis of salmon encounters with delousing operations
Mats W. Langseth	M	Q1–2 2021	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 2021	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 2021	Department of Marine Technology, NTNU	Mobile slaughterhouses at sea – do stun-and-bleed vessels meet Norwegian salmon farming requirements?
Vilde Xiu Drønen	F	Q3 2021 – Q2 2021	Department of Marine Technology, NTNU	Guidance and navigation principles for autonomous ROV missions in an aquaculture context
Henning Ødeby Karlsen	M	Q3 2021 – Q2 2021	Department of Marine Technology, NTNU	Autonomous Aquaculture: Implementation of autonomous mission control for unmanned operations
Kenny Hoang Nguyen	M	Q3 2021 – 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
Kyrre Haugland	M	Q3 2021 – Q2 2021	Department of Engineering Cybernetics, NTNU	Cybernetics smart and resilient sensor fusion and bathymetric SLAM for future autonomous aquaculture

Name	Gender	Period	Affiliation	Topic
Esten Solem Dalseg	M	Q3 2021 – Q2 2021	Department of Engineering Cybernetics, NTNU	Smart and resilient visual tracking for future autonomous aquaculture
Lindis Rokseth	F	Q3 2021-Q2 2022	Department of Industrial Economics and Technology Management (IØT)	Personal safety and automated aquaculture operations
Ingeborg Sofie Gumdal	F			

APPENDIX 2: SCIENTIFIC 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 – journal paper

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 – journal papers

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 – journal papers

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 – journal papers

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 – journal papers

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 – journal papers

Hassan, Waseem; Føre, Martin; Pedersen, Magnus Oshaug; Alfredsen, Jo Arve. 2020. A new method for measuring free-ranging fish swimming speed in commercial marine farms using Doppler principle. IEEE Sensors Journal 2020. Volum 20.(17) s.10220-10227

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

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

Riseth, Erling Nilsen; Fraser, Thomas; Sambraus, Florian; Stien, Lars Helge; Hvas, Malthe. 2020. Is it advantageous for Atlantic salmon to be triploid at lower temperatures? Journal of Thermal Biology 2020. Volum 89

2021 – journal papers

Bjerkeng, M., Kirkhus, T., Caharija, W., Thielemann, J. T., Amundsen, H. B., Ohrem S. J., and Grøtli, E. I., ROV Navigation in a Fish Cage with Laser-Camera Triangulation, Journal of Marine Science and Engineering, vol. 9, no. 1, p. 79, Jan. 2021

Føre, H.M., Endresen, P.C., Norvik, C., Lader, P., 2021. Hydrodynamic loads on net panels with different solidities. ASME. J. Offshore Mech. Arct. Eng. October 2021; 143(5): 051901. https://doi.org/10.1115/1.4049723

Føre, M., Svendsen, E., Økland, F., Gräns, A., Alfredsen, J. A., Finstad, B., Hedger, R. D., Uglem, I. 2021. Heart rate and swimming activity as indicators of post-surgical recovery time of Atlantic salmon (Salmo salar). Animal Biotelemetry. vol. 9.

Hassan, W., Føre, M., Pedersen, M. O., Alfredsen, J. A. 2021. A new method for measuring free-ranging fish swimming speed in commercial marine farms using Doppler principle. IEEE Sensors Journal; Volume 20. (17) s. 10220-10227 OCEAN NTNU

Holmen, I.M., Utne, I.B., Haugen, S. 2021. Identification of safety indicators in aquaculture operations based on fish escape report data. Aquaculture, 544, 737143.

Hvas, M., Folkedal, O., Oppedal, F. 2021a. 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., 2021b. The effect of fasting period on swimming performance, blood parameters and stress recovery in Atlantic salmon post smolts. Comp. Biochem. Physiol. A 255, 110913.

Hvas, M., Folkedal, O., Oppedal, F. 2021c. What is the limit of sustained swimming in Atlantic salmon post smolts? Aquacult. Env. Interact. 13. DOI: 10.3354/aei00401

Hvas, M., Folkedal, O., Oppedal, F. 2021d. Fish welfare in offshore salmon aquaculture. Reviews in Aquaculture.

Macaulay, Georgia; Warren-Myers, Fletcher; Barrett, Luke T.; Oppedal, Frode; Føre, Martin; Dempster, Tim. 2021. Tag use to monitor fish behaviour in aquaculture: a review of benefits, problems and solutions. Reviews in Aquaculture 2021; Volum 13.(3) pp. 1565-1582

Riseth, E. N., Fraser, T. W. K., Sambraus, F., Stien, L. H. & Hvas, M. 2021. Is it advantageous for Atlantic salmon to be triploid at lower temperatures? Journal of Thermal Biology, 89, 102548

Warren-Myers, F., Hvas, M., Vågseth, T., Dempster, T., Oppedal, F. Sentinels in salmon aquaculture: heart rates across seasons and during crowding events. Frontiers in Physiology. 12. DOI: 10.3389/fphys.2021.75565

Yang, X., Utne, I.B. and Holmen, I.M., 2021. Methodology for hazard identification in aquaculture operations (MHIAO). Safety Science, 121, pp.430-450.

2022 – journal papers

Hvas, M. 2022. Influence of photoperiod and protocol length on metabolic rate traits in ballan wrasse Labrus bergylta. Journal of fish biology. DOI: 10.1111/jfb.14981

Hvas, M. 2022. Swimming energetics of Atlantic salmon in relation to extended fasting at different temperatures. Conservation Physiology. DOI: https://doi.org/10.1093/conphys/coac037

Hvas, M., Bui, S. 2022. Energetic costs of ectoparasite infection in Atlantic salmon. J. Exp. Biol. DOI: 10.1242/jeb.243300

Hvas, M., Nilsson, J., Vågseth, T., Nola, V., Fjelldal, P. G., Hansen, T., Oppedal, F., Stien, L. H., Folkedal, O. 2022. Full compensatory growth before harvest and no impact on fish welfare in Atlantic salmon after an 8-week fasting period. Aquaculture. 546. https://doi.org/10.1016/j.aquaculture.2021.737415

Johannesen, A., Patursson, Ø., Kristmundsson, J., Pætursonur Dam, S. Mulelid, M., Klebert, P. 2022. Waves and currents decrease the available space in a salmon cage. PLoS ONE. https://doi.org/10.1371/journal.pone.0263850

McIntosh, P, Barrett, L. T., Warren-Myers, F., Coates, A., Macaulay, G., Szetey, A., Robinson, N, White, C., Samsing, F., Oppedal, F., Folkedal, O., Klebert, P., Dempster, T. 2022. Supersizing salmon farms in the coastal zone: A global analysis of changes in farm technology and location from 2005 to 2020. Aquaculture. 553. https://doi.org/10.1016/j.aquaculture.2022.738046

Moe Føre, H., Endresen, P. C., and Bjelland, H., 2022. Load coefficients and dimensions of Raschel knitted netting materials in fish farms. ASME. J. Offshore Mech. Arct. Eng. doi: https://doi.org/10.1115/1.4053698

Risholm, P., Mohammed, A., Kirkhus, T., Clausen, S., Vasilyev, L., Folkedal, O., Johnsen, Ø., Haugholt, K. H., Thieleman, J. 2022. Automatic length estimation of free-swimming fish using an underwater 3D range-gated camera. Aquacult. Eng. https://doi.org/10.1016/j.aquaeng.2022.102227

Ohrem, S. J., Amundsen, H. B., Caharija, W., & Holden, C. 2022. Robust adaptive backstepping DP control of ROVs. Control Engineering Practice, 127, 105282. https://doi.org/10.1016/j.conengprac.2022.105282

Slette, H. T., Asbjørnslett, B. E., Pettersen, S. S., & Erikstad, S. O. 2022. Simulating emergency response for large-scale fish welfare emergencies in sea-based salmon farming. Aquacultural Engineering, 97, 102243. https://doi.org/10.1016/j.aquaeng.2022.102243

Yang, X., Holmen, I. M., & Utne, I. B. 2022. Scenario analysis of fish escapes in Norwegian aquaculture for implementation of barrier management and improved learning from accidents. Marine Policy, 143, 105208. https://doi.org/10.1016/j.marpol.2022.105208

2023 – journal papers

Neis, B., Gao, W., Cavalli, L., Thorvaldsen, T., Holmen, I. M., Jeebhay, M. F., ... & Tapia-Jopia, C. 2023. Mass mortality events in marine salmon aquaculture and their influence on occupational health and safety hazards and risk of injury. Aquaculture, 566, 739225. https://doi.org/10.1016/j.aquaculture.2022.739225

Bjerkeng, Magnus Christian; Grøtli, Esten Ingar; Kirkhus, Trine; Thielemann, Jens Toivo; Amundsen, Herman Biørn; Su, Biao; Ohrem, Sveinung Johan. Absolute localization of an ROV in a Fish Pen using Laser Triangulation. IEEE Mediterranean Conference on Control & Automation 2023. https://ieeexplore.ieee.org/document/10185747

Ohrem, Sveinung Johan; Evjemo, Linn Danielsen; Haugaløkken, Bent Oddvar Arnesen; Amundsen, Herman Biørn; Kelasidi, Eleni. Adaptive Speed Control of ROVs with Experimental Results from an Aquaculture Net Pen Inspection Operation. IEEE Mediterranean Conference on Control & Automation 2023 https://ieeexplore.ieee.org/document/10185714

Thorvaldsen, Trine; Salomonsen, Cecilie; Ranum, Stine Albertsen; Trædal, Petter; Misund, Andreas Ugelvik; Holmen, Ingunn Marie. Prepared for the worst? Emergency preparedness in Norwegian fish farming - Status and further improvements. Aquaculture 2023. https://www.sciencedirect.com/science/article/pii/S0044848623006956

Conference papers

2016 – conference paper

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 – conference papers

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APPENDIX 3: POPULAR DISSEMINATION

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15.04.23: https://www.radionordkapp.no/nyheter/22847/har-studert-fartoyene-som-opererer-pa-oppdrettsanlegg/

13.04.23: https://ilaks.no/dette-ser-de-i-havbrukets-krystallkule/

13.04.23, Podcast Smart forklart: https://play.acast.com/s/60b75c5b8c26f80013d5ebce/6436e4e23b34ac0011a09eda

12.04.23: https://forskning.no/hav-og-fiske-havforskning-oppdrett/hvordan-kan-batene-operere-godt-pa-oppdrettsanlegg-i-storm-og-havstrommer/2178426

29.03.23: https://maritimt.com/nb/maritimt-magasin/hvordan-ser-fremtidas-havbruksflate-ut

22.03.23: https://www.kyst.no/forsking-sfi-exposed-sintef/felles-kunnskapsgrunnlag-for-videre-fartoyinnovasjon/1502665

18.03.23: https://www.intrafish.no/arbeidsliv/andre-maritime-naringer-har-etablerte-operasjonsgrenser-vi-oppfordrer-havbruk-til-a-gjore-det-samme/2-1-1418967

08.03.23: https://kolnegar.ir/2023/03/13/%D8%AF%D9%88%D9%82%D9%84%D9%88%D9%87%D8%A7%DB%8C-%D8%AF%DB%8C%D8%AC%DB%8C%D8%AA%D8%A7%D9%84-%D8%A8%D9%87-%D9%85%D8%AD%D9%82%D9%82%D8%A7%D9%86-%D8%A7%D9%85%DA%A9%D8%A7%D9%86-%D8%AF%D8%B3%D8%AA%D8%B1/

16.03.23: https://www.sintef.no/siste-nytt/2023/enter-the-title-atte-ar-med-eksponert-oppdrett-oppsummert-of-the-page/

08.03.23: https://technewsboy.com/digital-twins-offer-researchers-access-to-new-knowledge/?amp=1

28.02.23: https://ilaks.no/tester-naturkreftenes-virkning-pa-mannskap-og-utstyr/

21.02.23: https://www.tu.no/artikler/slik-kan-digitale-tvillinger-gi-oss-tilgang-pa-helt-ny-viten/526058

13.02.23: https://www.intrafish.no/kommentarer/forskning-pa-eksponert-oppdrett-star-ved-et-veiskille/2-1-1403119

09.02.23: https://www.kyst.no/sfi-exposed/slutt-for-sfi-exposed/1487287

09.02.23: https://www.kyst.no/exposed-konferansen-2023/1487339

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23.01.23: https://www.kyst.no/havbruk-til-havs-sintef-ocean/slik-vil-forskerne-gjore-livet-lettere-for-oppdrettsnaeringen/1479656

31.12.22: https://todayuknews.com/tech/deep-learning-may-help-to-prevent-salmon-escapes-in-rough-seas/ (betalingsmur)

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30.12.22:https://www.reddit.com/r/FishFarming/comments/zz3qgk/deep_learning_may_help_to_prevent_salmon_escapes/

30.12.22: https://aquahoy.com/deep-learning-may-prevent-salmon-escapes-rough-seas/

29.12.22: https://www.sintef.no/en/latest-news/2022/deep-learning-may-help-to-prevent-salmon-escapes-in-rough-seas/

30.12.22:http://www.ipacuicultura.com/noticias/en_portada/82756/sintef_y_sfi_exposed_desarrollan_inteligencia_artificial_para_evitar_los_escapes_de_salmon.html

30:12.22: https://thefishsite.com/articles/new-techniques-to-prevent-farmed-salmon-escapes

20.12.22: https://ilaks.no/slik-kan-datafangst-gjore-oppdrettsanlegg-mer-effektive/

24.10.22: https://weareaquaculture.com/featured/offshore-closed-pen-indepth/26663/

10.10.22: https://www.tu.no/artikler/mye-sollys-ga-problemer-for-autonom-undervannsfarkost/522675

08.10.22: https://www.tu.no/artikler/modellforsok-forte-til-strengere-oppdrettskrav/522523

27.09.22: https://forskersonen.no/debattinnlegg-etikk-fisk/forvirring-om-fisk-som-forsoksdyr/2084184

21.09.22: https://gemini.no/2022/09/forsok-forte-til-strengere-oppdrettskrav/

19.09.22: https://www.sintef.no/siste-nytt/2022/dyp-laring-kan-hindre-lakseromming-i-roff-sjo/

19.09.22: https://gemini.no/2022/09/dyp-laering-kan-hindre-lakseromming-i-roff-sjo/

14.09.22: https://www.aftenbladet.no/meninger/debatt/i/veQLVB/forsoeksfisk-for-bedre-dyrevelferd

12.09.22: https://forskersonen.no/debattinnlegg-fiskehelse-forsoksdyr/vare-dyreforsok-skal-fremme-fiskevelferd/2076121

08.09.22: https://www.intrafish.no/kommentarer/fra-nyttar-gjelder-en-ny-teknisk-standard-i-oppdrettsnaringa-derfor-gikk-vi-inn-for-skjerpede-krav/2-1-1292767

08.09.22: https://www.hi.no/hi/nyheter/2022/september-1/skremmende-tall-om-dyreforsok-er-storm-i-vannglass (HI forteller at de gjengir Adressa-kronikken)

08.09.22: https://www.an.no/forsoksfisk-for-bedre-dyrevelferd/o/5-4-1650396

05.09.22: https://forskning.no/dyrevelferd-fisk-fiskehelse/fisk-kan-ogsa-oppleve-smerte-sult-og-stress-men-pa-en-annen-mate-enn-andre-dyr/2071646

02.09.22: https://www.midtnorskdebatt.no/meninger/i/1OQQdK/skremmende-tall-om-dyreforsoek-er-storm-i-vannglass (og to sider i Adressas papirutgave)

01.09.22: https://www.nationen.no/motkultur/debatt/forsoksfisk-for-bedre-dyrevelferd/

01.09.22: https://www.kyst.no/pressemelding-sfi-exposed/ikke-skremt-av-strengere-krav/1407631

30.08.22: https://ilaks.no/teknologiske-svar-pa-ministerens-krav/

25.08.22: https://www.midtnorskdebatt.no/meninger/i/OrRr4b/slik-driver-vi-dyp-laering-under-vann

25.07.22: https://ilaks.no/vil-vi-fa-velferd-eller-vantrivsel-i-eksponert-fiskeoppdrett/

01.07.22: https://issuu.com/international_aquafeed/docs/iaf2207_w1 side 42-43

24.06.22: https://gemini.no/2022/06/forskere-etterlyser-helhetstenkning-etter-dodsulykke/

22.06.22: https://maritimt.com/nb/maritimt-magasin/ma-gjores-mer-oke-sikkerheten-i-havbruk

21.06.22: https://www.intrafish.no/arbeidsliv/sjomat-norge-det-er-veldig-viktig-at-man-larer-av-disse-ulykkene/2-1-1241678

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17.06.22 https://www.smp.no/meninger/kronikk/i/Kz5Gme/nye-spilleregler-for-havbruk-til-havs

16.06.22: https://www.an.no/nye-spilleregler-for-havbruk-til-havs/o/5-4-1606439

16.06.22: https://www.midtnorskdebatt.no/meninger/i/qW9xvO/sikkerheten-i-havbruksnaeringa-maa-styrkes

14.06.22: https://www.nordnorskdebatt.no/nye-spilleregler-for-havbruk-til-havs/o/5-124-185430

13.06.22: https://www.kyst.no/havbruk-til-havs-kronikk-offshore-havbruk/nye-spilleregler-for-havbruk-til-havs/1013314

07.06.22: https://www.sintef.no/siste-nytt/2022/heftige-havforhold-krever-nye-losninger/

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APPENDIX 4: FINANCING THROUGH THE LIFE OF THE CENTRE, COST & FUNDING

Financing through the life of the centre

Name	Cash	In-kind	Total
Research Council of Norway	96 000	-	96 000
Host institution (SINTEF Ocean)	-	12 399	12 399
Research partners*	-	24 673	24 673
Enterprise partners**	4 571	55 014	59 585
Public sector partners	-	-	-
Total	**100 569**	**92 086**	**192 655**

(All figures in NOK 1000)

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

** 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

Annual Work Report Total - Project Characteristics and **Costs** (All figures in 1000 NOK)

Item	SINTEF Ocean (SFH og Marintek)	IMR	SINTEF Digital (ICT)	NTNU IMT	NTNU IDI	NTNU ITK	Abroad University of Melbourne	Abroad Fiskaaling	Mowi/ Marine Harvest	Cermaq	SalMar	Kongsberg Seatex	Kongsberg Maritime Subsea	Kongsberg Merchant Marine	Kongsberg Maritime Offshore	Scale AQ/Aqualine	Møre Maritime	ÅF Engineering	Reinertsen	Anteo	Argus	Lerow	AQS	Marine Design	DNV	MacGregor Norway	Safetec Nordic	Total cost
Area 1 - Autonomy	7 801	-	9 925	-	-	-	-	-	44	30	58	26	377	146	-	55	-	-	-	-	726	1 201	56	-	34	741	-	**21 220**
Area 2 - Monitoring	8 557	-	-	-	2 258	-	-	-	3 830	1 615	1 441	3 134	6 397	101	6	168	-	-	-	1 650	-	-	-	-	9	-	-	**29 166**
Area 3 - Structures	10 363	-	-	-	-	-	-	-	134	366	87	-	-	-	-	3 030	-	546	-	-	-	145	40	-	236	52	-	**14 999**
Area 4 - Vessels	7 425	-	-	456	-	-	-	-	79	59	38	526	133	1 613	856	124	3 177	-	-	-	302	174	705	6 540	29	1 005	-	**23 241**
Area 5 - Safety	6 031	-	-	962	-	-	-	-	23	1 104	353	-	7	68	12	390	-	-	-	72	-	170	6	-	361	113	531	**10 203**
Area 6 - Fish	1 548	5 763	3 253	-	-	371	1 750	-	120	1 127	292	-	1 044	-	-	259	-	-	-	-	-	-	-	-	4	-	-	**15 531**
Area 7 - The effect project	3 198																											**3 198**
Future concept and solutions for exposed fish farming	3 132	-	416	-	-	-	-	-	219	129	200	199	320	296	-	113	47	29	139	407	34	347	14	-	2	-	-	**6 043**
Governance and regulations	350	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	57	-	-	**407**
Students	0	6 569	0	19 287	7 809	4 047	0	3 385	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**41 097**
Administration	22 241	0	20	238	462	24	0	0	0	625	221	1 035	98	264	85	732	24	82	48	127	108	0	47	0	882	187	0	**27 550**
Total budget	**70 646**	**12 332**	**13 614**	**20 943**	**10 529**	**4 442**	**1 750**	**3 385**	**4 449**	**5 055**	**2 690**	**4 920**	**8 376**	**2 488**	**959**	**4 871**	**3 248**	**657**	**187**	**2 256**	**1 170**	**2 037**	**868**	**6 540**	**1 614**	**2 098**	**531**	**192 655**

Annual Work Report Total - **Funding** (All figures in 1000 NOK)

Item	SINTEF Ocean (SFH og Marintek)	IMR	SINTEF Digital	NTNU IMT	NTNU IDI	NTNU ITK	Abroad University of Melbourne	Abroad Fiskaaling	Mowi/ Marine Harvest	Cermaq	SalMar	Kongsberg Seatex	Kongsberg Maritime Subsea	Kongsberg Merchant Marine	Kongsberg Maritime Offshore	Scale AQ/Aqualine	Møre Maritime	ÅF Engineering	Reinertsen	Anteo	Argus	Lerow	AQS	Marine Design	DNV	MacGregor Norway	Safetec Nordic	RCN Grant	Total funding
Area 1 - Autonomy	1 407	0	1 782	0	0	0	0	0	344	280	359	26	377	146	0	55	0	0	0	0	726	1 201	56	0	34	741	0	13 686	**21 220**
Area 2 - Monitoring	452	0	0	0	2 259	0	0	0	3 980	1 615	1 441	3 134	6 397	101	6	168	0	0	0	1 650	0	0	0	0	9	0	0	7 954	**29 166**
Area 3 - Structures	163	0	0	0	0	0	0	0	133	366	87	0	0	0	0	3 030	0	546	0	0	0	145	39	0	210	52	0	10 228	**14 999**
Area 4 - Vessels	252	0	0	456	0	0	0	0	79	59	38	526	133	1 613	856	124	3 177	0	0	0	302	174	705	6 540	28	1 005	0	7 174	**23 241**
Area 5 - Safety	0	0	0	165	0	0	0	0	23	1 304	371	0	7	68	12	390	0	0	0	72	0	170	6	0	361	113	531	6 610	**10 203**
Area 6 - Fish	0	3 662	178	0	0	326	0	0	120	1 127	272		1 044	0	0	259	0	0	0	0	0	0	0	0	4	0	0	8 539	**15 531**
Area 7 - The effect project																												3 198	**3 198**
Future concept and solutions for exposed fish farming	389	0	0	0	0	0	0	0	294	204	275	199	320	296	0	114	47	29	139	407	34	347	13	0	2	0	0	2 934	**6 043**
Governance and regulations	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	57	0	0	350	**407**
Students	0	0	0	7 522	6 472	678	0	550	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	25 875	**41 097**
Administration	9 736	0	0	137	462	24	0	0	600	1 225	971	1 035	98	414	235	732	24	382	48	127	108	0	47	0	1 058	337	300	9 450	**27 550**
Total budget	**12 399**	**3 662**	**1 960**	**8 280**	**9 193**	**1 028**	**0**	**550**	**5 573**	**6 180**	**3 814**	**4 920**	**8 376**	**2 638**	**1 109**	**4 872**	**3 248**	**957**	**187**	**2 256**	**1 170**	**2 037**	**866**	**6 540**	**1 763**	**2 248**	**831**	95 998	**192 655**

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