
EXPOSED
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REPORT
2015

CONTENT

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EXPOSED
AQUACULTURE OPERATIONS
CENTRE FOR RESEARCH-BASED INNOVATION

exposedaquaculture.no

SUMMARY

*Significant parts of the Norwegian coast is today unavailable to industrial fish farming due to **remoteness and exposure** to harsh wind, wave, current and ice conditions. Regular as well as infrequent **operations** are challenging.*

*The Exposed Aquaculture Operations Centre (EXPOSED) will draw upon Norway's strong position in the aquaculture, maritime and offshore sectors to enable **safe and sustainable seafood production** in exposed coastal and ocean areas.*

EXPOSED is a Centre for Research based Innovation (SFI), a funding scheme administered by the Norwegian Research Council's Division for Innovation[1]. A SFI has the main objective to enhance the capability of the business sector to innovate by focusing on long-term research based on creating close alliances between research-intensive enterprises and prominent research groups. The EXPOSED Centre brings together global leading salmon farmers, key service and technology providers, SINTEF Fisheries and Aquaculture and other strong research groups, including AMOS (the Norwegian Centre of Excellence for Autonomous Marine Operations and Systems). The centre budget is composed of roughly 50% from the Research Council, 25% from the industry partners and 25% from the research partners.

Eight initial projects have been defined for 2015/2016 and onwards. In 2015, an initial project (P1) has documented the knowledge base and innovation opportunities. Other projects have focused on developing methodology (P5), establishing research infrastructure (P8), carrying out preliminary studies (P4) and initiating PhD candidates (P6 and P7). Full project activity will commence in 2016.

To support cross-disciplinary innovation and good communication within the centre, the centre has arranged a two-day EXPOSED Days during spring and a one-day EXPOSED Day during autumn. Such events will be arranged yearly, in addition to PhD/post-doc workshops and more targeted project related meetings. The EXPOSED Days will serve as a meeting place for innovation, presentation of results, and exchange of ideas as well as creating new projects.

There has been a significant industrial, as well as political interest in EXPOSED and its objectives in 2015. This interest is driven by a combination of:

- An ambition to increase salmon production, given that key environmental challenges are addressed
- Increasing salmon prices
- Low oil prices and suppliers to the oil & gas sector looking for other industries
- Industrial and political will to adapt competence and capacity from other industries in to seafood
- A new opportunity for farmers to apply for development concessions regime that drives innovation towards technological concepts for more exposed farming.

Also internationally, the topic of exposed farming raises significant interest. The research areas of the centre have been presented in various national and international forums to support future collaboration with other stakeholders.

sfi Centre for Research-based Innovation
The Research Council of Norway

[1] http://www.forskningsradet.no/prognett-sfi/Forside/1224067021121

VISION AND OBJECTIVES

EXPOSED will develop knowledge and technology for robust, safe and efficient fish farming at exposed locations.

Significant parts of the Norwegian coast is today unavailable to industrial fish farming due to remoteness and exposure to harsh wind, wave and current conditions. The EXPOSED aquaculture operations Centre will take advantage of Norway's strong position in the aquaculture, maritime and offshore sectors to enable safe and sustainable seafood production in exposed coastal and ocean areas. Technological innovations, such as more autonomous systems, offshore structures and vessels are needed to sustain farm production under all conditions and enable more robust, safe, controlled and continuous operations.

Main objective

To develop knowledge and technologies for EXPOSED aquaculture operations, enabling a sustainable expansion of the fish farming industry.

Industry objectives

- Enable safe and profitable operations at exposed fish farming sites to increase sustainable seafood production.
- Develop new technologies to underpin Norway's global leading position in aquaculture and maritime competence and technology.

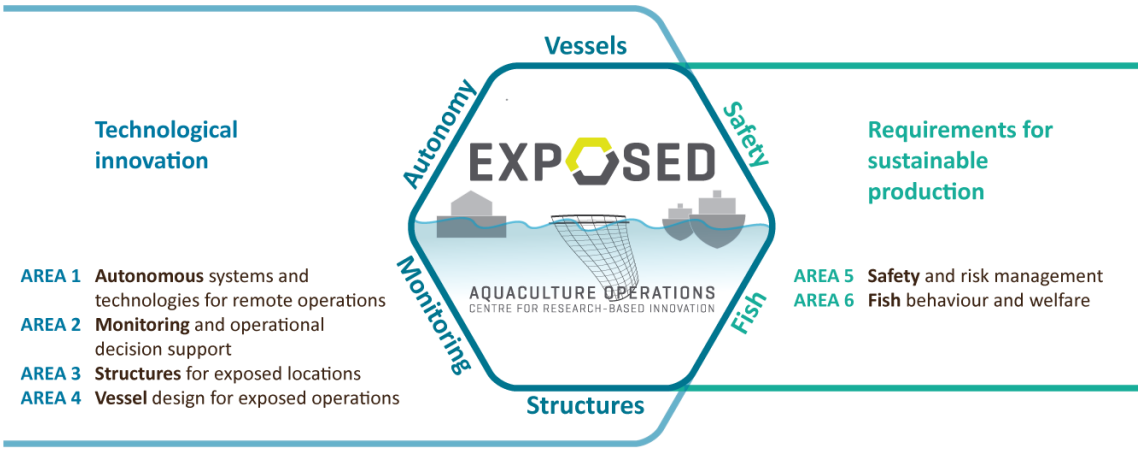
Research objectives

- Conduct fundamental and applied research into key knowledge gaps related to exposed aquaculture operations by combining research fields from the aquaculture, maritime and offshore sectors.
- Build knowledge and competence capacity through educating at least 11 PhD candidates, 4 post-docs and 30 MSc candidates.

EXPOSED brings together global leading salmon farmers, key service and technology providers, SINTEF Fisheries and Aquaculture and other strong research groups, including AMOS (the Norwegian Centre of Excellence for Autonomous Marine Operations and Systems).

RESEARCH STRATEGY AND PLAN

EXPOSED has identified six core research areas that will be crucial to address the challenges described.



Four of these focus on technological innovations for safe and reliable aquaculture operations:

- ### Area 1: Autonomous systems and technologies for remote operations
  Daily routine work and periodical operations must become less dependent on close human intervention.

- ### Area 2: Monitoring and operational decision support
  Severe weather conditions and remoteness impede access and increase the need for robust monitoring of structures, systems and fish welfare to assess system state and support operational decisions.

- ### Area 3: Structures for exposed locations
  Aquaculture structures need to be operational at exposed sites with respect to sea load response, personnel safety and fish welfare. Flexible and rigid systems, active regulation, and new concepts will be studied.

- ### Area 4: Vessel design for exposed operations
  Vessels, on-board equipment and logistical solutions must be designed to enable safe and efficient operations in exposed areas.

Two research areas focus on key requirements for sustainable production:

- ### Area 5: Safety and risk management
  Exposed operations require improved risk management strategies and systems.

- ### Area 6: Fish behaviour and welfare
  The technologies and new operational solutions must ensure fish performance and welfare in exposed conditions

Activities in EXPOSED will be organised in projects, combining research areas, partners and methods. Eight initial projects have been defined for 2015/2016 and onwards. These are described in *Scientific activities and results*.

ORGANISATION

Organisational structure

The organisation and implementation of the centre are governed by a **consortium agreement**, describing the obligations and rights of the partners, as well as roles and responsibilities of the different parts of the organisation. The **General Assembly** with representation from all partners elects the **Centre Board** of seven members among the centre partners. The board is the operative decision-making body for the execution of the centre.In 2015, the following people where members of the board:

Member of Centre Board	Affiliation
Arne Rinnan (Chairman)	Kongsberg Seatex
Noralf Rønningen	Aqualine
Harald Ellingsen	NTNU
Arne Fredheim	SINTEF Fisheries and aquaculture
Olai Einen	Cermaq
Ove Løfsnes	AQS
Frode Oppedal	Institute of marine research
Kjell Emil Naas (Observer)	The Norwegian Research council

Figure 1 EXPOSED Days 29. October 2016

The **Centre Director**, Hans Bjelland manages the Centre on behalf of the Host institution, SINTEF Fisheries and aquaculture, and reports to the Centre Board. Together with the **Management Group**, the Centre Director manages centre activities related to **projects**, **education** and **innovation**. The Management Group consists of Research Managers for the six core research areas, Project Managers, and a NTNU representative:

Member of Management Group	Role and responsibility
Hans V. Bjelland SINTEF Fisheries and Aquaculture	Centre Director Area 2 Project P1 and P6
Esten Ingar Grøtli SINTEF ICT	Area 1 Project P2
David Kristiansen SINTEF Fisheries and Aquaculture	Area 3 Project P7
Dariusz Eirik Fathi SINTEF MARINTEK	Area 4 Project P3
Ingunn M. Holmen SINTEF Fisheries and Aquaculture	Area 5 Project P4
Frode Oppedal Institute of marine research	Area 6 Project P5
Gunnar Senneset SINTEF Fisheries and Aquaculture	Project P8
Leif Magne Sunde SINTEF Fisheries and Aquaculture	Aquaculture operations
Ingrid Schjølberg NTNU	NTNU representative

Projects are set up with a **Project Manager** and a **Steering Committee**. The project leader has the responsibility for carrying out the project, while the Steering Committee has the responsibility to follow up on the progress and objectives. The Steering Committee is headed by one of the industrial partners.

Education is primarily maintained through the three NTNU departments, Marine Technology, Computer and Information Science, and Engineering Cybernetics. In addition, PhD and MSc candidates are educated at the University of Bergen through a collaboration with the Institute of Marine Research. PhD and post.doc candidates are associated with related projects. Several other NTNU departments have been involved in MSc and Bachelor student activities related to the centre.

Innovation is supported through arranging a yearly two-day EXPOSED Day in the spring, a one-day EXPOSED Day in the fall, and two yearly PhD/post-doc workshops. The EXPOSED Days will serve as a meeting place for innovation, presentation of results, exchange of ideas and creation of new projects. Further partner involvement and cross-disciplinary interaction will take place in the individual projects.

The centre host, SINTEF Fisheries and aquaculture, is physically located at SINTEF Sealab in Trondheim, which serves as a centre hub for centre activities. Other activities are carried out elsewhere in Trondheim and other parts of Norway, where partners and field activities are located.

Research facilities

The centre has access to an extensive research infrastructure through its research partners:

- A full-scale Aquaculture Engineering test site (ACE) at SalMar locations in Mid-Norway and exposed Marine Harvest and Cermaq locations in West and North Norway for both technological and biological studies. Technical e-infrastructure integrating the ACE aquaculture research sites with SINTEF Sealab SSO, will enable secure access for project partners.
- Ocean Basin (80 x 50 x 10 m), Ship Towing Tank (260 x 10.5 m), Marine Cybernetics Laboratory (40 x 6.45 x 1.5 m) and Marine structures laboratory at MARINTEK/NTNU.
- Flume tank (21 x 8 m) at SINTEF Fisheries and Aquaculture
- Applied Underwater Robotics Laboratory (ROVs and AUV), RV Gunnerus and Unmanned Aerial Vehicles Laboratory at NTNU.
- IMR experimental farms at Solheim and Austevoll and at IMR's land-based facilities in Matre to conduct scaled-down biological trials.
- Extensive hydrodynamic and structural testing laboratories through the international partners.

Figur 1 One of the full-scale test sites

Industry partners	Contribution/Role	AREA
Marine Harvest World's largest salmon and trout fish farmer. Runs large operations in Norway, Scotland, Canada and Chile.	End user of technology and solutions	All
Cermaq World's third largest salmon and trout fish farmer with operations in harsh environments especially in the northern parts of Norway.	End user of technology and solutions	All
SalMar World's fourth largest salmon and trout fish farmer. Operates large fish farms in particular at exposed locations in mid Norway.	End user of technology and solutions	All
Kongsberg Seatex and **Kongsberg Maritime** Supplier of technology and systems to the global maritime and offshore sector. Provides knowledge of and systems for communication, control, navigation, decision support, AUV etc.	Technology/solution provider	All
Aqualine Major international supplier of equipment and complete fish farms.	Technology/solution provider	1, 2, 3, 5, 6
Møre Maritime Provides maritime consulting, engineering and 3D modelling.	Technology/solution provider	4, 5
Reinertsen A leading provider of engineering, procurement, construction and installation to the oil companies, as well as the aquaculture sector.	Technology/solution provider	1, 3, 5
Anteo Operates and develops technical solutions and decision support systems for fish farming companies.	Technology/solution provider	2, 3, 4, 5, 6
Argus Remote Systems Performs research, development and manufacturer of electrical ROVs.	Technology/solution provider	1, 2
Lerow Service provider for inspection and cleaning of net cages and moorings by advanced use of ROV.	Service provider	All
AQS Service provider for inspection, maintenance and a range of operations, including delousing.	Service provider	1, 3, 4, 5, 6
Marin Design Provides vessel design and maritime consulting.	Technology/solution provider	4, 5

Research partners

	AREA
SINTEF Fisheries and Aquaculture is a multidisciplinary research organisation which contributes to solutions along the whole fisheries and aquaculture value chain - from biological and marine production, aquaculture and fisheries to processing and distribution.	All
The Norwegian Marine Technology Research Institute (MARINTEK) performs research and development for companies in the field of marine technology.	2, 3, 4
SINTEF ICT provides research-based expertise, services and products ranging from robotics, microtechnology, communication and software technology, computational software, information systems and security and safety.	1, 2
NTNU Department of Marine Technology (IMT) The department carries out research within the field of marine technology, and is the largest in its field in the western world. IMT hosts the Centre for Autonomous Marine Operations and Systems (AMOS), a Norwegian Centre of Excellence. AMOS will have a key role within the EXPOSED centre.	1, 3, 4, 5
NTNU Department of Computer and Information Science (IDI) The department conducts research in fields of computer and information science, covering hardware related research, intelligent systems and social implications of information systems.	1, 2
NTNU Department of Engineering Cybernetics (ITK) The department conducts research on 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
The Institute of Marine Research (IMR) is Norway's largest centre of marine science. The main task is to provide advice to Norwegian authorities on aquaculture and the ecosystems.	6

SCIENTIFIC ACTIVITIES AND RESULTS

The year 2015 was an initial year, and focus has been on establishing the organization and channels of communication, dialogue between partners, and planning and initiating activities.

Project plan

Eight initial projects have been defined for 2015/2016 and onwards. These projects, combine research areas, partners and methods. In 2015, an initial project (P1) has documented the knowledge base and innovation opportunities.

Other projects have focused on developing methodology (P5), establishing research infrastructure (P8), carried out preliminary studies (P4) and initiated PhD candidates (P6 and P7). Full project activities will commence in 2016.

Project 1: Future concepts

This project explores the areas of opportunity and future concepts for exposed aquaculture operations. It has been a centre-wide activity involving all partners and research areas, and serves as a foundation for future research and collaboration. This project is an important tool to form strategies and plans for the centre. The results will also benefit each partner to make better strategic decisions.

The project will study current knowledge, challenges, research needs and potential for innovation:

- Identify each partner's competence, ambitions and needs.
- Within each research area, compile, describe and evaluate possible technologies and strategies for exposed aquaculture.
- Describe current exposed locations, their environment and management experiences.
- Define the term "Exposed aquaculture operations".
- Compile a set of scenarios for future concepts for exposed aquaculture.
- Derive requirement specifications from the scenarios to establish a quality assured basis for the innovation processes.
- Use the project results to form internal strategies and centre plans.
- Use the project results as a basis for general communication about the centre and exposed aquaculture.

A collaboration with the Norwegian Industrial Property Office is to analyse the current state of intellectual property rights related to the research areas of the centre.

Project 2: In-cage multi-operation robot system for inspection and intervention

Human access to exposed sites will be limited compared to traditional fish farms, due to longer travel time, and because the environmental conditions at the location will make it indefensible to reside there. To still secure regularity in conduction of daily processes it will be necessary with increased level of autonomy and use of remote control.

Since a large portion of the production process in aquafarming takes place under water, mobile underwater vehicles such as ROVs and AUVs represent a natural starting point to carry out inspection, maintenance and repair operations.

Underwater vehicles have already proven to be a secure, robust and cost efficient alternative to divers at today's fish farms. At exposed sites there will be a need for underwater vehicles to carry out operations under harsher weather conditions and without humans present at the farm.

An example of a typical application is inspection of net cages. In modern aquaculture using gravity net cages, holes in the net and other type of net failures constitute a challenge with respect to fish escapees. To prevent escapees it

is necessary to carry out periodic inspection of the net cage, and repair the net when damaged.

Research topic for this project covers machine vision for inspection and estimation of biological growth on the net cage, autonomous functionalities for net cleaning, underwater navigation, compensation for environmental effects on the vehicles motion, concepts for launch- and recovery of vehicles, and underwater docking.

The project will be supported by a PhD at NTNU Department of Marine Technology planned to start in 2016.

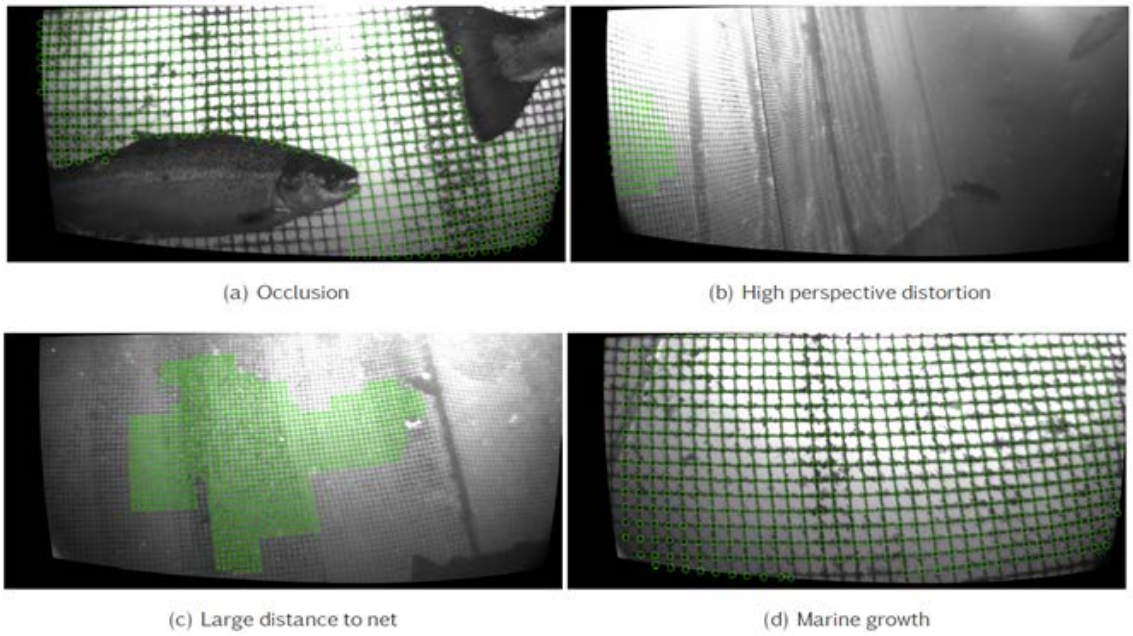


Figure 2 Example of applications for machine vision

Project 3: Vessels – Structures Interaction

Exposed aquaculture operations will impose new requirements on vessels and equipment to ensure safe operations, good operability and profitability. During operations, interactions between vessels and aquaculture installations will be of high importance. Ideally, such interactions should be optimised, reduced or avoided in order to improve safety and expand the operating window. To enable high profitability, attention should focus on minimising production losses.

This project will investigate new design concepts for vessels and structure interfaces for the increased reliability of exposed aquaculture operations. It is expected that larger vessels will lead to new requirements on the design of floating collar and mooring systems, which means that the interaction between the flexible collar and the rigid ship side will be essential. Analysis of actual operations will be important in order to reduce risk and increase safety, operability and profitability.

Firstly, the project will begin with a study on Identification of challenges (understanding the challenges and risks in exposed operations). Furthermore, there will be separate work packages on Vessel design concepts (studying new vessel designs and solutions), Exposed operations (new technologies/new procedures) and Feasibility studies (analysing the total concept of vessel-structure-operation).

The project will combine expertise and knowledge from several of the Research Areas in SFI EXPOSED. The project will be supported by a PhD at NTNU Department of Marine Technology planned to start in 2017, supervised by Professor Harald Ellingsen.

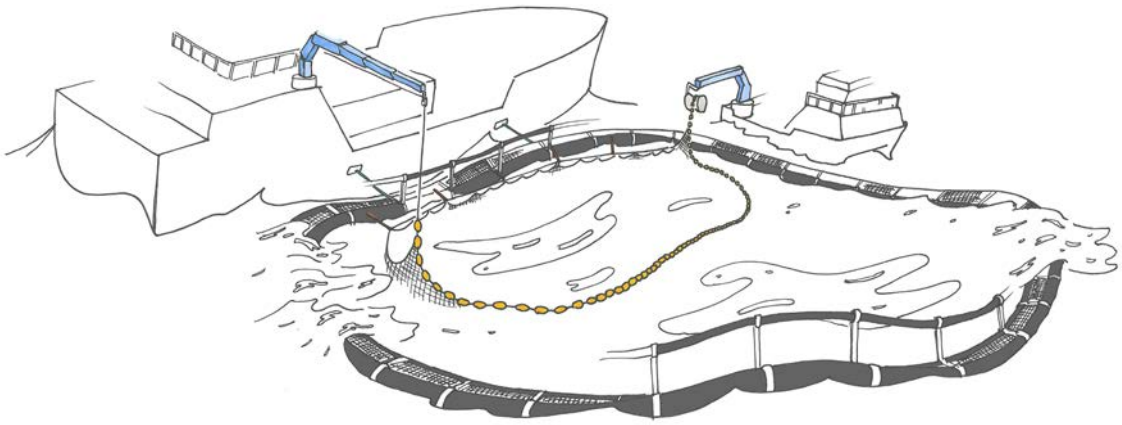


Figure 3 Vessel - Structures interactions

Project 4: Safety at sea

The sea-based aquaculture industry is the second most risk exposed occupation in Norway after fishing vessels. A previous study showed that today's fish farms operate at the safety limit of available technology and management systems. Interviews with fish farm workers have identified some aquaculture operations that imply especially high risk for occupational accidents and escape of fish. These are work on the net cage or the sinker tube; delousing with tarpaulins; and well boat operations in the fish farm. Such operations involve extensive use of cranes and the first two also the use of workboats and service vessels. In addition, there is still a large degree of manual operations and the success of the operations are dependent on the competence and abilities of individuals.

A brief and initial comparison of operations conducted by service vessels shows that there is a low degree of standardisation regarding the design and arrangements of work decks, as well as the work practices. Our hypothesis is that a standardised design, supporting safe operational practices, will be an important safety measure in itself. Additional benefits for the companies is that standardisation also may lower the design and building costs for these vessels. The project work will include visits to several service vessels of different designs and descriptions of the work operations in different regions and companies. Systematic risk assessments will be performed. The outcome of this work will be recommended operational practices as well as a recommended design and fitting of the work deck on board service vessels.

PhD candidate, Ingunn M. Holmen, (please see profile below) at NTNU Department of Marine Technology, started in January 2016 will be supporting the project. This PhD will be supervised by Professor Ingrid B. Utne and co-supervised by Professor Stein Haugen. The hypothesis laying the ground for the PhD is that safety levels in aquaculture operations can be increased by implementing systematic risk management adapted to the distinctive characteristics of this industry. Risk management deals with identifying, analysing, assessing and controlling occupational risk and major accident risks, through development of mitigating measures. Initially, the project will develop best practices for safety and risk management during planning and operation of complex and daily work operations at exposed fish farms. Examples of existing and implemented safety procedures and barriers will be identified, and describe how they function in daily operations. These practices will be analysed and compared with other industries to find out if learning across industries can be beneficial. Based on this we will determine organisational safety indicators and a method for the companies to perform internal safety audits. In a longer term, the outcome of the analysis will also be a set of guidelines and procedures for following best practices at exposed sites, which will serve as a foundation for standardising systems and operations to improve safety and reduce risks.

The P4 work will be interlinked with project P3 Vessel-structure interaction, and also exchange knowledge and data with P2 and P8.

Figure 4 Challenging environmental conditions

Project 5: Salmon behaviour and welfare in exposed aquaculture operations

Salmon farming in exposed areas require safeguarded animal welfare. As of today, there is no detailed knowledge of salmon behaviour and tolerances in high water flows and waves. Due to increasing water speeds in cages, salmon's swimming behaviour is changed. Instead of maintaining their circular swimming pattern around and around the cage, salmon position themselves towards the incoming water. The salmon can sprint for seconds, move rapidly in minutes and swim for ages at optimal speeds. Individuals, or more often, the shoal chooses its own optimal speed, which in turn varies with the day, night, expectations and hunger level. At moderate speeds exercise has a positive effect, but where is the limit for exposed sites in relation to the water flow? This project will describe behaviours under exposed conditions, documenting optimal and tolerance limits for water flow under variable other impact (temperature, oxygen, fish size, stress and more), and develop a system of welfare assessment in exposed aquaculture operations. Two PHD students will be hired to work with this topic. Infrastructures among the industrial and research partners will be used, and includes new on-line tool to assess individual behaviours and welfare. Field observations will be carried out at commercial farms and experimental trials will be performed in swim tunnels and push cages.

The project will be supported by two PhDs planned to start in 2016. One PhD will be at the Institute of Marine Research, supervised by Senior Scientist Frode Oppedal. The other will be at NTNU, Department of Engineering Cybernetics, supervised by Associate Professor Jo Arve Alfredsen and co-supevised by Scientist Martin Føre at SINTEF Fisheries and Aquaculture.

Project 6: Decision support systems

The project will develop decision support systems, initially focusing on vessel operations, where some of the important aspects are structural loads and deformations, interaction between structures and vessels, and fish welfare during crowding. Key functional requirements:

- Data integration from multiple systems, sensors and numerical models as a basis for predictions of the overall state of the operation.
- Evaluation of knowledge based methods suitable for the application domain, such as case based reasoning, for utilising past operational experiences and probabilistic networks to capture dependencies between system states, actions and effects.
- Adaptability to relevant user categories, and flexibility with respect to various technical systems.

The project is supported by PhD (Bjørn Magnus Matisen, see profile below) at Department of

Computer and Information Science starting who started autumn of 2015. The PhD is supervised by Professor Agnar Aamodt, and co-supervised by Professor Helge Langseth and Senior Researcher Gunnar Senneset at SINTEF Fisheries and Aquaculture.

Project 7: Reliable structures

Fish farming at exposed locations require robust and reliable structures that facilitate sustainable, safe and efficient production. Cages, mooring systems and feed barges used by the industry today are capable of operating at the sites in present use, but how will they perform when waves and current increases beyond the current level? As wave and current exposure increase, the forces on, and the response of, the structures increases and changes. Performance of structural components under increased exposure must be evaluated relative to the behaviour of the complete system. In this project, the performance of today's aquaculture structures at tomorrow's locations will be analysed using numerical models and physical experiments.

The main objective of the project is to develop knowledge-based design criteria for main components of aquaculture structures for exposed locations. This will be achieved by first establish objective descriptions of different levels of exposure based on measurements on selected sites and statistics of waves and current on all Norwegian sites. Secondly, cages, mooring systems and feed barges will be simulated at high waves and current exposure using physical and numerical models. The results from these simulations will then be analysed to identify problem areas related to increased exposure. In cooperation with AMOS/NTNU, the project will also educate a PhD candidate (Pål Takle Bore) within the field of marine structures addressing research-based design criteria for net cage systems.

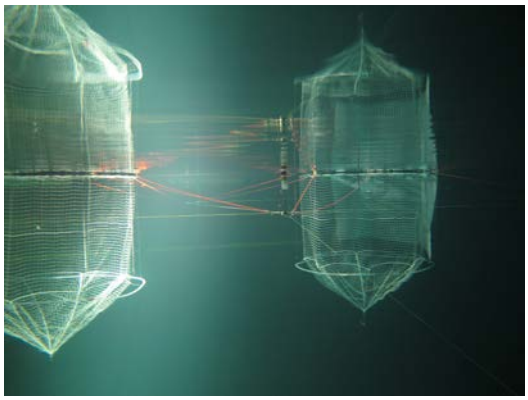


Figure 5 Example of physical simulations of cages in waves and current

Project 8: e-Infrastructure

Field experiments for testing and verification of new technical solutions for exposed aquaculture sites are expected to be a major part of the work in SFI Exposed. To facilitate such experiments, the three aquaculture companies participating in Exposed have all chosen a site where the conditions are among the most difficult with respect to wave and currents. This ensures realistic testing conditions of the new technical solutions. During the project period, new and even more exposed sites can be used for experiments.

Technical solutions for e-Infrastructure will be established at all these sites. In addition to instrument cabinets with standardised interfaces for digital and analogue sensors, local computers for data logging and battery backup will reduce the risk of data loss. All data is transferred to database servers at SINTEF SeaLab over broadband data links, with redundancy over permanent encrypted links over a mobile network.

In addition to e-Infrastructure for field experiments, long-term data series will be established as basis for designing new technical solutions for exposed sites:

- Oceanographic buoys: Currents, wind and wave data for 'next generation sites'
- Kongsberg Seatex MRU (accelerometer/gyro): Movements on cage and feed barge related to logging of what kind of operations which must be postponed due to weather conditions

Figure 6 Oceanic buoys

Associated projects

To further support research and innovation among the centre partners and for the centre goals in general, the EXPOSED centre aims to initiate or encourage associated projects, in addition to the centre-funded projects. These may involve one or more of the centre partners, and potentially others. They may vary between researcher based projects (e.g. funded by the Norwegian Research Council or EU) or more innovation-driven projects. The centre will seek to establish agreements within these to allow mutual benefits and synergies between EXPOSED and the associated projects. In 2015 the following associated projects where granted:

Project name	Duration, project type and funding	Host institution
Reducing risk in aquaculture – improving operational efficiency, safety and sustainability	2016-2019 Research based in HAVBRUK2	NTNU Department of Marine Technology
Safer operations and workplaces in fish farming	2016-2018 Research based in HAVBRUK2	SINTEF Fisheries and Aquaculture
Real-time hybrid model testing for extreme marine environments	2016-2019 Knowledge-Building Project for Industry in MAROFF	SINTEF MARINTEK

Results

Selected results in 2015 are presented below, with a reference to the associated EXPOSED project.

Description of challenges and future opportunities for exposed aquaculture (P1)

Current challenges of exposed aquaculture and future opportunities have been addressed, both in a published academic paper, and in an internal report. The paper describes research needs and research strategy planned for the Exposed Aquaculture Operations centre. The report is a more extensive account of the scientific basis for the centre plans, and outlines future concepts in aquaculture production. The results will be valuable in future strategies and plans for the centre, as well as for general communication about the centre and exposed aquaculture.

EXPOSED has collaborated with seven student groups from NTNU Department of Product Design to get fresh visions and views on the aquaculture future. The students handed in their assignments with focus on control room on land, the barge and various future cage solutions.

Figure 7 Third year students from the Department for Product Design are working with SFI Exposed on "Future Concepts" and where on a field trip to learn more about the Aquaculture industry

Figure 8 One of the student concepts by Tuva Haddal, Alexander Jonassen, Javier Núñez & Viktor Rydal

Analysis of wind generated waves on all Norwegian salmon sites (P1/P7)

What does "exposed locations" actually mean? This is hard to answer objectively since there is no clear overall definition to this term. The term is, however frequently used when the aquaculture industry is discussed, and it usually refers to a site where the most common sea state (and current) is more energetic than what is experienced on an average site. However, no overall long time wave statistics of Norwegian aquaculture sites exists, and in order to quantitatively discuss exposure this is necessary. Therefore, a method to estimate long time statistics of wind generated waves on all Norwegian salmon sites was developed.

All Norwegian aquaculture sites are registered at Directories of Fisheries. There are a total of 1070 salmon sites in Norway (according to the register pr. October 27, 2015), and all these sites were used in the analysis.

The method used fetch analysis on each site coupled with available wind statistics in order to produce a frequency distribution of significant wave height (H_s) and peak period (T_p). Fetch is defined as *the length of water over which a given wind has blown* (en.wikipedia.org), and can be used to estimate the wave condition if it is coupled with wind speed and duration. The fetch length was calculated by using the coordinates of each site and map data of the coastal region.

The wind data was obtained from the ERA-interim reanalysis available from the European Centre for Medium-Range Weather Forecasts. For each aquaculture site, the geographical position was looked up in the grid of the ERA-interim data, and linearly interpolated for each wind component between the closest grid cells. Data from the period 2002 to 2014 was used in the analysis.

Based on the wind and fetch the significant wave height H_s and peak period T_p was calculated for each 6h interval, thus creating a 12 year continually time series of H_s and T_p for all sites. However, please notice that this method is crude with respect to the assessment of each individual site. Bathymetry is for instance not included, and deep water conditions are assumed all over. The main motivation is however to get a statistical description of all sites in Norway, and to objectively identify sites that are significantly more exposed than the average. This will in the continued work with this method be used to propose objective descriptions of how exposure should be quantified.

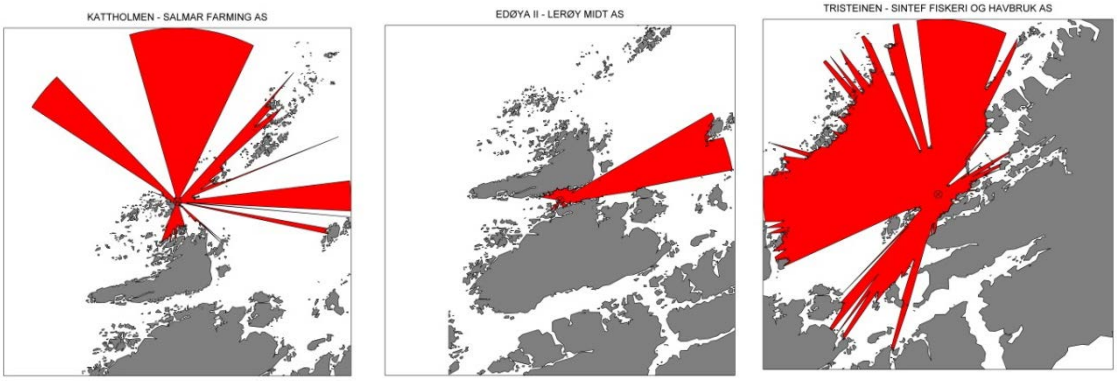


Figure 9 Example of fetch analysis of three sites in Sør-Trønderlag county. The red area indicates the area where the wind unobtrusively can blow towards the site position. The fetch is limited upwards to 40 km, and the resolution is 1 deg sectors and 200 m in the fetch direction.

Utilisation of results from the SEATONOMY project (P2)

Results from the project SEATONOMY is utilised in the EXPOSED centre. SEATONOMY encompasses strategic research collaboration between SINTEF ICT, SINTEF Materials and Chemistry, SINTEF Fisheries and Aquaculture, and MARINTEK (also part of the SINTEF Group). SINTEF is a Norwegian research organisation and all the aforementioned entities in SINTEF are developing or utilizing autonomous mobility technologies in cooperation with industry customers. During this work, we have found that there is a need for coherent, structured and scientifically rooted methods and tools for designing autonomous technologies for industrial use. By combining our efforts and know-how with current state-of-the-art research within disciplines such as ergonomics, autonomy and mobile robotics we are creating a common

methodology – the SEATONOMY methodology – for design of marine autonomous mobile systems that is useful for engineering of industrially viable solutions. A methodology is a systematic set of tools, methods, principles, rules, and analyses for regulating a given discipline. In other words, the SEATONOMY methodology offers a way to understand which methods, techniques, etc. that can be applied to designing autonomy for marine systems.

An outline of the methodology is presented in [1]. A method for designing autonomous marine operations is presented in [2], where as [3] deals with the relationship between levels of autonomy (LoA) and availability of communication, and how adaptivity of LoA can increase robustness in performance and handling in abnormal situations. In 2016, the methodology will be applied to the case of autonomous net inspection of a fish cage in project 2 in EXPOSED.

[1] E.I. Grøtli, T. A. Reinen, K. Grythe, A. A. Transeth, M. Vagia, M. Bjerkeng, P. Rundtop, E. Svendsen, Ø. J. Rødseth, and G. Eidnes, "SEATONOMY: Design, development and validation of marine autonomous systems and operations", In: Proc. of the MTS/IEEE OCEANS'15,2015

[2] E. I. Grøtli, M. Vagia, S. Fjerdingen, M. Bjerken, A. A. Transeth, E. Svendsen, and P. Rundtop, "Autonomous Job Analysis: A Method for Design of Autonomous Marine Operations", In: Proc. of the MTS/IEEE OCEANS'15, 2015

[3] K. Grythe, T. A. Reinen and A. A. Transeth, "Autonomy levels versus communication in an underwater environment", In: Proc of the MTS/IEEE OCEANS'15, 2015

Safety assessment on board service vessels (P4)

Cermaq Norway initiated this project in order to increase the employees' safety and well-being at work. This project gives special attention to the service vessel crews and how to make their work environment as safe as possible. During the recent years, the trend has been that specialised service vessels conduct the heaviest and most risky operations at the fish farms. This is for example anchoring and mooring line work. They also assist in delousing operations. The crews on board gradually become specialists and are thus highly competent in doing these operations. However, it is of high importance that the safety management system on board are up to date and well-functioning. Researchers have been on board the service vessels in Cermaq, including one hired from an external service provider, and conducted an evaluation of the overall safety work on board. At a later stage, the service vessel crews, safety representatives and fish farm operation managers participated in workshops to do risk assessments of a number of service operations. First they described the operations in detail and identified possible hazards, and the next step was to evaluate risks and suggest possible preventive measures. The results from the project have been used as input for the work in P4.

Requirements for safety management at fish farms (P4)

A summer student was hired in 2015 to develop an overview of state-of-the-art safety management in the aquaculture industry, with special emphasis on the operation of the fish farms. The focus was regulatory requirements, discrepancies between these and company-internal procedures, nonconformity practices, and a short description of previous R&D in the field. The summer student has continued working with this theme as a master student at NTNU.

Critical swimming speed as a relevant upper velocity tolerance limit for Atlantic salmon (*Salmo salar*) in exposed aquaculture sea cages (P5)

In order to define a limit for acceptable peaks in current velocity within exposed Atlantic salmon sea cages, a study measured the maximum swimming speed that this species can uphold for a limited period of time (< 20 min), *i.e.*, the critical swimming speed (U_{crit}). To achieve relevant U_{crit} data for commercial aquaculture, the test was performed with groups of post-smolt (0.29 ± 0.09 kg, mean ± SE) and adult (1.96 ± 0.09 kg) A. salmon in a larger swim tunnel than what has previously been used (248 cm, 17–23 kg/m^3). The extent to which U_{crit} is sensitive to experimental set-up, was investigated by comparing the outcome with U_{crit} obtained with individual fish in a smaller respirometer swimming chamber, under otherwise identical experimental conditions. The mean U_{crit} found for

post-smolts tested in the swim tunnel was significantly higher than for fish tested in the respirometer (3.18 ± 0.05 vs. 2.31 ± 0.12 BL/s, $p < 0.001$), emphasizing the importance of using relevant experimental conditions to obtain U_{crit} values that are suitable as guidelines for aquaculture management. The U_{crit} of adults was 1.82 ± 0.45 BL/s, considerably lower than in post-smolts. Fork length explained 80 % of the total variability in U_{crit} for all fish tested in the swim tunnel and the relationship between fork length and U_{crit} was presented for fish ranging in size from 24 to 61 cm. This relationship may be used to calculate a size specific velocity tolerance limit for A. salmon, during short-term peaks in current velocity (< 20 min). It is however emphasized that considerably lower velocities are required for efficient feeding and growth, that U_{crit} is expected to be temperature-dependent and that recovery from exhaustive swimming may reduce the capacity for growth between peak velocity periods. The present results represent a starting point for the development of a knowledge base on suitable current velocity profiles for A. salmon on-growth at exposed farming sites.

Figure 10 Swimming tunnel

Effect of ectoparasite infection density and life-history stages on the swimming performance of Atlantic salmon *Salmo salar* (P5)

Farm sites in offshore locations are one future solution, however the animal's welfare and tolerance to high-current velocity sites must be considered, particularly when health status is compromised by pathogens. A study tested the effect of parasite density and life-history stage on the swimming performance of Atlantic salmon *Salmo salar* using a swim tunnel. Salmon with three different sea lice *Lepeophtheirus salmonis* densities (0, 0.02 ± 0.01 and 0.11 ± 0.01 lice cm^{-2}) were tested across the four major life-history stages of lice (copepodid, chalimus, pre-adult and adult) for critical swimming performance (U_{crit}). Salmon U_{crit} declined slightly by a mean of 0.04 – 0.10 BL sec^{-1} with high parasite densities compared to uninfected and low densities, across the lice stages. Progression through the parasite life-history stages also reduced swimming performance, a relationship that interacted with body length and parasite density. Sub-lethal infection by sea lice can incur negative fitness consequences for farmed Atlantic salmon held in high-current velocity sites, while the lowered fitness of infected wild salmonids could partially be attributed to their reduced swimming capacity.

Figure 11 Salmon swimming in current

INTERNATIONAL COOPERATION

Also internationally, the topic of exposed farming raises significant interest.

The research areas of the centre have been presented in various international forums to support future collaboration with other stakeholders:

- European Maritime Day, Athens, Greece May
- ESREL'15, Zürich, Switzerland, September
- OCEANS'15, Washington DC, USA, October
- European Aquaculture, Rotterdam, The Netherlands, October
- Transatlantic Science Week 2015, Boston, USA, November

First meeting for international partners, Trondheim 18-20 August 2015

Representatives from five of the seven international partners in EXPOSED met in Trondheim during the tradeshow AquaNor i August 2015. Three days were spent to get to know each other and to get to know Exposed.

The meeting started Tuesday with a workshop at the offices of SINTEF Fisheries and Aquaculture (SFA) at SeaLab, where the international partners met with the managers of the six different research areas in EXPOSED. Planned research in EXPOSED was presented by the EXPOSED Director Hans V. Bjelland, and each of the research managers. After lunch the international partners presented their institutions, highlighting their possible contribution to EXPOSED. Discussions were made on how to match the partners with the research projects soon to be launched by Exposed.

On the second day, Wednesday, it was organised a field trip to the island of Frøya where the production facilities of Aqauline AS and the research facility of ACE Aquaculture Technology at Rataren was visited. Both Aqualine AS and ACE are partners of Exposed.

The third and last day of the meeting, Thursday, was spent to visit the aquaculture labs at SINTEF SeaLab and the hydrodynamic laboratories at Marintek. Marintek is a research partner in Exposed. The visit at Marintek included a demonstration of Aqualine's cage concept Midgard which has been tested at Marintek's ocean basin. The meeting was finalised at the legendary Shrimp Party at SINTEF Fisheries and Aquaculture Thursday night.

Figure 12 Participants from five international institutions: Univ. Melbourne (Francisca Samsing, Tim Dempster and Daniel William Wright), Shanghai Jiao Tong Univ. (Jinsong Xu), CNR-INSEAN (Claudio Lugni), Fraunhofer CML (Johannes Oeffnes), Robert Gordon Univ. (Stewart Massie and Susan Craw)

Workshop on Innovative and sustainable aquaculture, European Maritime Day, Athens, Greece 28-29 May 2015

EXPOSED co-hosted a workshop on future opportunities for sustainable aquaculture at the European Maritime Day in Athens. The EU Blue Growth strategy aims to boost its aquaculture sector as a means to meet future seafood demands and as a potential source of employment and economic growth. This growth has to be based on sustainable development principles and farming practices as various environmental challenges remain. Technological and practical innovations are possible means to enable more robust, safe and sustainable operations; allowing the increase of seafood production. This workshop highlighted the pros and cons of a number of innovative future approaches for aquaculture. Arne Fredheim chaired the session, while Hans Bjelland presented Norwegian perspectives.

Visit to Shanghai Jiao Tong University and Zhejiang Ocean University, China, 2-4 February 2015

SFI-EXPOSED co-arranged two workshops together with Chinese research partners in February 2015. Participants from Exposed were Director Hans V. Bjelland, and researchers Pascal Klebert and Pål Lader.

February 2: Seminar on Hydrodynamics of Fish Farming Structures at Shanghai Jiao Tong University (SJTU). Host at SJTU was associate professor Jinsong Xu, and the folowing talks were given:

- Research Overview on Hybrid Simulations of Fish Farming Structures in SJTU (Jinsong Xu)
- Flexible Closed Cages in Waves and Current (Pål Lader)
- Hydrodynamic Responses of Gravity Fish Cages in Current and Waves (Ke Hu)
- New Design for Offshore Fish Cages (Pascal Klebert)
- Hybrid Methods in the Simulations of Fish Farming Structures (Leixin Ma)
- Introduction on SFH-Exposed Project (Hans Vanhauwaert Bjelland)

Figure 13 Visit to Shanghai Jiao Tong University

February 3-4: The Sino-Norwegian Academic Seminar on Marine Aquaculture Engineering Technology at Zhejiang Ocean University. Host was Dr. Fukun Gui (Zhejiang Key Lab of Marine Aquaculture Facilities and Engineering Technology at Zhejiang Ocean University). Several researchers from Dalian University of Technology also participated in this workshop. The following talks were given:

- Flexible Closed Cages in waves and current (Pål Lader)
- Experimental study on scattering waves around a porous horizontal elliptic plate (Zhao Fenfang)
- Hydrodynamics of metal fishing net (Chen Changping)
- Flow hydrodynamics and oxygen consumption in a salmon cage (Pascal Klebert)
- Hydro-coefficients of a straight bar structure in waves (Yao Xiaojie)
- Structural analysis of float collar for gravity cage in waves (Xu Tiaojian)
- Presentation of EXPOSED (Center for research) : A room for collaboration (Hans Vanhauwaert Bjelland)
- Large scale net enclosure aquaculture technology in deep waters (Gui Fukun)
- New design for offshore fish cages (Pascal Klebert)
- Exposed Farming: Cage deformation and Salmon Behavior (Pascal Klebert)
- Structural analysis and fatigue life estimation of the floating pipes of the fish cage (Bai Xiaodong)
- Two-dimensional numerical simulation of the flow around three-stranded rope (Wang Xinxin)
- Numerical investigation of hydrodynamic properties of submersible mussel raft in waves (Liu Jie)

RECRUITMENT

EXPOSED has recruited three PhDs during 2015.

Bjørn Magnus Mathisen (PhD)

Monitoring and operational decision support of exposed aquaculture operations

Bjørn Magnus Mathisen was the first PhD scholar of EXPOSED. He has working experience from Telenor, NTNU and SINTEF ICT and will contribute to the state of the art of monitoring and operational decision support of exposed aquaculture operations (Project 6). His project will start by doing a rigorous and systematic literature review of current and previous research done in data processing and analysis for decision support systems in the domain. The methods uncovered in the review will be benchmarked using data gathered from partners with live operations to make it as realistic as possible without a live test. This process will single out the most promising methods for data processing for decision support systems for exposed aquaculture. This two step process of rigorous literature review and benchmarking will also be applied to the next level of abstraction in a decision support system; taking the processed and analysed data and building or augmenting a high-level model for the domain. Finally, if the methods identified in the previous steps are applicable, they will be developed further to fit the domain. If no methods are found suitable, new methods will be developed for the task. The new methods will be tested and validated using live data, as well as benchmarked along with other comparable methods.

The PhD is supervised by Professor Agnar Aamodt, and co-supervised by Professor Helge Langseth, both from NTNU, Department of Computer and Information Science, co-supervised by Senior Researcher Gunnar Senneset at SINTEF Fisheries and aquaculture.

Pål Takle Bore (PhD)

Aquaculture structures

Pål Takle Bore holds a Master of Science degree in marine technology from NTNU with specialization in hydrodynamics and marine structures. His PhD project will investigate load effects, structural resistance and reliability of fish farm structures by performing advanced nonlinear analyses in time domain and, if possible, validate this against experimental results. This will contribute to a better understanding of the governing physical load phenomena relevant for an exposed aquaculture structure and the resulting structural response. Based on the results, the goal is to develop rational and knowledge-based design criteria for main components of fish farm structures to be used in an industry expanding toward more exposed locations. Professor Jørgen Amdahl at NTNU, Department of Marine Technology/AMOS is the supervisor for the PhD-candidate while David Kristiansen is co-supervising.

Ingunn Marie Holmen (PhD)

Occupational safety for employees in the aquaculture industry

Senior scientist and now PhD candidate at NTNU, Ingunn Marie Holmen, will study health, safety and work environment issues (HSE) and how to reduce the risk of occupational accidents and injuries. She was recruited in 2015 and formally started her PhD studies in January 2016. Good surveillance and management of safety and risk during operations will provide safer operation of the fish farms.

The aquaculture industry is growing and there is a need to systematize knowledge and identify best practice in terms of safety management. This becomes increasingly important as the aquaculture farms, and thus jobs, eventually move further offshore, making sites more exposed which in turn pose new challenges. Crew and equipment are at the mercy of the elemental forces, and technology and operational practices must allow for more extreme weather, including larger waves, stronger winds and currents, Holmen explains.

– A special focus will be assigned operations where the most serious accidents occur, namely lifting with cranes, and operations on moorings and lines in tension. We will study how we can improve safety during the service operations performed. We need to look at both the working procedures as well as the equipping and layout of the service vessels. Some operations are conducted by different teams in cooperation. Therefore, it is important to know who does what and when. To ensure this, the systems must be well implemented and have integrated safety functions as a standard, Holmen points out.

With her background from different research projects in extreme working environment, the chartered engineer, who has worked in SINTEF since 1992, has a solid experience in the field.

During the PhD work, Holmen will cooperate with aquaculture companies, vessel designers, service providers and equipment suppliers that are partners in EXPOSED. She emphasizes that it is especially rewarding and motivating to be working with an industry that is facing many challenges but also has an exciting future.

– I look forward to develop recommendations for the industry – together with the industry. There has been a tendency to “forget” the people in favour of the product, the fish. However, if the aquaculture industry wants to reach its goal to grow, we must design an attractive working environment also for the future employees, emphasizes Holmen.

COMMUNICATION AND DISSEMINATION ACTIVITIES

As a Centre for Research based Innovation, EXPOSED has a responsibility to disseminate research results to the public, as well as a need for effective communication internally between partners and activities.

To support cross-disciplinary innovation and good communication within the centre, the centre has arranged a two-day EXPOSED Days in the spring and a one-day EXPOSED Day in the autumn. Such events will be arranged yearly, in addition to PhD/post-doc workshops and more targeted project related meetings. The EXPOSED Days will serve as a meeting place for innovation, presentation of results, and exchange of ideas and creation of new projects.

EXPOSED has developed a logo and graphical profile elements that will be used in documents, presentations and on the web. Roll-ups are being used at internal and external events. A web-page has been established to present information about and news from the centre to both internal and external target groups. A facebook-page is being used to further promote the news from the centre[2]. The facebook-page links all new articles from the web-page, in addition to other smaller, but relevant information that is not prioritised for the web-page.

There has been a significant industrial, as well as political interest in EXPOSED and its objectives in 2015, and the centre has been invited to present at a number of national events, such as:

- NTNU OCEAN Week, Trondheim, May
- NorShipping, Lillestrøm, May
- Future Prospects-seminar under AquaNor, Trondheim, August
- Verftskonferansen, Ålesund, November
- Tekmar, Trondheim, December

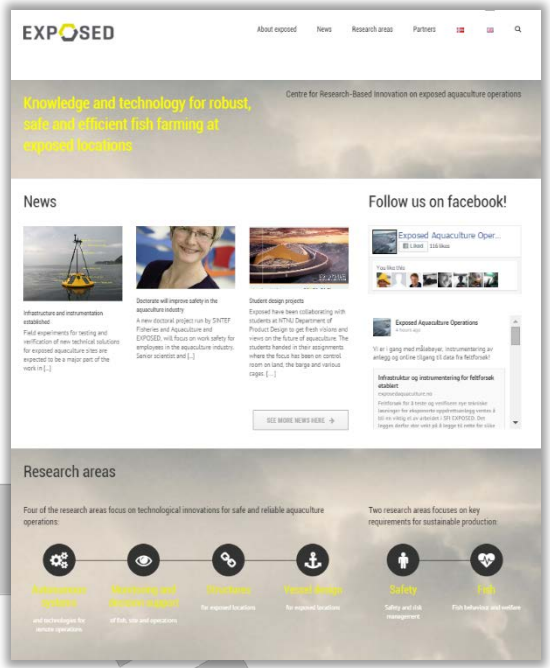


Figure 15 The EXPOSED web page

Figure 14 A number of news papers have covered EXPOSED

[2] www.exposedaquaculture.no and https://www.facebook.com/eksponert

PERSONNEL

Key Researchers

Key Researchers	Institution	Main research area
Hans V. Bjelland	SINTEF Fisheries and Aquaculture	Decision support systems and aquaculture operations
David Kristiansen	SINTEF Fisheries and Aquaculture	Aquaculture structures
Ingunn Marie Holmen	SINTEF Fisheries and Aquaculture	Safety and risk management
Andreas M. Lien	SINTEF Fisheries and Aquaculture	Vessel design and aquaculture operations
Leif Magne Sunde	SINTEF Fisheries and Aquaculture	Aquaculture operations
Per Rundtop	SINTEF Fisheries and Aquaculture	Autonomous systems
Pål Lader	SINTEF Fisheries and Aquaculture	Aquaculture structures
Heidi Moe Føre	SINTEF Fisheries and Aquaculture	Material science
Arne Fredheim	SINTEF Fisheries and Aquaculture	Aquaculture structures
Gunnar Senneset	SINTEF Fisheries and Aquaculture	Field measurements and infrastructure
Martin Føre	SINTEF Fisheries and Aquaculture	Telemetry and biological modelling
Frode Oppedal	Institute of marine research	Fish behaviour and welfare
Ole Folkedal	Institute of marine research	Fish behaviour and welfare
Esten Ingar Grøtli	SINTEF ICT	Autonomous systems
Trine Kirkhus	SINTEF ICT	Optical Measurement Systems and Data Analysis
Dariusz Fathi	MARINTEK	Vessel design
Vegard Ø. Aksnes	MARINTEK	Aquaculture structures
Jørgen Amdal	NTNU, Department of Marine Technology	Marine structures
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
Helge Langseth	NTNU, Department of Computer and Information Science	Intelligent systems and decision support
Jo Arve Alfredsen	NTNU, Department of Engineering Cybernetics	Telemetry and biological modelling

PhD students	Nationality	Period	Sex [M/F]	Topic
Bjørn Magnus Mathisen	Norwegian	20151007-20191007	M	Monitoring and operational decision support.
Pål Takle Bore	Norwegian	20150901-20180831	M	Intelligent Aquaculture Structures
Ingunn Marie Holmen	Norwegian	20160101-20192131	F	Safety and risk management

PUBLICATIONS

Published conference papers

Utne IB, Schjølberg I, Holmen IM (2015). Reducing risk to aquaculture workers by autonomous systems and operations. In: Safety and Reliability of Complex Engineered Systems. Edited by: L Podofillini, B Sudret, B Stojadinovic, E Zio, Wolfgang Kröger. European Safety and Reliability Conference (ESREL) 2015, CRC Press, Switzerland, 2015. Print ISBN: 978-1-138-02879-1

Bjelland, H., Føre, M., Lader, P., Kristiansen, D., Holmen, I.M., Fredheim, A., Grøtli, E.I., Fathi, D.E., Oppedal, F., Utne, I.B., Schjølberg, I., 2016. Exposed aquaculture in Norway- Technologies for robust operations in rough conditions. Proceedings from OCEANS' 15 MTS/IEEE, Washington, USA, 19-22 October 2015. http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=7404486.

STATEMENT OF ACCOUNTS

Name	Funding	Cost
The Research Council	5 528 (45 %)	-
The Host Institution (SINTEF Fisheries and aquaculture)	697 (6 %)	4 731
Research Partners*	2 224 (18 %)	3 943
Enterprise partners**	3 817 (31 %)	3 592
Public partners	-	-
Equipment	-	-
Total	**12 266**	**12 266**

* MARINTEK, IMR, SINTEF ICT, NTNU IMT, NTNU IDI, NTNU ITK

(All figures in 1000 NOK)

** Marine Harvest, Cermaq, SalMar, Kongsberg Seatex, Kongsberg Maritime, Aqualine, Møre Maritime, Reinertsen, Anteo, Argus Remote Systems, Lerow, AQS, Marine Design,

EXPOSED

AQUACULTURE OPERATIONS

CENTRE FOR RESEARCH-BASED INNOVATION

SINTEF Fisheries and Aquaculture · Marine Harvest Norway · Cermaq Norway · SalMar Farming
Kongsberg Seatex · AQS · Kongsberg Maritime · Aqualine · Marine Design · Reinertsen · Anteo Argus
Remote Systems · Lerow · Møre Maritime · SINTEF MARINTEK · Institute of Marine Research
Norwegian University of Science and Technology · SINTEF ICT

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