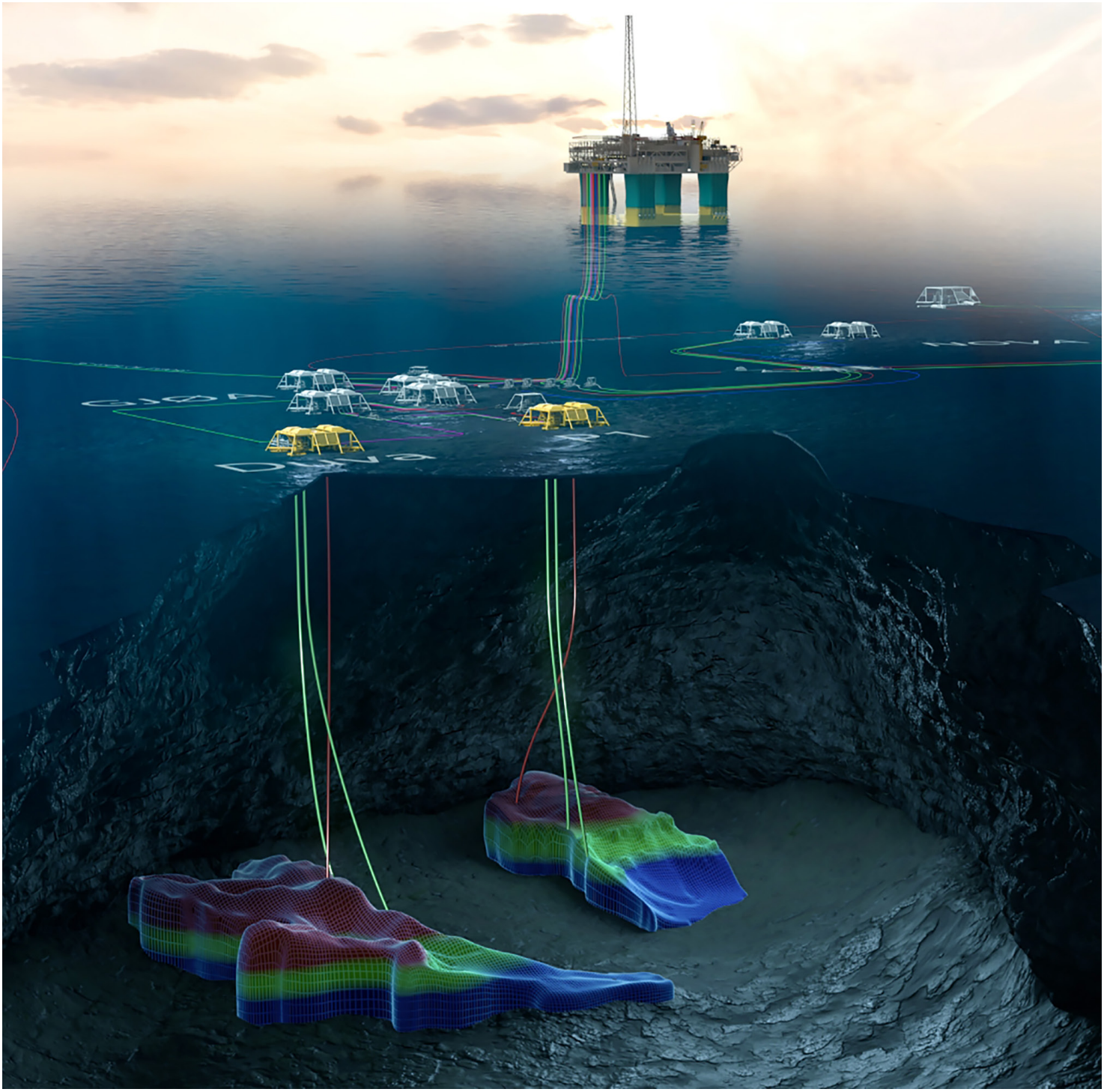
SUBPRO

SUBSEA PRODUCTION AND PROCESSING

Annual Report

2018

2019



sfi Centre for Research-based Innovation

Established by the Research Council of Norway

NTNU

Norwegian University of Science and Technology

What is SUBPRO?

SUBPRO is a centre for research based-innovation (SFI) funded by the Research Council of Norway and 7 industrial partners. Norwegian companies have been in the forefront of developing and implementing subsea technology for many years, and the purpose of starting up SUBPRO was to bring the academic community in Norway to a similar top international level in selected areas of subsea technology, and use this as a basis for further innovation in the industry. Subsea technology covers many areas, and in SUBPRO we focus on five main areas:

- Field architecture
- Reliability, availability maintenance and safety
- Fluid chararacterization and flow assurance
- Separation process concepts
- System control

SUBPRO started up in August 2015, so we are now almost half way into the planned 8 years duration of the centre. Almost all the research work is done at the Norwegian University of Science and Technology (NTNU) where SUBPRO has funded 28 full time PhD students and Postdoctoral fellows in 2018. In addition, 20 professors and 10 researchers contribute to the projects on a part time basis.

In addition, SUBPRO is educating about 20 master students each year, many of which take jobs in the oil and gas industry. The direct transfer of knowledge through people is a very effective way of contributing to innovation in the companies. In addition, we have started a portfolio of innovation projects, with the aim of practical implementation of the results from the PhD and postdoc works.

Many of the projects in SUBPRO are of fundamental nature and may be used by the industry on a long term. For example, we have several PhD projects related to studying how droplets form and break up. This knowledge is critical for understanding how oil and water can be separated subsea, and can be used on a longer term to improve the design of new compact oil-water separators.

SUBPRO is the most comprehensive academic research programme in Norway within oil and gas and it's also the largest academic subsea R&D centre in the world. We have large ambitions and we think we will fulfil them!

Why SUBPRO?

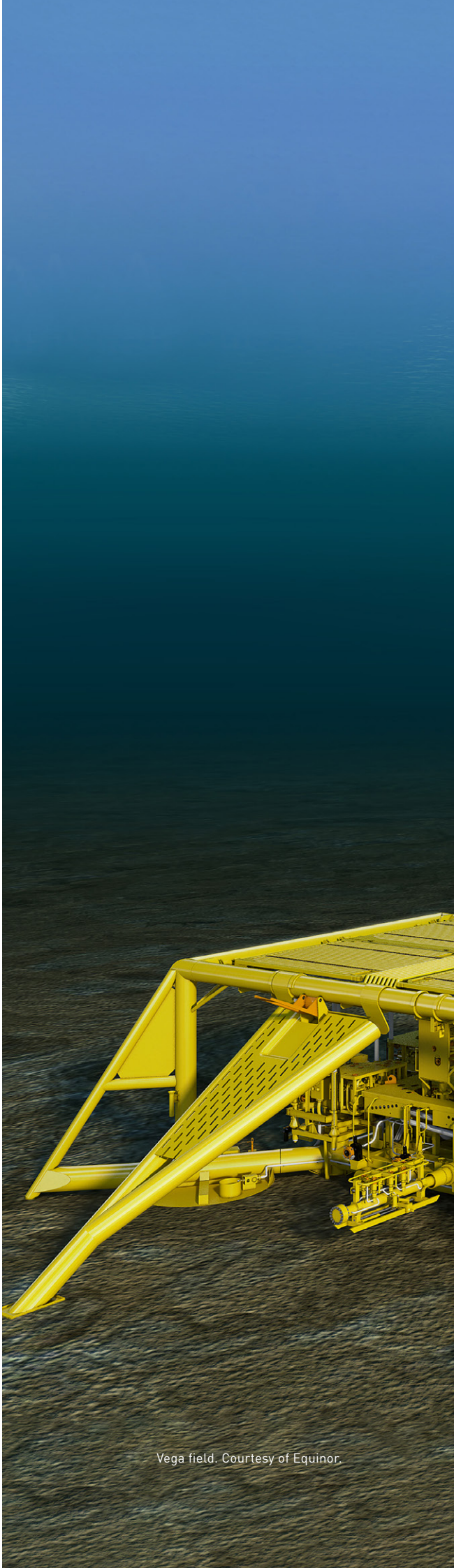
There are still gaps in knowledge and technology for subsea systems that need to be covered, to:

- reduce cost and complexity of subsea field developments
- enable development of new and more demanding oil and gas fields
- increase production and extend life of existing fields
- reduce environmental footprint of subsea field developments
- maintain safety levels

FUTURE CHALLENGES REQUIRE

- multi-disciplinary collaboration
- accelerated innovation based on novel research

Front page picture: Duva and Gjøa field. Courtesy of Neptune Energy Norge.



Vega field. Courtesy of Equinor.

Vision and goals

The vision and primary goals for SUBPRO is to become a global leader for research based innovation for subsea production and processing, providing

International excellence in fundamental and applied research

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Knowledge, methods, technology and system understanding – as a basis for industrial innovation

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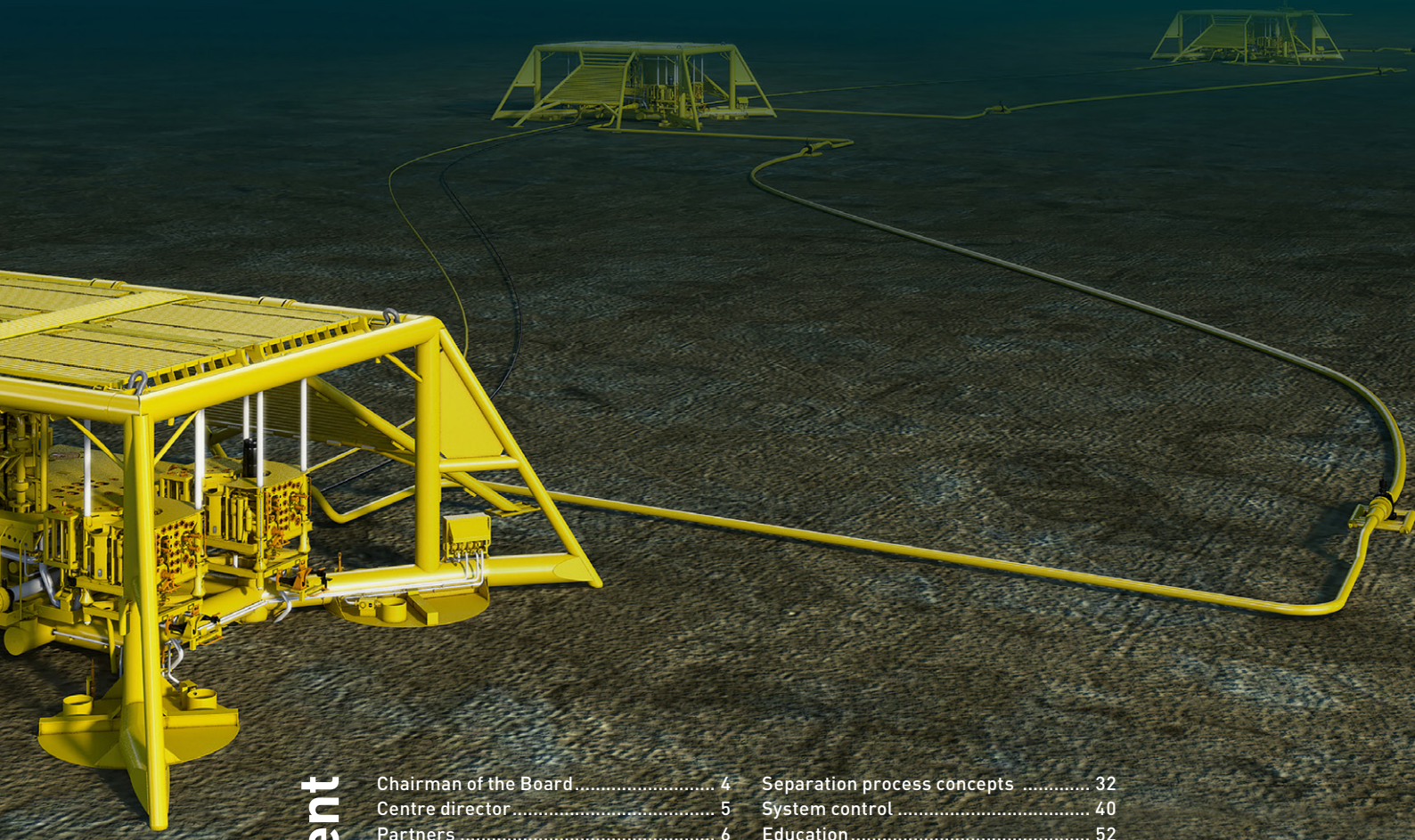
Internationally high level of graduated master and PhD students



Content

Chairman of the board

Subsea technology out of Norway has a strong international position in the oil and gas industry. If we want this industry to prosper and continue its development we need to continue and even strengthen our efforts into R&D.

STIG LYDER STØME
CHIEF ENGINEER
LUNDIN NORWAY

CHAIRMAN OF THE
SUBPRO CENTRE
BOARD

Subsea technology out of Norway has a strong international position in the oil and gas industry. The Norwegian Continental Shelf (NCS) is an innovative arena for development, testing, qualification and implementation of new subsea technology. In particular, the Norwegian subsea cluster industries are significant exporters of deep-water technology goods and services to subsea field developments in Brazil, West Africa, Malaysia and the Gulf of Mexico, i.e. to fields with water depths ranging at 300 - 2500m. The majority of the oil companies operating on the NCS have also a leading position in development and operation of subsea oil and gas fields throughout the world and thus have the opportunity to exploit the technology developments being matured on the NCS.

The NCS initiative for the Centre for Research-based Innovation (SFI) within Subsea production and processing technology (SUBPRO), has been taken to accelerate the level of innovation within the subsea oil and gas industry. The technology developments of the NCS have shown a great ability to cope with the benign conditions of this region with deep waters, stormy conditions and cold climate. However, even higher ambitions in subsea technology developments have been realized during the last couple of decades, namely a full subsea processing capability eliminating the need for surface support at the place of hydrocarbon extraction. This approach has proven cost effective. However, the technology is surely in its infantry and subsea processing thus has a huge potential for further rationalization and efficiency improvements. This is where initiatives like the ones offered by SUBPRO can make a difference by combining academia, research institutions, suppliers and the end users in achieving our goals for a safe and cost effective technology development.

Experience from subsea production and processing systems in operation, like the Aasgard and Gullfaks Subsea Gas Compression Systems (both Equinor) and the recent decision made for an equivalent technology approach at Ormen Lange (Shell), will be valuable for identifying areas for research and technology improvement. It will be an important task in the continuation of the Centre to collaborate with these oil companies and their suppliers with a view to evaluate the contributions from such experiences.

In the continuation of the SUBPRO Centre, a more targeted cooperation between NTNU, oil companies and suppliers will be emphasized to exploit project results for enabling innovation of new products and services. SUBPRO shall serve the industry's need for long term research and innovation by organising relevant resources within the process industries, and combining this effort with highly recognised research in the university environment at NTNU, which successfully has served the NCS for many decades already.

Centre director

We are now three and a half year into the planned eight year duration of the SUBPRO project, and the progress is very good. We have developed a close collaboration between industry partners and academia, and are delivering scientific results with a high potential for industrial innovation.

PROFESSOR
SIGURD SKOGESTAD

SUBPRO CENTRE DIRECTOR

As a Centre for research-based innovation (SFI), SUBPRO has two major goals; academic excellence and industrial innovation. The focus in the oil and gas industry in the last five years has been on cost cutting, and there has been limited resources left to consider innovation and new technology. SUBPRO started just as the oil price plummeted from a historic high level of more than USD 100 in August 2014 to USD 50 in March 2015 and further down to a low of USD 28 in January 2016. This sent a shock to the oil industry, and especially the service companies were hit very hard with large lay-offs. Despite this situation, we are very pleased to see that SUBPRO has managed to retain most of the industry partners through this period, and even recruited some new, making it possible to keep up the planned activities in collaboration with our industry partners.

With the oil price stabilizing around USD 60, things are now changing and we are happy that two new service companies (Kongsberg Digital and Aker Solutions) have decided to join SUBPRO from January 2019. During 2018, SUBPRO has hired two Adjunct Professors (20%) in subsea technology; Audun Faanes and Gunleiv Skofteland from the research center of Equinor. The aim is that they will contribute to transferring the scientific results to innovations. The first batch of PhD candidates are just graduating and many of them are recruited by the oil and gas industry. During 2018 the work has resulted in 51 journal and conference papers . NTNU/SUBPRO educated 17 Master students in 2018, who specialised in various fields of subsea technology. We are happy to report that we are close to reaching the goal of 30% females among PhD students, Postdoctoral fellows and Master candidates.

SUBPRO has been instrumental in starting up an associated JIP project with 8 industrial partners, "Safety 4.0 – Demonstrating safety of novel subsea technologies". This project aims at supporting decision-making and concept selection in field development projects in the industry.

SUBPRO takes part in an extensive international research collaboration. Our close cooperation with several leading universities in Brazil continues, partly through the INTPART program. We also have close cooperation with several other renowned universities throughout the world. We aim at working closely with a new oil and gas research program at NTNU, called BRU21, where close to 20 industrially funded PhD projects have just started up.

SUBPRO is responsible for organizing the subsea technology sessions at the "Subsea Valley Conference" in April 2019. Most of the 12 presentations will be from industry, and we are also planning three presentations of the latest results from SUBPRO.

SUBPRO has also released a new video for presentation of the Centre at industrial conferences etc. which can be found on our web site.

Partners

STATEMENTS FROM TWO OF OUR INDUSTRY PARTNERS

AUDUN FAANES

LEADING ENGINEER
SUBSEA TECHNOLOGY
DEVELOPMENT

EQUINOR

What is the main outcome and value of participating in SUBPRO for Equinor?

- Subsea production and processing are important to Equinor, as the new challenges that we are facing require new technology. In general, technology development takes place inside the oil companies, in the supplier industry and in academic institutions. In SUBPRO, all these parties work together on selected areas of high relevance. We have seen that the work of the experienced, high-class academic resources adds value. An important outcome is PhD and Master candidates with highly relevant competence and networks, who are ready to contribute in the oil companies and the supplier industry. The results within all the SUBPRO research areas are also important, giving a potential for further development by the industry. Examples are new control and optimization methods, new work methods for systematic analysis of safety and reliability, considering both the physical equipment and the control system, new insight in separation and produced water analysis, application of micro experimental laboratory set-ups, insight in membrane systems for new applications and not least new subsea field development tools, where both the reservoir, wells and the subsea facilities are handled in a holistic manner.

Equinor has been a member of SUBPRO since the start of the Centre in 2015.

JOSTEIN KOLBU

SENIOR MANAGER
SUBSEA PROCESS

AKER SOLUTIONS

What is the main motivation for Aker Solutions to join SUBPRO?

- Aker Solutions has a long history of working with subsea production and processing solutions. Being part of SUBPRO will let us build our knowledge together with key academic and industry partners, and help us prepare for future technology development, qualification and commercialization efforts.

Aker Solutions re-joined SUBPRO from 2019.

Project structure

RESEARCH AREAS

Field Architecture Sigbjørn Sangesland	Reliability, Availability, Maintenance and Safety Mary Ann Lundteigen	Separation – Fluid characterization Johan Sjöblom / Gisle Øye	Separation – Process Concepts Hugo Jakobsen	System Control Sigurd Skogestad

PROJECTS

Subsea gate box	New safety and control philosophy for subsea systems	Produced water quality and injectivity	Membranes for gas dehydration	Dynamic simulation model library
Field development concepts	Associated project: Safety 4.0 - Demonstrating safety of novel subsea technologies	Influence of production and EOR chemicals on produced water quality	Membrane testing for gas dehydration	Modelling and multi-variable control of subsea processes
Multiphase booster models	Reliability and availability assessment in subsea system design	Re-injection of produced water - dispersion in porous media	H_2S and hydrate control	Automatic Control of Subsea Separation
Methods for minimizing cost and risk in subsea field development	Condition based maintenance models	Wax crystallization and inhibition	Characterization of fluid particle breakup in turbulent flow	Adaptive control of subsea processes
	Optimizing condition monitoring	Sequential separation	Mechanistic modeling of droplet breakage	Estimation of un-measured variables
	Performance management of safety-critical systems for unmanned facilities	Modeling of coalescence	Compact separation concepts	Enhanced virtual flow metering
		A digital twin library for multiphase separation and transport processes		Control for extending component life
				Validation of methods for optimizing remaining useful life (RUL)
				Production optimization under uncertainty

PROFESSOR
SIGBJØRN SANGESLAND

RESEARCH AREA MANAGER

RESEARCH AREA

Field Architecture

The goal is to improve the technical and economic performance of integrated subsea production and processing systems.

The objective for this research area is to develop new concepts and configurations for subsea production/processing systems and new optimization tools for subsea field development.

This covers new methods, systems elements and production process configurations for improving the technical and economic performance of an integrated subsea production and processing system. The subsea system in this context extends from the reservoir, through the wells and the seabed gathering system, the processing and boosting facilities and to the field delivery point, whether this is a subsea storage and offloading system, a host platform, a floating vessel or an onshore terminal.

Specific industrial and research challenges and goals:

- Increase field production by enabling a "smart" synthesis of the diversified wells potential, constraints, and recovery targets.
- Employ "near the source" seabed separation and boosting whenever this improves the recovery, saves energy, reduces the transport costs or prolongs the economic life of the field.
- Cost effective strategies for developing and operating remote offshore oil and gas reservoirs with low pressure and low temperature in harsh environments. Such strategies include two scenarios; long distance tie-ins and near field receiving facilities.

Three business cases with relevant data and information are formulated to guide and narrow the scope of the R&D work. They represent reference oil and gas fields with current gaps and challenges to subsea production and processing:
Case 1:
Gas field with low Gas Oil Ratio (GOR)
Case 2:
Remote, low energy oil field (typical example: Barents Sea)
Case 3:
Oil field with future tie-ins

PROJECTS OF FIELD ARCHITECTURE
During 2018, one PhD project has been completed:

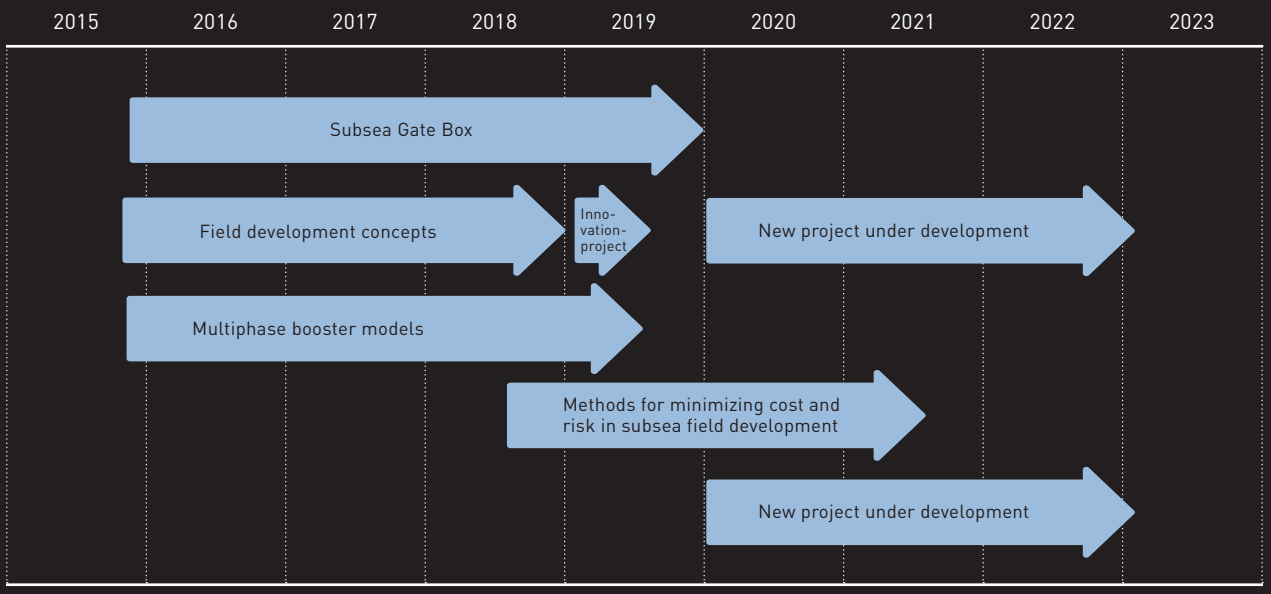
- Field development concepts.
  This PhD project is followed up by an innovation project.

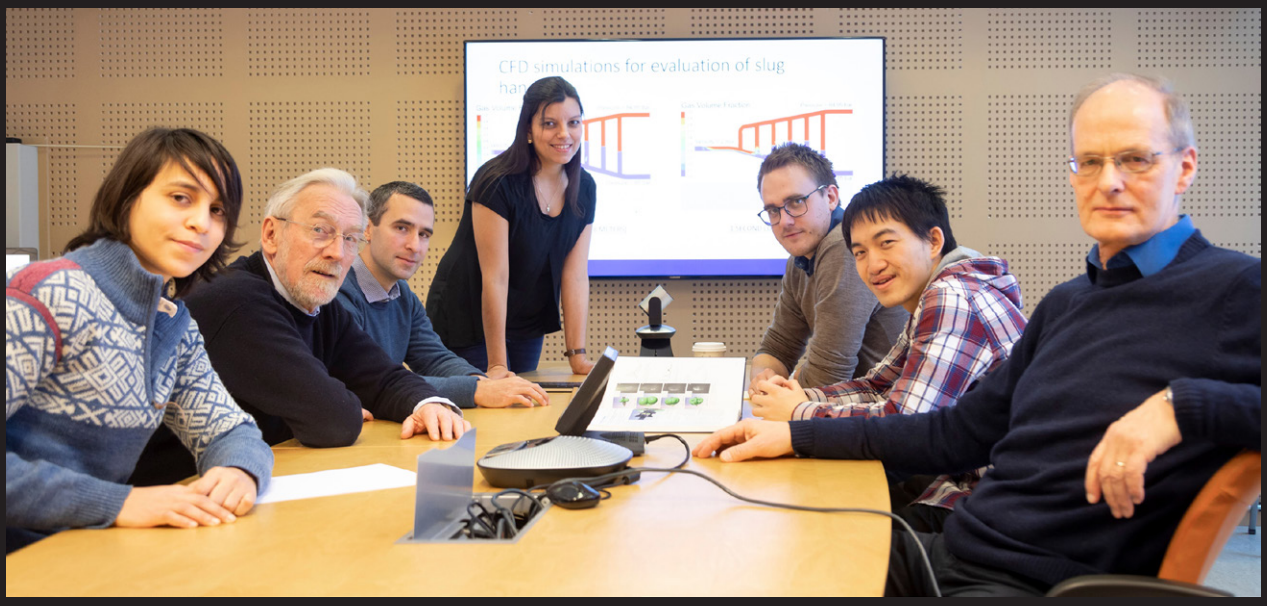
One new project has started up:

- Methods for minimizing cost and risk in subsea field development

An overview of completed, ongoing and planned projects is shown in the figure to the right.

Completed, current and planned projects





The Field architecture team. From left: PhD student Diana Gonzáles, Professor Tor Berge Gjersvik, Associate professor Milan Stanko, Postdoctoral fellow Mariana Diaz, PhD student Håvard S. Skjefstad*, PhD student Haoge Li, Professor Sigbjørn Sangesland. (PhD student Gilberto Nunez is not present in the picture).
*Håvard S. Skjefstad's project is a part of the Research area Separation process concepts. Being a PhD at the Department of Geoscience and Petroleum, Skjefstad is also associated with the Field architecture team.

Subsea gate box

A new concept for improving production management of oil and gas fields with large heterogeneity among wells.

Postdoc: **Mariana Diaz**

Project manager:
Prof. Sigbjørn Sangesland

Co-supervisor:
Associate
Prof. Milan Stanko

BACKGROUND

During the early phases of field development, important decisions are taken while the knowledge of the system is very limited. Therefore, design decisions are often based on system characteristics that are likely to change during the life of the field. It is therefore essential to include flexibility in the production and processing system to manage effectively the heterogeneity of the field and the uncertainty of the system conditions over time.

Standard field architectures tend to create a strong interdependence of the flow rates and production pressures of the individual wells. Such a strategy might lead to a sub-optimal use of the naturally available reservoir energy.

THE SUBSEA GATE BOX CONCEPT - A POSSIBLE WAY TO ENHANCED PRODUCTION

The subsea gate box (SGB) in Figure 1, is a novel concept that opens the opportunity for increasing the production management capability along the subsea facilities network and over the lifetime of the field. The project aims to evaluate the SGB concept in terms of its applicability and contributions within subsea field developments. Some of the project results include:

- Performance evaluation using an integrated production model for a synthetic case, which has demonstrated the possibility to increase the overall production by around 10% when comparing the SGB to a typical central boosting station.
- A cost evaluation of different field architectures. The study has analyzed the additional cost associated to the development of a central boosting system and cost associated to the SGB approach for two operational philosophies; "System demand" and "Simultaneous running" versus a base case scenario without any boosting. The results have shown that for SGB operating in Simultaneous running philosophy, the SGB might give a better cost-effective solution, as shown in figure 2.
- A Computational Flow Dynamics model for a pipe-type gas-liquid separator that can be used in the SGB. The model offers an interesting tool to explore the performance maps and separation efficiencies for such separators.

In conclusion, the subsea gate box might be an alternative solution for field developments that include large heterogeneity among different producing regions. The study has shown that by using the SGB, it may be possible to increase the oil production such that the life cycle costs per barrel could be lower than with a centralized boosting solution, and with the advantage of improving the system flexibility. Planned activities for 2019 are focused on developing a methodology framework for screening process functionalities on the SGB and its location along the field layout within a given subsea field development.

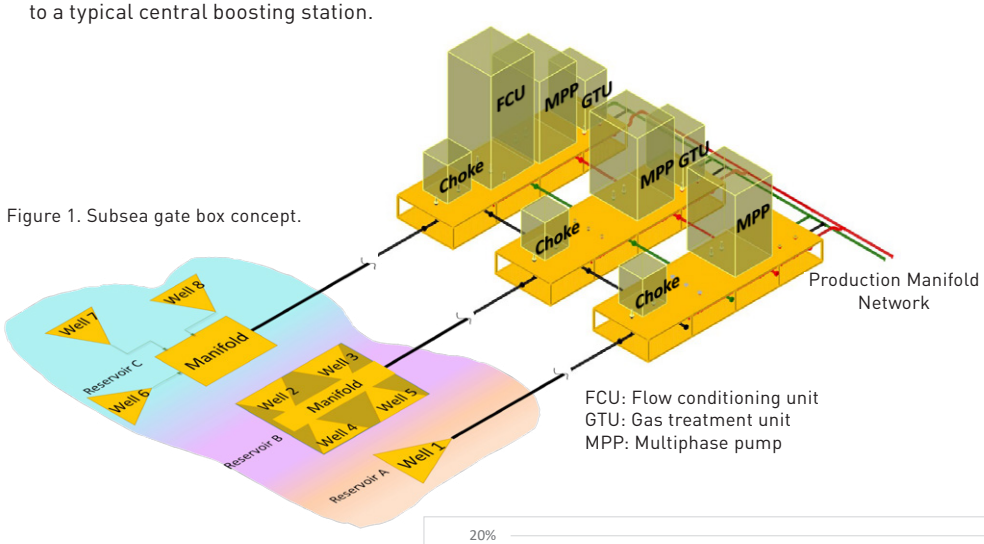


Figure 1. Subsea gate box concept.

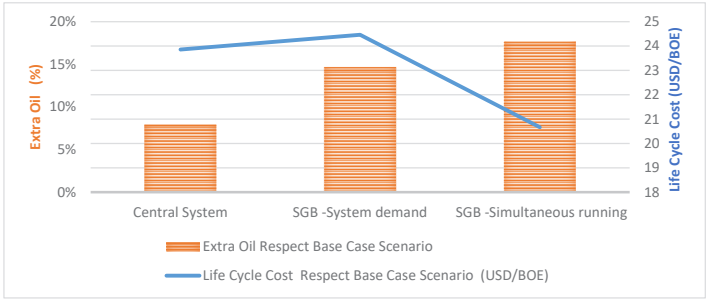


Figure 2. Test results for the Subsea Gate Box (SGB) concept applied to a synthetic oil field case. The figure shows extra oil produced and total life cycle costs per barrel including costs of required modifications, for three different study cases, compared to the base case scenario; without boosting. As seen, the SGB alternative with Simultaneous running philosophy gave the highest oil production and the lowest life cycle cost per barrel of the three alternatives.

Field development concepts

Novel methodologies for the development of remote offshore oil reservoirs with low energy.

PhD student:
Diana Gonzáles

Project manager and main supervisor:
Associate prof.
Milan Stanko

OBJECTIVES

The objective of this project is to create better methods to determine and evaluate cost effective strategies to develop remote offshore oil reservoirs with low pressure and temperature. Additionally, some cost effective solutions were studied that allow wax-free subsea hydrocarbon transportation in pipes over long distances.

AUTOMATED DECISION SUPPORT FOR FIELD DEVELOPMENT OPTIMIZATION

The main contribution of this project is an automated method for decision support that uses integrated asset modelling, mathematical optimization and analysis of uncertainties to perform field design in early stages of the field development process. The method employs proxy models of the production system that reduce complexity and computational simulation time, and, at the same time, give an accurate representation of the field performance, considering reservoir and subsea production and processing system. Mathematical optimization is used to determine the best production profile and well drilling schedule that maximizes economic profit for a specific field development strategy. The effect of uncertainty and different design alternatives is quantified using probability trees.

The workflow of the methodology is presented in the figure below.

EVALUATION OF THE METHOD, BASED ON WISTING FIELD DATA

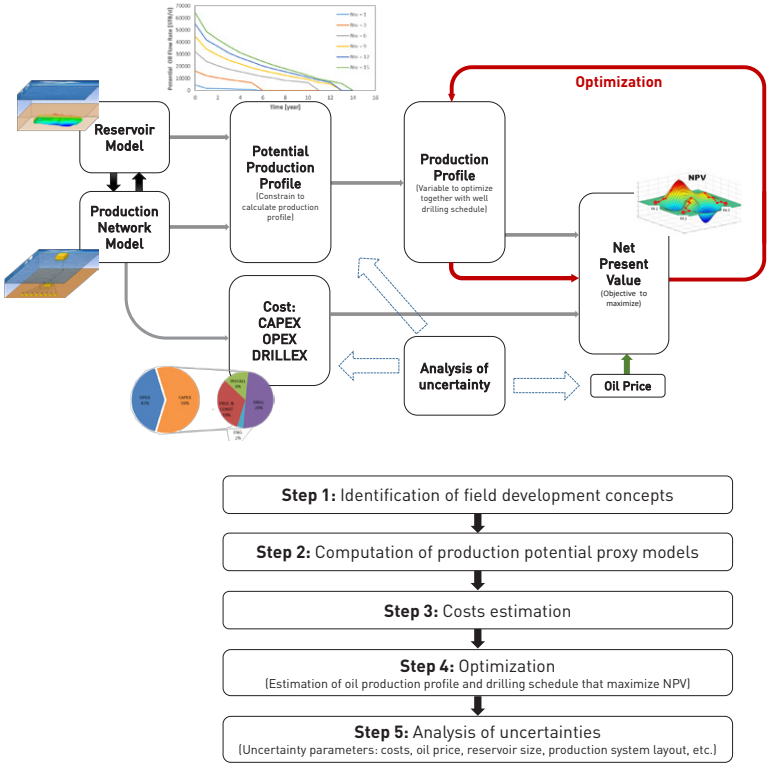
The method was evaluated on a synthetic oil field based on public data of the Wisting field, located in the Barents Sea. Results seem to indicate that the proposed methodology successfully finds optimal field design features while quantifying the effect of uncertainty with running times suitable for current field development workflows.

This methodology allows to obtain optimum early field design features in an automated fashion within practical running times. At the same time, it ensures global optimality and takes uncertainty into account. The methodology has the potential to be applied in real fields to get a preliminary idea of which concepts, production strategies, production profiles and drilling schedules are the most adequate to produce and operate the field.

PRACTICAL USE OF THE METHOD, INNOVATION PROJECT WITH AKER BP AND EQUINOR

The potential value of the methodology has been recognized by AkerBP, Equinor and AkerSolutions. The methodology has been presented in internal workshops in AkerBP. A master project has been performed in cooperation with Aker Solutions. Here, the methodology was implemented to optimize the plateau duration of a field with three independent reservoirs, and to find the optimum plateau rate that maximizes the net present value (NPV) of the field. In addition, the influence of cost uncertainty on the NPV was addressed.

The PhD project will be followed up in 2019 by an innovation project with Aker BP, Equinor and other companies, to develop and demonstrate a practical web based tool for optimization of field development strategies.



Workflow of methodology for optimization of field design.

Multiphase booster models

Prediction of boosting performance will contribute to integrated modelling of subsea field solutions and production optimization.

PhD student:
Gilberto Nunez

Main supervisor:
Prof. Sigbjørn Sangesland

Project manager and Co-supervisor:
Postdoctoral fellow
Jesus De Andrade

Co-supervisor: Associated Prof. Milan Stanko

THE NEED FOR PERFORMANCE CALCULATION TOOLS FOR BOOSTING EQUIPMENT

Subsea boosting technologies have been developed, tested and implemented for more than 30 years. However, for development of new fields, it will be valuable to have available a toolbox that comprises suitable performance prediction models for the evaluation of different boosting schemes, such as the type of booster, size, placement and required power over its service lifetime. SUBPRO has developed a suite of such simplified boosting prediction models. The models have been used to develop a methodology for technical screening and preselection of multiphase helico-axial pumps for planning of subsea boosting systems. These are now available for the industry partners, exemplifying an integrated modelling of the production system in an early design phase of a field development project. A great effort has been made to make the models user-friendly, to make the implementation of the tool in the work processes of the industrial partners easier.

Although simplified performance models do have their limitations, they may, when extensively validated, be used to increase the understanding of thermodynamics and fluid dynamics phenomena during the boosting process. Implementing such results into the next generation of models for predicting boosting performance is the final goal of this project.

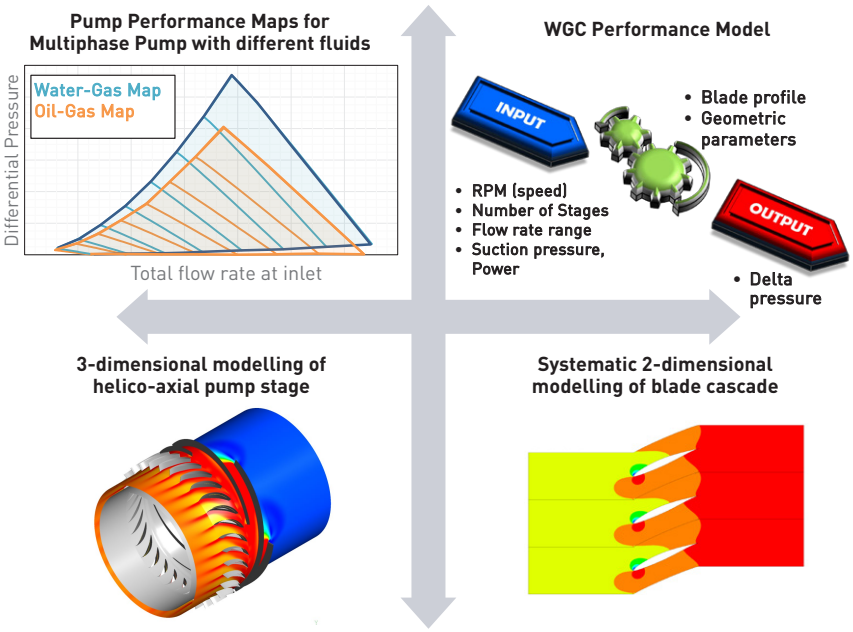
PRACTICAL CALCULATION TOOLS AVAILABLE FOR THE INDUSTRY PARTNERS

It is expected that more comprehensive and accurate modelling tools for simulation of the complex multiphase boosting phenomena will contribute to better concept selection and model-based decision making during field development. For example, a methodology has been developed to estimate the pressure increase of an axial counter-rotating wet gas compressor from a thermodynamic and fluid mechanic standpoint. The results have been compared against data in the public domain, showing that the pressure rise can be predicted within an accuracy of 2.5%.

This project has ended up with a new methodology based on Computational Fluid Dynamics (CFD) for multiphase boosting performance prediction of axial and semi-axial pumps with GVF below 80%. The main steps of the CFD simulations have been automated and the source code is available for the industry partners. Once again, the main driver has been the automation of the methodology, so it can be reproduced and easily deployed by the industry.

The project was completed at the end of 2018.

Gilberto Nunez is now working as a subsea rotating equipment engineer at Aker Solutions, Tranby, Norway.



Development of models for predicting booster performance.

Methods for minimizing cost and risk in subsea field development

PhD student: **Haoge Liu**

Project manager
and main supervisor:
Prof. Tor Berge Gjersvik

Co-supervisor:
Dr. Audun Faanes,
Equinor

BACKGROUND

At present, field development work processes are iterative and depend on manual input of data and compilation of total cost of each layout alternative. Therefore, a research effort has been identified aiming to improve these work processes and to save time on the engineering in early design phases.

OBJECTIVES

The project will develop and model important interfaces between cost and risk factors, allowing swift comparison of different subsea configurations and determining sensitivities to different uncertainties.

The research objective is to build a comprehensive field development model where users can:

- Assign their own cost and uncertainty data to components and operations.
- Automatically determine optimal subsea field layout; i.e. wellhead positions, well trajectories and flowline routing, in order to minimize cost and risk.

ACTIVITIES AND EXPECTED RESULTS

Generally, the cost of subsea field developments includes the following three cost classes: drilling and well construction cost, subsea facilities cost, and installation cost.

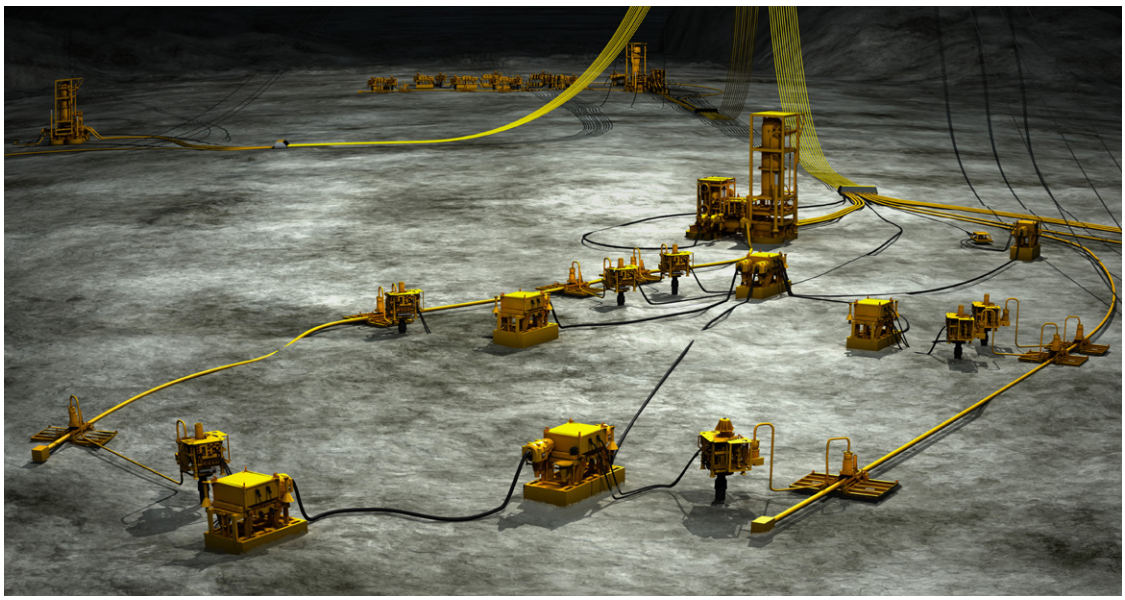
From our preliminary study, we have found some classical graphic algorithms and machine learning techniques that can minimize any individual cost item. However, the different cost items are interrelated and mutually dependent, making it hard to achieve the overall minimum cost. For example, if we only use satellite wells for subsea layout, we can obviously reach the minimum cost for drilling and well construction, however it will incur higher subsea facilities cost and installation cost compared to a typical layout of 4-slots templates, making the satellite-only layout very likely to have a higher overall cost. Therefore, clarifying the interrelationship between cost items is crucial for finding the global optimum of cost.

As for the risk component, we are planning to use probabilistic theory to quantify the risk as a special type of cost. With such treatment of risk, we can obtain not only the optimum for cost or risk separately, but also the optimum for both combined.

COLLABORATION WITH EQUINOR; BRIDGING THE PROJECT TO INDUSTRIAL NEEDS

Originally, this project was proposed by Equinor. The company has provided a co-supervisor for the project, who will help bridging the gap between the academic research and the industrial needs. Likewise, other SUBPRO partners will be invited to engage and participate in the project.

The result of this research project will be a systematic solution for the industry in optimizing cost and risk factors in subsea field development. It is also in line with the OG21 Strategy document "Oil and gas for the 21st century", regarding production, processing and transport.



Example of subsea field layout (Courtesy of TechnipFMC).

PROFESSOR
MARY ANN LUNDTEIGEN
RESEARCH AREA MANAGER

RESEARCH AREA

Reliability, Availability, Maintenance and Safety (RAMS)

Cost efficient solutions without compromising safety and environment.

2018 was an eventful year for the RAMS research area. The first two PhD projects were completed when Yun Zhang (Condition based maintenance models) and Juntao Zhang (Reliability and availability assessment in subsea system design) successfully defended their theses by the end of the year. Both of them have now accepted job offers in the oil and gas industry. Their employments enable transfer of knowledge and methods from SUBPRO to the industry, in specific in areas related to RAMS and digitalization. Before leaving SUBPRO, Yun Zhang completed a three month innovation project in collaboration with Equinor and DNV-GL, where she aligned her models and results from the PhD project with tools used by the two companies, to enable industrial use of project results.

Postdoc HyungJu Kim left his position in the end of 2018 as Postdoc in the project "Safety and control philosophy for subsea systems" as he acquired a new position as an associate professor in Maritime Safety at the University of South-East Norway. From now, he will develop education and research in the area of Maritime safety, building further on his research in SUBPRO. His effort can build new capacity in solving problems and challenges that the oil and gas industry is facing.

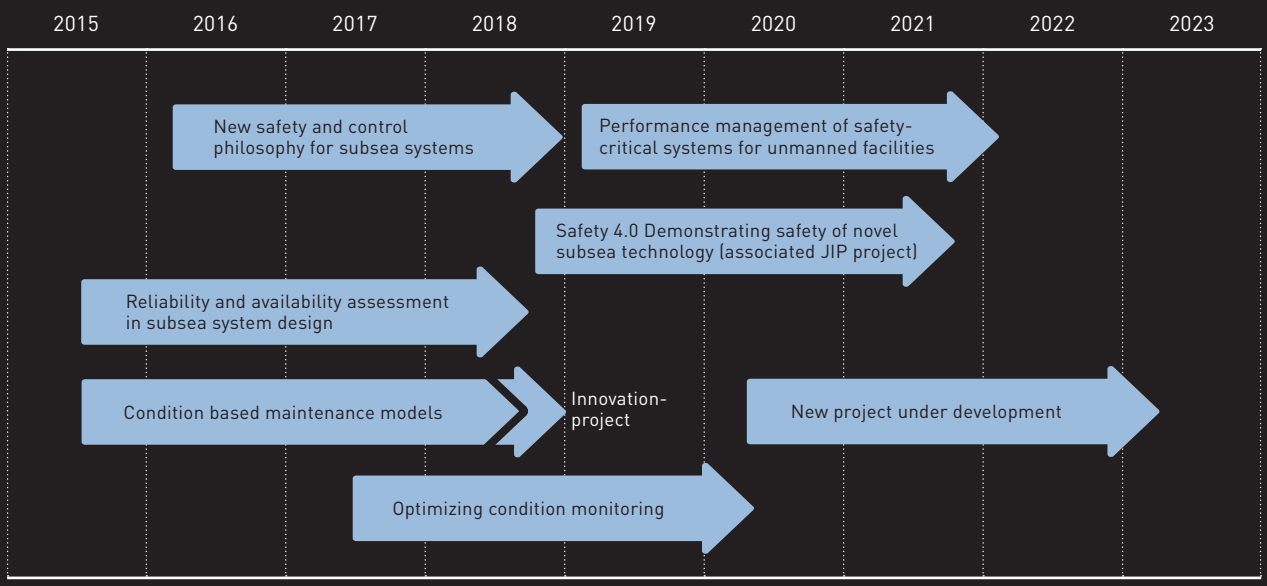
Seeds from SUBPRO have generated new activities beyond the scope of the Centre. The spin-off project "Safety 4.0 Demonstrating safety of novel subsea technologies", represents an extension of work done in SUBPRO with the aim to develop and demonstrate new industrial methods for verifying safety of novel subsea technology. The project consortium comprises 8 supplier companies and oil companies, led by DNV GL. The project is supported by the Research Council of Norway.

Looking into 2019, we are expecting further development of results from the ongoing PhD project on optimizing condition monitoring. Some models have already been suggested, and a collaboration with another PhD project in System control has been initiated. Also, a new PhD project is scheduled to start in 2019:

- Performance management of safety-critical systems for unmanned facilities

The figure to the right shows an overview of completed, on-going and future projects within the research area.

Completed, current and planned projects



The Reliability, Availability, Maintenance and Safety team.
From 1 o'clock: Himanshu Srivastav, Yiliu Liu, Anne Barros, Yun Zhang, Mary Ann Lundteigen, HyungJu Kim, Juntao Zhang.
(PhD student Nanda Anugrah Zrikullah is not present in the picture).

New safety and control philosophy for subsea systems

Deriving new safety requirements to ensure robust and safe subsea operations.

Postdoctoral fellow:
HyungJu Kim

Project manager:
Prof. Mary Ann Lundteigen

THE NEED FOR A NEW SAFETY AND CONTROL PHILOSOPHY

Today, the current safety and control philosophies for the design of subsea production and processing systems build on experience from topside systems. Unfortunately, it is not straightforward to apply the same philosophies for subsea systems, due to different technical design constraints, different operation conditions, and different associated risks, compared to topside. In addition, modern subsea systems have become more complex and software-intensive, and this may lead to a new type of failures that are not covered by existing safety philosophies. The new philosophies aim to reduce complexity of subsea systems and their internal interactions, while maintaining a high integrity of critical functions.

PROJECT ACTIVITIES AND RESULTS, COLLABORATION WITH EQUINOR, DNV GL AND MIT BOSTON

In the first year of this project (2016), we focused on detailing the challenges of existing subsea control and safety systems and identifying subsea hazards, associated protection measures, and relevant regulations and standards. In the second year (2017), based on the results of the first year, we investigated and applied a new control and safety philosophy, Systems-Theoretic Accident Model and Process (STAMP), to subsea systems. We conducted two case studies that applied Systems-Theoretic Process Analysis (STPA) to isolation of subsea wells and subsea gas compression system. The two case studies were conducted in close collaboration with Equinor and DNV-GL.

In the last year of this project (2018), we conducted one more case study that applied STPA to conventional control and adaptive control of subsea processes, and compared the hazards of the two different systems.

This case study was conducted in collaboration with the project, "Adaptive control of subsea processes".

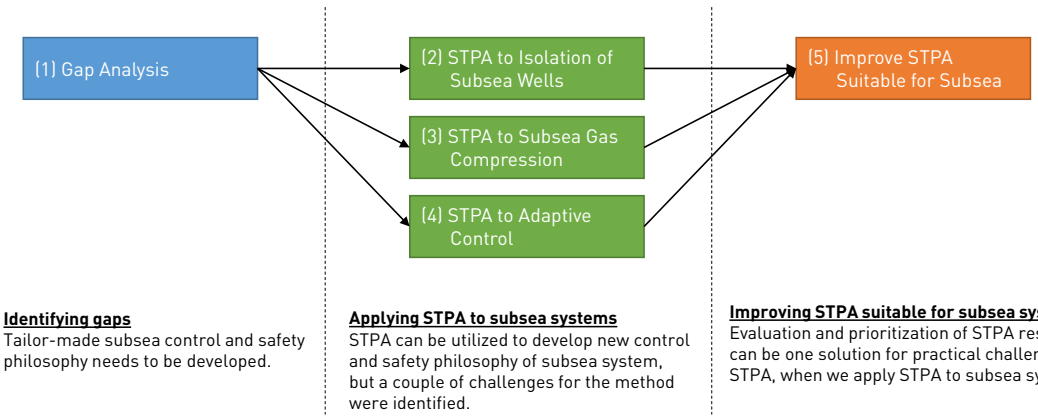
The conclusion of the three case studies is that the STPA method is well suited for the analyses of subsea systems in principle, but a couple of challenges were identified. Therefore, we developed an improved STPA method suitable for subsea systems by introducing additional evaluation procedures. The improved STPA method was developed in collaboration with DNV-GL and Massachusetts Institute of Technology (MIT).

INNOVATION AND FURTHER WORK

The improved STPA method can be used for both analyzing subsea systems and developing new safety philosophies for subsea operations. This project has already contributed to initiate a spin-off/Petromaks2 project, "Safety 4.0 – Demonstrating safety of novel subsea technologies". A PhD candidate of Safety 4.0 project expands the findings of this project to develop a new framework to demonstrate safety of novel subsea technologies.

We need further research on suitable approach to obtain Risk Priority Numbers that can be utilized for STPA. More aggressive approach, like screening-out less critical Unsafe Control Actions (UCAs) and loss scenarios, may also need to be developed for applying STPA to the early stage of a project or for analyses with limited time and resources available. How to extract unique contributions of STPA is another essential research topic to utilize STPA optimally, in combination with system specifications and other hazard analysis methods.

After the completion of the postdoc project in SUBPRO, HyungJu Kim is working as an associate professor in the field of marine engineering, at the University of South-Eastern Norway (USN).



Overall summary of the project.

Safety 4.0 – Demonstrating safety of novel subsea technologies

An associated JIP project.

Tore Myhrvold, DNV GL
Project manager

PhD student:
Nanda Anugrah Zikrullah

Main supervisor:
Prof. Mary Ann Lundteigen

Safety 4.0 is a good example of how innovation and knowledge is transferred and expanded from the SUBPRO centre to create new R&D activities.

The collaboration between industry partners and NTNU in SUBPRO on reliability and safety led to the development of a new independent joint-industry R&D project outside the Centre. The project is named "Safety 4.0 – Demonstrating safety of novel subsea technologies" and is headed by DNV GL with participation from NTNU, University of Stavanger, and eight industry partners, of which three are current members of SUBPRO. The project is funded by the Petromaks 2 program and the involved partners, and the project started up in in the second quarter of 2018. The Petroleum Safety Authority takes the important role as observer throughout the whole project.

The objective of the Safety 4.0 project is to enable faster demonstration of safety for novel subsea solutions. This is done by developing a new safety demonstration framework, which is: modular, facilitating reuse of safety arguments, risk based, and addressing safety from a systemic and life cycle perspective. The framework is developed based on relevant use cases together with industry partners: i) All-electric safety systems, ii) Integration of process control and safety, and iii) Efficient use of sensors and data analytics. The intermediate results are expected to be of direct support to the partners decision-making and concept selection.

The project funds a PhD project at NTNU that started in August 2018 with PhD candidate Nanda A. Zikrullah. The main supervisor is Professor Mary Ann Lundteigen, and co-supervision includes Dr. Meine van der Meulen from DNV-GL. The project title is "Ensuring functional safety of novel technologies". It aims to develop a framework for identifying distinct feature(s) of novel subsea systems and to recommend an approach to assess and demonstrate functional safety of these features. The framework is to be tested with the proposed use cases for validation. The PhD project represents a nice extension of research which started in a SUBPRO project, "New safety and control philosophy for subsea systems".

Reliability and availability assessment in subsea system design

A new framework to support design of cost-efficient, reliable and safe subsea systems.

PhD student:
Juntao Zhang

Project manager and main supervisor:
Prof. Mary Ann Lundteigen

BACKGROUND; USE OF RAM ANALYSIS TOOLS IN THE EARLY DESIGN PHASE

Reliability, availability and maintainability (RAM) analyses are essential for evaluating novel subsea technologies, to express the level of confidence in the future operating environment. Unfortunately, RAM analyses are often carried out too late to provide valuable direct input to subsea design. In addition, modern subsea systems have become more complex, which implies new issues that are not sufficiently addressed in existing RAM methods, such as limited accessibility to subsea equipment, modularized structure and control-related failures. This project aimed at improving existing methods and frameworks for RAM analyses to support subsea design at the early stage.

USE OF SYSTEMS ENGINEERING APPROACH

The project applied Systems Engineering (SE) theory and models in existing RAM analysis processes. SE is a discipline that develops systematic models for the design of complex systems. The application of SE models in this project resulted in a new framework named RAM-SE with 4 steps, see figure 1. The application has been demonstrated through a design case (subsea fiscal flow metering system) provided by Equinor. The proposed framework enables the early concept evaluation of system redundancy, modularity and accessibility and/or possibility to retrieve equipment.

Systems Theoretical Process Analysis (STPA) is a new failure analysis method. Unlike conventional methods, STPA applies systems thinking to focus on unintended interactions between components rather than single failures of individual components. STPA is well-suited to analyze control-related failures of subsea systems. However, it is currently challenging to interpret STPA results in a subsea design as it has no probabilistic aspect. In this respect, this project proposed a standard procedure to convert STPA results into stochastic Petri-nets. With this proposal, analysts can directly simulate the impact of control-related failures on system availability and production.

Five main topics were investigated in the project. The contributions for each topic and relations between each topic are illustrated in Figure 2.

APPLICATION OF RESULTS, FURTHER WORK

The results of this project are complementary to the existing standards and current industry practice. For example, RAM-SE framework can be integrated into adopted technology qualification programs (e.g.

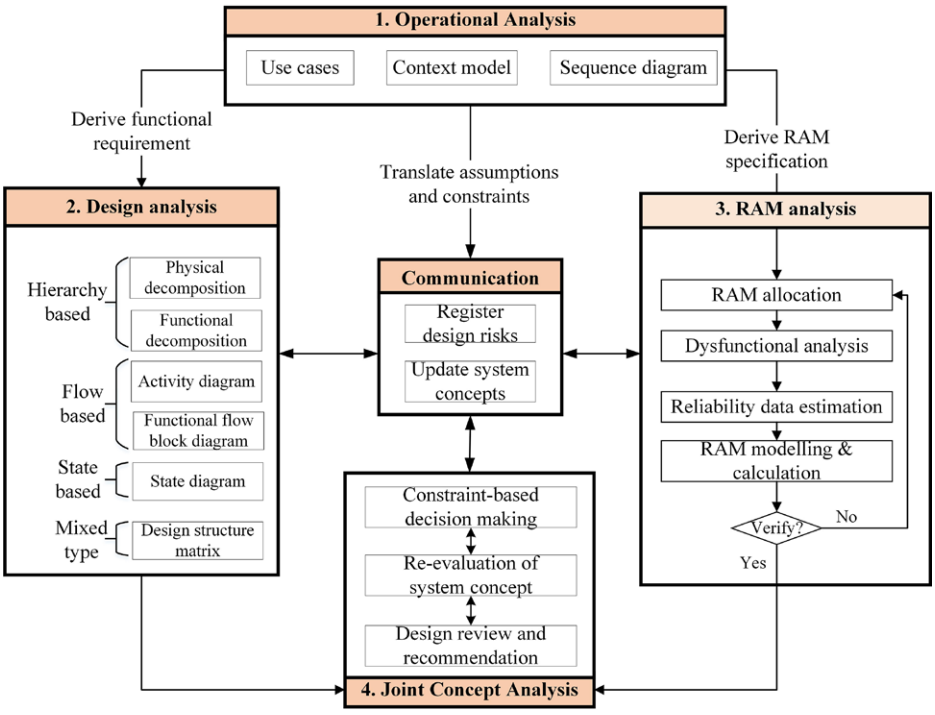


Figure 1. The RAM-SE framework.

DNV-RP-A203), in order to improve existing practices and methods from an SE perspective. The proposed guideline on modelling techniques can be seen as an extension to standard ISO/TR 12489 that is well-recognized in the oil and gas industry. The proposals such as the extension of STPA may be further explored, e.g. in the project "Safety 4.0 Demonstrating safety of novel subsea technologies".

The further work of this project can be twofold. One is to test out RAM-SE methods against an industry-scale design case, to derive more insights about challenges faced in the early design. Another is the refinement of existing proposals. For example, the proposed extension of STPA can be further improved with a proper means that evaluates and prioritizes STPA results, to enhance its applicability on large-scale systems. This further work relies on recent achievements of the project "New philosophy for safety and control of subsea systems".

The project was completed in 2018. Juntao Zhang is now working as a reliability engineer in the field of oil and gas and renewable energy, in the Wood group Kenny Norge AS.

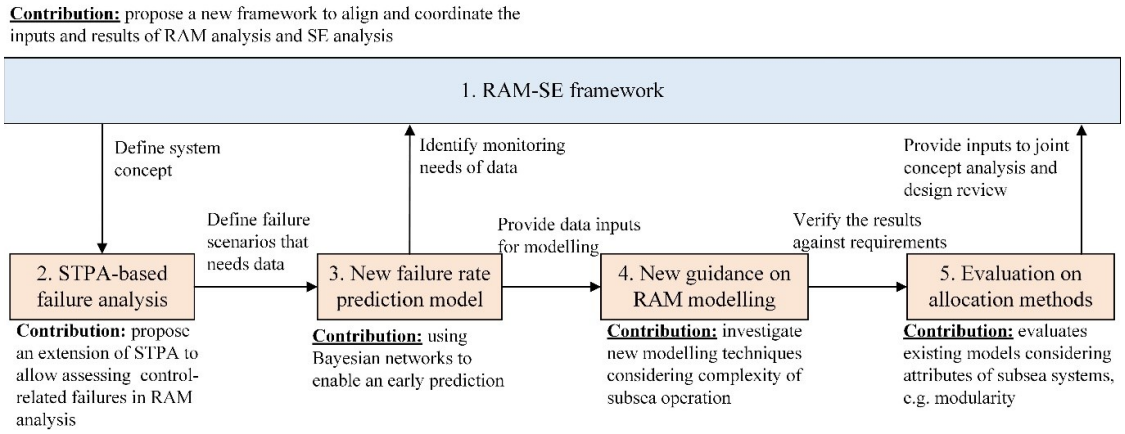


Figure 2. Summary of project results.

Condition based maintenance models

A new modelling methodology for the assessment of Condition Based Maintenance policies for subsea systems.

PhD student: **Yun Zhang**

Project manager and main supervisor: Prof. Anne Barros

OBJECTIVES

The objective of this project was to provide models to assess and optimize the maintenance policies for typical subsea safety systems in the arising context of digitalization. Optimization concerns the design phase (e.g. the number and locations of spare units) and the operation phase (e.g. the number and the frequency of maintenance operations, the maintenance decisions made during these operations, given health indicators at hand).

ACTIVITIES AND RESULTS

The main contribution of this project was a set of modelling methods and models to optimize condition based maintenance strategies. The core research activity evolved two aspects of work: degradation models and maintenance models with delay. They were elaborated at two levels: single-unit level and system level. The modelling formalisms involved joint use of stochastic processes as a basis for degradation modelling of single units, and state transition models plus high-level modelling language for system level. Discrete event Monte Carlo simulation was used to assess the performance of the maintenance strategies.

The methods were evaluated on a choke valve, on a HIPPS (High Pressure Protection System) and on a compressor. The obtained results showed that it is possible to challenge current time-based maintenance strategies by proposing less costly or safer condition-based approaches at the system level. It was also demonstrated that uncertainties related to remaining useful lifetime prediction can be better estimated in the decision process by using the proposed models at the unit level.

EQUINOR

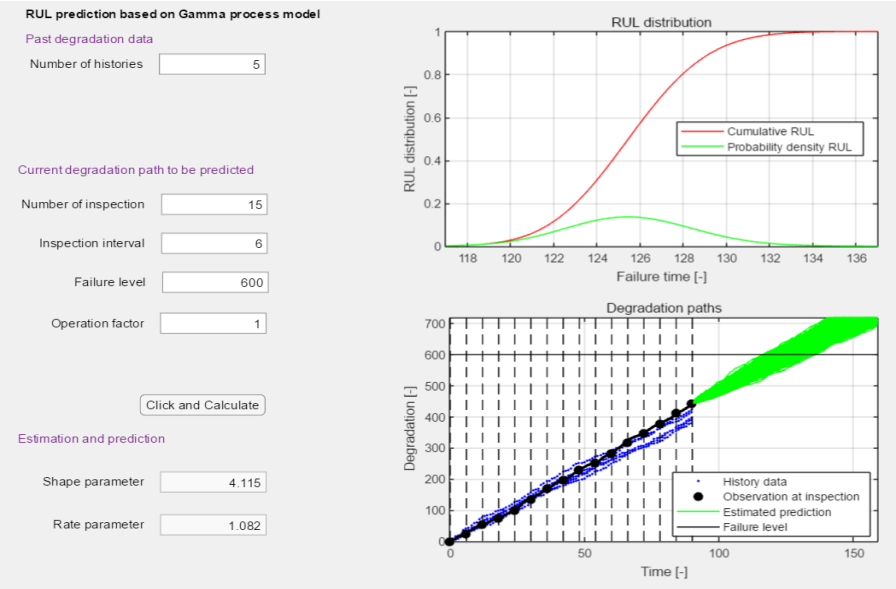
The potential value of the methodology has been recognized by DNV-GL and Equinor. The models have been presented in an internal seminar in DNV-GL, Høvik. Three master projects have been performed in collaboration with Equinor. The case study was a compressor. The models were implemented at the unit level (degradation modelling) and at the system level (availability for production).

The PhD project has been followed up by a 3 months innovation project with Equinor and DNV-GL to develop a prototype in Matlab, with a user interface. The case study was a choke valve (see illustration). The objective was to provide degradation prediction, and remaining useful lifetime estimation based on historical data. Equinor wants now to develop a web-based tool for an important data set encompassing more than 500 production chokes, all data to be stored in a cloud solution. DNV-GL is planning to improve the tool by adding usage and production profiles in the models.

The Matlab user interface for modelling of degradation and prediction of remaining useful life (RUL) for a choke valve

The project was completed in 2018. Yun Zhang is working as a Condition based maintenance analyst/Condition and Maintenance engineer at MHWirth (provider of drilling services and solutions).

INNOVATION IN COLLABORATION WITH DNV GL AND



The Matlab user interface for modelling of degradation and prediction of remaining useful life (RUL) for a choke valve.

Optimizing condition monitoring

Quantification of added value of condition information, optimization of inspection and monitoring strategies.

PhD student:
Himanshu Srivastav

Project manager and main supervisor:
Prof. Anne Barros

OBJECTIVE

The objective of this project is to provide methods and models to optimize the condition monitoring of subsea equipment. In the operational phase, it encompasses the optimization of inspection periods for subsea equipment and the optimization of replacement strategies, with sensor battery management as a case. In the design phase, the focus is currently on sensor allocation.

ACTIVITIES AND RESULTS

The main contribution of this project is a set of models to optimize decisions related to condition monitoring management. In 2018, the main focus was on a collaboration with DNV-GL on shut-down valves in low demand mode. Such systems are submitted to periodic tests that, as a side effect can degrade the condition of system components. The goal for the case study was to find the optimum testing frequency, which balances the added value of frequent testing versus the negative effect on wear caused by the testing (see illustration).

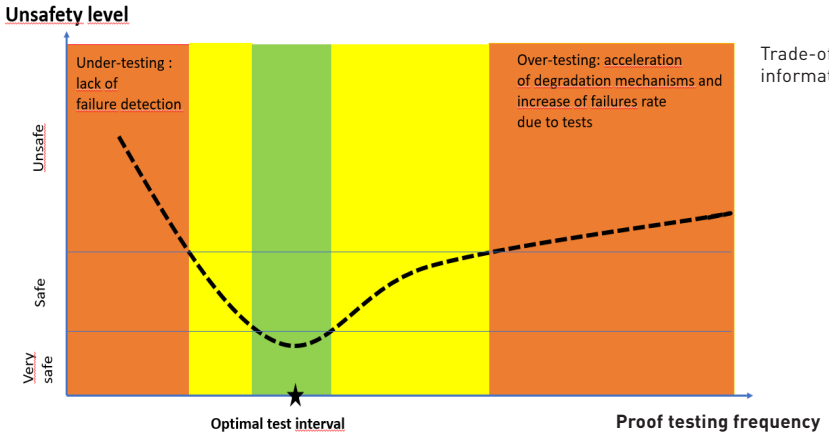
The project also hosted two master students, doing their specialisation projects under co-supervision from Equinor. One project was about condition monitoring and prognosis of remaining life for a heat exchanger, the other was about management of sensors batteries for condition monitoring equipment. The projects will be continued through Master theses in 2019.

The next contribution is to move to the design phase and optimise sensor allocation in multi-unit systems by using stochastic dependences. A PhD student from University of Technology of Troyes, France (Nan Zhang) has been employed as a researcher for three months in 2018 to prepare this next phase. In some cases, stochastic dependencies are caused by operating environment, for example high-pressure wells, where the degradation speed of several components which are exposed to the common pressure will be jointly increased in the same period of time. In other cases, the dependences may relate to complex interactions of subsea equipment, when for example the degradation of one component causes other components to degrade faster. Such phenomena may affect the reliability of the whole system and lead to an overestimation of the safety expected from design, if dependencies are not taken into consideration. The result of this study is a literature review on models and methods to handle different types of stochastic dependencies. The work will be a starting point for addressing system level in this project and investigating how stochastic dependences between units can be taken into account to optimize degradation monitoring in the design phase.

TESTING AND DEMONSTRATION OF RESULTS IN COLLABORATION WITH DNV GL

The further plans for the project include testing and demonstrating results on practical cases, as well as implementing them in business processes. To do so, the project has established a collaboration with DNV-GL in Norway and in Brazil. Numerical studies will be carried out to evaluate different modelling frameworks proposed by the industry (DNV-GL) and by existing literature, to identify complementarities, limitations and validation domains for shut down valves, as mentioned above.

Finally, the project is collaborating with another SUBPRO project "Control for extending component life" from the System Control research area. The aim is to develop a framework for integrating deterministic control laws and stochastic degradation models.



Trade-off between added condition information and increased wear.

Performance management of safety-critical systems for unmanned facilities

Safety management, from data acquisition to decision making.

Project manager and main supervisor:
Prof. Mary Ann Lundteigen

PhD student:
To be hired in 2019

This project will start up during the first half of 2019, and may still be subject to some changes regarding direction and scope.

BACKGROUND

The project, which will employ a PhD student, aims to innovate the performance management of safety-critical systems in unmanned facilities with restricted access. Performance management will cover aspects of both day to day decision-making as well as decision-making that relates to performance monitoring on a longer time scale. The project has an innovation potential for creating new ways to enhance the economical and safety benefits of digitalization of organizations and facilities. The focus is placed on the safety-instrumented systems, which play a key role in ensuring safety of unmanned facilities.

The project targets unmanned facilities with restricted access. The concept applies to both subsea and topside facilities, and it is of interest to seek opportunities of standardized solutions for their shared challenges: For example, being unmanned means that the level of automation and autonomy is increased, and restricted access means that the design and operation strategy must be simple, robust, and predictable enough to allow safe operation in periods where the facility cannot be accessed. It is assumed that more reliance is made on digital solutions for condition-monitoring, and possibly new needs for instrumentation or instrumentation coverage (including cameras) to confirm status of facility when people are not onboard to verify.

RESEARCH ACTIVITIES AND DELIVERABLES

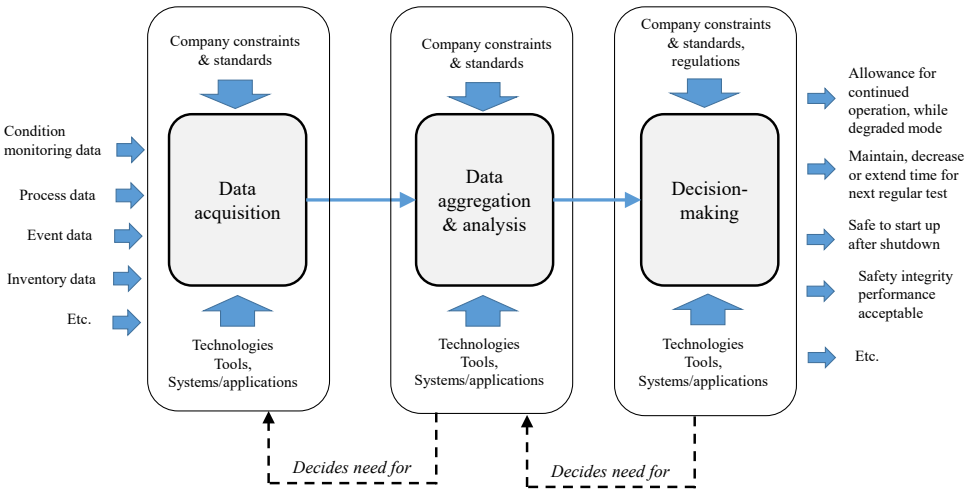
The scope of the project includes the whole loop from data acquisition to decision-making, as illustrated in the figure. More specific objectives and tasks of each stage are:

- **Decision-making:** The objective of this stage is to identify and formalize requirements to decision-making. This includes decisions that rely on information *from* the safety-instrumented systems *and* decisions that are impacted *by the state* of the safety-instrumented systems.
- **Aggregation of data and analysis:** The objective is to formalize the relationships between decision-making and information needed to support these. It is relevant to study what are existing indicators and information, and what are new, in light of needs for decision-making.
- **Data acquisition:** It is a question still how deep the project will enter the stage of instrumentation and data acquisition. However, it is of relevance to formalize the requirements to data acquisition, both for existing and potentially new parameters.

INDUSTRY PARTICIPATION; NEPTUNE ENERGY, LUNDIN, AKER BP AND DNV-GL

The project will connect to several of the ongoing SUBPRO projects. Four SUBPRO partners (Neptune Energy, Lundin, Aker BP, and DNV-GL) have confirmed interest to either participate in or follow the progress of this project.

In relation to DNV-GL, it is suggested to incorporate results from the Safety 4.0 project, use case no. 3 on "Advanced use of sensor data and data analytics: Demonstrate how monitoring can contribute to more effective and cheaper safety validation". It is also planned to investigate other collaboration networks regarding enhanced follow-up of safety-critical systems, e.g. as part of research initiated within PDS forum (www.sintef.no/pds).



Safety management loop from data acquisition to decision-making.

Postdoctoral fellow HyungJu Kim from SUBPRO presenting his project at a workshop at Massachusetts Institute of Technology (MIT) on Systems-Theoretic Accident Model and Process (STAMP). Kim has collaborated with the STAMP group at MIT in the development of an improved Systems-Theoretic Process Analysis (STPA) method.

PROFESSOR
JOHAN SJÖBLOM

RESEARCH AREA
MANAGER

PROFESSOR
GISLE ØYE

RESEARCH AREA
CO-MANAGER

RESEARCH AREA

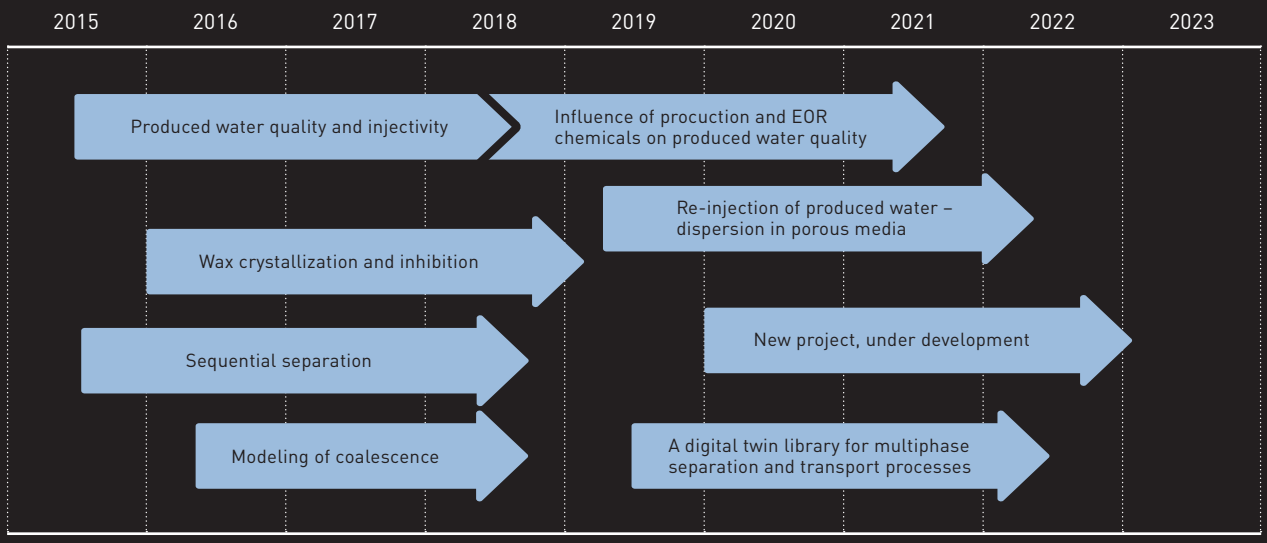
Separation - Fluid characterization

Enhancement of separation efficiency and flow assurance.

Successful subsea installations require high efficiency and minimal maintenance need of the processing equipment. This means that the behavior of the fluids must be well understood. Efficient separation of gas, oil and water and reliable transport of the hydrocarbons are central for optimization of subsea processes. Since the behavior of the fluids is strongly linked to their chemical composition, proper fluid characterization that provides fundamental understanding of the microscopic phenomena leading to efficient separation and transport is essential. The overall goal in this research area is to develop new methods for advanced fluid characterization at conditions relevant for subsea processing.

During 2018, four projects were completed. During 2018 and 2019 new projects have been started, where topics from earlier projects are further matured. The figure to the right shows an overview of all projects within the research area.

Completed, current and planned projects



The Separation - Fluid characterization team. From the left: Dr. Sebastien Simon, Professor Gisle Øye, Associate professor Brian A. Grimes, PhD student Jost Ruwoldt and Postdoc Marcin Dudek.
(Professor Johan Sjöblom, Postdoctoral fellow Aleksandar Y. Mehandziyski and PhD student Are Bertheussen are not present in the picture).

Produced Water Quality and Injectivity

Improved understanding of coalescence between oil drops and oil drop – gas bubble interactions can help designing more efficient subsea separators.

Phd student:
Marcin Dudek

Project manager
and main supervisor:
Prof. Gisle Øye

OIL DROPLET AND GAS BUBBLE BEHAVIOUR IS IMPORTANT DURING WATER TREATMENT PROCESSES

The treatment of produced water is a crucial aspect during crude oil production. The efficiency of many oil-water separation processes can be traced down to very fundamental interactions between small particles, such as coalescence or flocculation between oil droplets, and attachment of oil to gas bubbles. Furthermore, the role of crude oil chemistry in these processes cannot be neglected. Microfluidics, a science of behaviour and manipulation of fluids in microchannels, has been used to study these processes in this project. In the recent years, this methodology is becoming gradually more popular within the petroleum research, especially concerning applications within fluid analysis and fundamental phenomena associated with oil production, such as precipitation, mass transfer or coalescence.

STUDY OF DROP COALESCENCE AND DROP-BUBBLE INTERACTIONS WITH OIL SAMPLES FROM EQUINOR, SHELL AND NEPTUNE ENERGY

The project focused on the development of new microfluidic methodologies for studying fundamental aspects of produced water. The established microfluidic platform enabled precise control of the flow of various fluids through microfluidic chips with small channels, and simulation of the flow of dispersed oil droplets and gas bubbles in the water phase. All experiments are followed with high-speed imaging and later processed with image analysis tools. As a result, it was possible to determine the effect of different parameters, such as water composition, droplet size or pressure on the coalescence process (see Figure) and the interactions between gas bubbles and oil drops in water. Details regarding the produced water treatment methods and relevant experiments were discussed with Equinor and Aker Solutions, whereas the crude oils used during the project were supplied by Equinor, Shell Norge and Neptune Energy.

LOWER WATER PH OFTEN IMPROVES SEPARATION OF OIL FROM WATER

The main project results are:

- In general, lower pH of the water phase (that is expected in subsea conditions due to more dissolved CO_2) induced more coalescence and bubble-drop attachment, which could support the water treatment at higher pressures
- Microfluidic setups that are and will be utilized by subsequent SUBPRO projects in the Separation Research Area
- Methodologies and procedures for drop-drop coalescence and drop-bubble interaction experiments

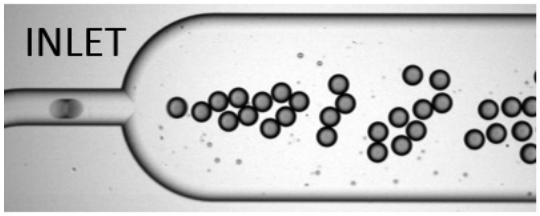
APPLICATION OF RESULTS AND FURTHER WORK

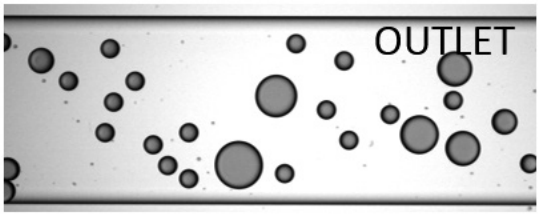
One of the interesting aspects of the project was the connection between microscale studies and crude oil properties, all of which can affect efficiency of macroscale processes. The developed methods can be used to evaluate the coalescence tendencies of specific crude oils in various conditions, which can help explain the separation with oil chemical or interfacial properties.

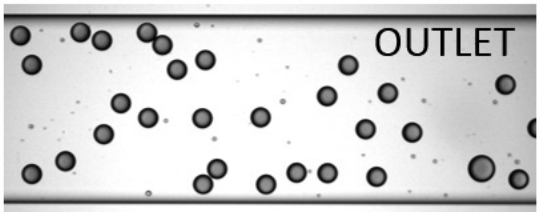
CAREER AFTER THE PHD PROJECT

This project was completed in 2018. After the completion, Marcin Dudek started working as a Postdoctoral fellow at NTNU, Department of Chemical Engineering, to continue his work for SUBPRO in a new research project: "Influence of production and EOR chemicals on the produced water quality".

Visual comparison between coalescence-favoring conditions – low pH (top right picture) and coalescence-limiting conditions – high pH (bottom right picture).







Influence of production and EOR chemicals on produced water quality

Production chemicals have a large impact on the treatment of produced water.

Postdoctoral fellow:
Marcin Dudek

Project manager:
Prof. Gisle Øye

BACKGROUND

This project started in 2018, following up the results from the completed project "Produced water quality and injectivity".

During the production of petroleum, the produced fluids can be exposed to many changes, such as drop of pressure, temperature or increased turbulence. To mitigate or prevent certain undesirable changes of state of the fluids, and to ensure predictable and continuous flow, production chemicals are added to the fluid stream. In general, these chemicals can help avoid fouling problems, decrease the stability of formed dispersions, lower the environmental footprint of the production and guarantee the integrity of the installation. With the increasing volumes of produced water, the unknown effect of these chemicals on the water treatment processes can become problematic. Furthermore, the fluids injected during the enhanced oil recovery (EOR) stages, containing various surfactants or polymers, can mix with the reservoir fluids and return to the production and separation units. The treatment of post-EOR produced water is more challenging and requires better fundamental understanding.

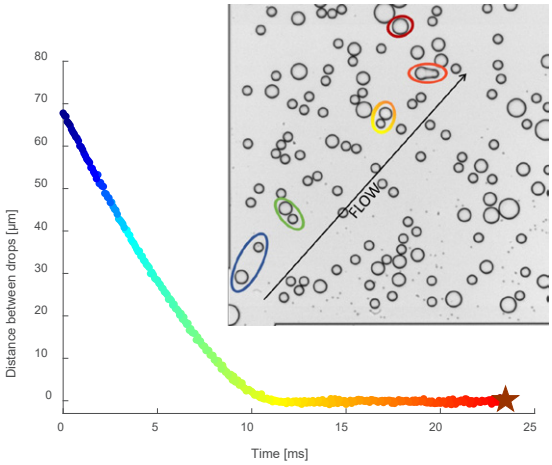
OBJECTIVE OF THE PROJECT

The principal objective of this project is to improve and use the previously developed microfluidic methodologies for systematic studies of the influence of production chemicals on the produced water treatment.

ACTIVITIES AND EXPECTED RESULTS

Microfluidics allows us to precisely control the flow of small volumes of fluids through transparent micro-channels. We generate monodisperse, micron-sized oil droplets and gas bubbles and follow with high-speed imaging, which enables to determine the effect of the additive on the stability of oil-in-water dispersion. The effect of the wax inhibitors, flocculants, scale inhibitors, EOR chemicals and corrosion inhibitors will be studied. Most of the experimental work will be performed with crude oils supplied by the industrial partners. Improvement of the existing methods for studying oil droplet coalescence and bubble-drop interaction, together with the introduction of new designs will also be important parts of this project. In 2018 we have extended our microfluidic toolbox with a method for coalescence time measurement (see the figure) and a setup for temperature-controlled measurements.

The knowledge obtained through this project will give a better understanding of the effect of production chemicals, both their type and concentration, on the fundamental phenomena occurring in produced water treatment. It will also create new methodologies for studying processes, associated with these chemicals, such as precipitation of scale or flocculation between drops and bubbles.



Visual representation of the coalescence time measurement method with an exemplary result. Two droplets, initially far away from each other (blue), start to get closer (green) and get in contact (yellow). After spending some time in proximity (from yellow through orange to red), they coalesce (red) and form a bigger droplet (dark red). The method allows to measure thousands of coalescence times per experiment.

Re-injection of produced water – dispersion in porous media

Project manager:
Prof. Gisle Øye

Phd student/
Postdoctoral fellow:
To be hired in 2019

BACKGROUND

Produced water re-injection (PWRI) can become a cost-effective of way handling the large amounts of water produced along with oil and gas production. It is attractive environmentally, as it decreases produced water discharges to sea, and economically, since it may limit the need for processing large amounts of produced water for discharge with strict regulations and secure extra injection water. PWRI is often considered to be the base case for new fields as well as for mature fields upon implementation of chemical enhanced oil recovery (EOR) methods. It is also likely to be the preferred way of handling produced water in particularly environmentally sensitive locations (Artic regions) and when using subsea production and processing facilities.

Implementation of PWRI faces several challenges, including the risk of scaling, reservoir souring, biofouling and corrosion control of installations. However, the main limitation for implementing PWRI is often the risk of uncontrolled permeability decline in the injection reservoirs. Understanding the behaviour of the water injected into porous reservoirs is essential to obtain predictive models for simulating and optimising water injection. A major shortcoming in the current models is the lack of detailed understanding of transport, plugging and deposition mechanisms.

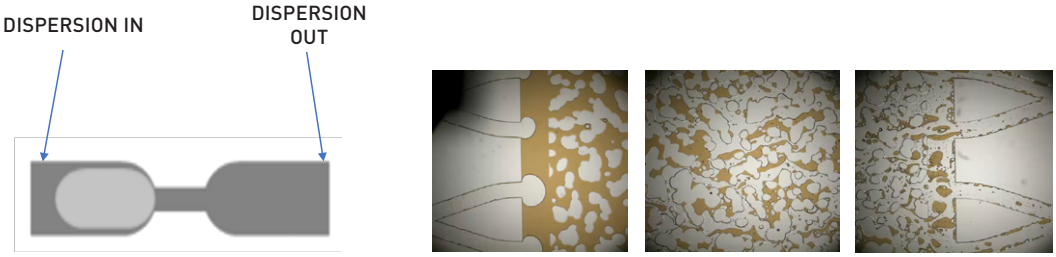
THE GOALS

1) Develop microfluidic methodology to follow transport and clogging of particles and drops in porous networks. Microfluidic methods will provide faster, more accurate and more reproducible results than conventional methods (normally core floodings)
2) Acquire new knowledge about transport and retention of particles and droplets in porous networks. This will provide understanding of how produced water properties relates to water injectivity, and about its potential reuse to maximize the oil recovery.

EXPERIMENTAL APPROACH

A microfluidic system is a lab-on-a-chip (here reservoir-on-a-chip) device were the behaviour of fluids in micro-channels or networks of micro-channels can be followed and visualised. Different "reservoir-on-a-chip" designs will be used to represent single-pores and simplified, two-dimensional porous networks (see Figure below), while a digital video microscope equipped with a high-speed camera will be used to follow the dynamics and clogging phenomena of the dispersed components. The outcome is visualization of transport, immobilisation and plugging phenomena in simplified reservoir models.

The project starts in 2019 and will last for 3 years.



Examples of "reservoir-on-a-chip" designs that will be used in the project. A single pore throat model is shown on the left-hand side. Several pore throats in series can also be envisaged. The right-hand side shows a model with a network of pores and pore throats, which will be used for retention and immobilisation studies.

Wax crystallization and inhibition

New characterization techniques for wax inhibition can help the development and selection of better chemical additives for flow assurance.

Phd student:
Jost Ruwoldt

Project manager
and main supervisor:
prof. Johan Sjöblom

Co-supervisor:
Adjunct professor
Hans-Jörg Oschmann

PARAFFIN WAX CRYSTALLIZATION – A MAJOR CHALLENGE FOR FLOW ASSURANCE

Paraffin wax crystallization is one of the major challenges faced by flow assurance. During crude oil production, cold ambient temperatures can induce wax crystallization. Different wax prevention and remediation tools are in place, which include measures such as pipeline insulation and heating, mechanical wax removal (pigging), and the use of wax inhibitors. The latter has proven efficient in delaying the onset of waxy gelling and ensuring low crude oil viscosity, even after wax crystallization. However, the efficiency tends to be limited and inhibitors must be evaluated on a case by case basis. A great potential is therefore associated with improving the understanding of wax inhibition and corresponding testing methods.

NEW TECHNIQUES FOR INVESTIGATING WAX CRYSTALLIZATION AND INHIBITION

The project has been dedicated to developing new procedures and techniques for investigating wax crystallization and inhibition. Moreover, the new approaches were used to obtain a better understanding of inhibitor wax interactions. Extensive experimental work was performed to enable:

(1) More accurate assessment of wax appearance temperature (WAT) from experimental data.
(2) Expanding research on inhibitor wax interactions via the use of isothermal titration calorimetry (ITC), nuclear magnetic resonance (NMR) spectroscopy, and gas chromatography (GC).
(3) Fractionation of asphaltenes or wax inhibitors into groups with more distinct properties.

A BETTER UNDERSTANDING OF WAX INHIBITION MECHANISMS

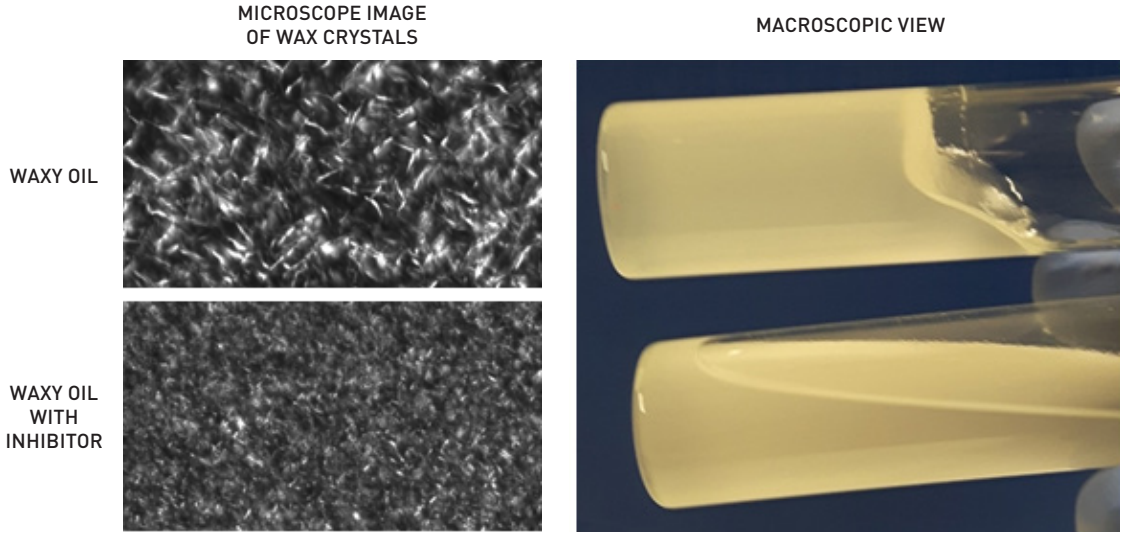
Results indicate that ITC technique is suitable for qualitative studies only, but procedures developed for NMR and GC could reflect inhibitor efficiency to some extent. The results from this project match the common perception that inhibitors act by affecting wax nucleation, wax crystal morphology, and wax solubility. In addition, wax inhibitors were shown to differ in interaction strength and influence on wax precipitation, compositional changes, and liquid wax mobility. Moreover, asphaltenes were shown to interact with paraffin wax in manifold ways.

POTENTIAL FOR INDUSTRIAL APPLICATIONS

The new application of laboratory techniques such as ITC and NMR have shown good sensitivity, high resolution, and reproducibility. They will provide good characterization possibilities for choice, selectivity and comparison of commercial wax inhibitors for different oil fields in the future. A potential for industrial innovation is consequently given directly by the capability to test and select wax inhibitors, and indirectly by the use of fundamental knowledge about wax inhibition to develop next generation high performance and environmentally friendly chemical additives.

CAREER AFTER THE PHD PROJECT

The project was completed early 2019. Jost Ruwoldt is now working as a Postdoctoral fellow at NTNU, Department of Chemical Engineering, in a research project on lignosulfonates with application to petroleum systems.



Demonstration of the effect of wax inhibitor: At low temperature, wax crystallizes to long and large crystals that form a solid-like gel (top). Addition of a wax inhibitor causes wax to crystallize to smaller and more compact crystals that do not overlap, hence delaying gelling and improving flow-ability (bottom).

Sequential Separation

Study of soap-like crude oil components for prediction of separation efficiency and produced water quality in subsea processing facilities.

Phd student:
Are Bertheussen

Project manager and main supervisor:
Prof. Johan Sjöblom

Co-supervisor:
Dr. Sébastien Simon

BACKGROUND FOR THE PROJECT

The worldwide production of high acid crudes is increasing, to keep up with energy demands. The acidity is mainly caused by soap-like components in the crude oil called "naphthenic acids". These acids can slow down the separation of the crude oil phase and the water phase and hence degrade the quality of the produced water. These effects are linked to changes in the water solubility of naphthenic acids, which is prone to increase as the release of CO_2 during pressure drops elevates the water phase pH. For subsea oil-water separation it is crucial to gain more knowledge about the physio-chemical behavior of these naphthenic acids to attain a predictable production. Hence, the goal of this project was to study how naphthenic acids are transferred between the oil phase and water phase, as a function of the composition of the aqueous phase.

RESEARCH ACTIVITIES, COLLABORATION WITH EQUINOR

The first part of the project studied a simple single acid system with experiments and computer simulations. In order to study the more complex systems of crude oil acid mixtures, it was necessary to develop a new analysis method. A method using gas chromatography (GC) and mass spectrometry (MS) was chosen and tested on two different crude oil acid mixtures. The last part of the project studied how water-soluble naphthenic acids in the produced water affect the removal of oil droplets in the produced water treatment.

Equinor has contributed to the project with valuable advice, samples of real crude oil acids and laboratory analysis. IFE has contributed with computer simulations.

PROJECT RESULTS

The transfer of single model organic acids from the oil to the water phase was successfully described through mathematical models in both experiments and computer simulations.

A new analysis method to study acid mixtures was developed and validated on two acid mixture samples. Results point to universal properties for naphthenic acids regarding the transfer between the phases.

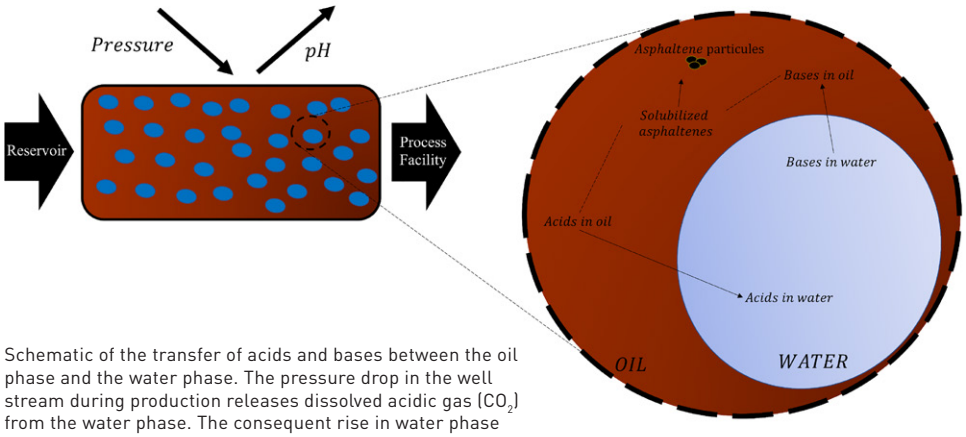
Of the water-soluble crude oil components, naphthenic acids were shown to cause the dominant influence on the oil removal efficiency in produced water, and the effects were prominent even at pH 6.

POTENTIAL FOR INDUSTRIAL APPLICATION OF RESULTS

The new analysis method can be used for a specific field or well to predict the concentration and composition of crude oil acids in the water phase, based on current and future production parameters. This knowledge can be used for predicting separation efficiency.

CAREER AFTER THWE PHD PROJECT

The project was completed in 2018. Are Bertheussen is now working as a process engineer in the Oil and Gas consulting company Origo Process AS.



Schematic of the transfer of acids and bases between the oil phase and the water phase. The pressure drop in the well stream during production releases dissolved acidic gas (CO_2) from the water phase. The consequent rise in water phase pH induces a transfer of acids from the crude oil phase to the water phase. Asphaltenes are solubilized in the oil by acids and bases in the oil phase.

Modelling of coalescence

Development of a multi-scale model of coalescence in petro-emulsions, which takes into account the chemical composition of crude oil.

Postdoctoral fellow:
Aleksandar Y. Mehandzhiyski

Project manager:
Associate Prof.
Brian A. Grimes

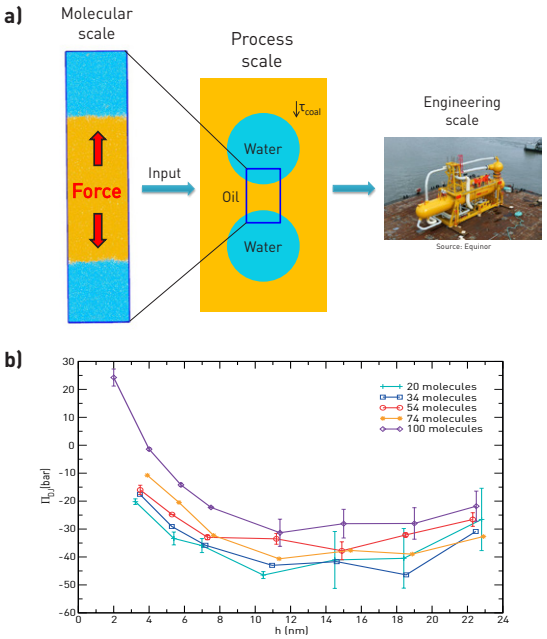
In order to enhance efficiency of subsea separators, the separation process can be sped up with droplet coalescence (merging of smaller droplets forming larger droplets).

The project has developed a new method for calculating the coalescence time (time for two droplets to merge) in water-in-oil emulsions, which can be used in subsea separation engineering. This is based on the following project results:

- Molecular dynamics formulation of a crude oil based on SARA composition (Saturates, Aromatics, Resins and Asphaltenes)
- Calculation of the disjoining pressure from Molecular Dynamics simulations as a function of an asphaltene model compound and film thickness for water-in-oil systems
- Fitting of the disjoining pressure isotherms to an analytical function

This project was finalized in February 2018. It will be followed up by the new project "A digital twin library for multiphase separation and transport processes" from 2019.

Aleksandar Y. Mehandzhiyski is now working as a Postdoctoral fellow on Computational chemistry at Department of Science and Technology at Linköping university in Sweden.



(a) Project concept to calculate surfactant specific Disjoining Pressure (DJP) at molecular resolution and employ the DJP curves in film drainage models to generate coalescence time equations for use in engineering models
(b) Calculated DJP curves for different interfacial concentrations of asphaltene molecules.

A digital twin library for multiphase separation and transport processes

Project manager:
Associate Prof.
Brian Arthur Grimes

PhD student/
Postdoctoral fellow:
To be assigned in 2019

The project is motivated by the apparent necessity for a digital tool to link other projects in SUBPRO from the Separation research area with projects within Field architecture, Reliability, availability, maintenance and safety and System control. The tool should be packaged in a way that facilitates easy incorporation into existing modeling and simulation tools to allow researchers in the industry and academia to utilize the results of coalescence and breakage studies without having to construct advanced multiphase transport models themselves. Therefore, this project will develop a multidimensional C++ class library of population balance models that can utilize user defined droplet coalescence and breakage relationships and be used to construct modular process models involving multiphase fluids in a manner similar to the previous approaches developed in the System control area. Consequently, the model library will be employed to build on the approaches initiated in the projects "Dynamic simulation model library" and "Estimation of unmeasured variables" to build advanced models for oil-water separation systems. The further goal is to incorporate the coalescence and breakage data and models from separation projects and to apply the library to build models to simulate experimental data obtained from our laboratory projects. Equinor has indicated willingness to participate by working with NTNU to define master student projects to apply the model library to industrial multiphase fluid processes.

The project starts in 2019 and will last for three years.

PROFESSOR
HUGO ATLE JAKOBSEN

RESEARCH AREA MANAGER

RESEARCH AREA

Separation process concepts

Enabling new solutions for subsea separation.

The goal of subsea processing is to reduce the need for topside installations and for some fields to eliminate this need by locating all the required gas and liquid processing subsea.

The first case could be a concept where the gas is treated to pipeline specifications directly and the oil stabilization and chemical systems are handled on a floater or platform (which may be an existing installation). Such a system will unload the topside gas processing making tie-back of new discoveries possible and also make long distance gas transport possible, for instance from the Barents sea down to the existing pipeline grid.

The second case could be a completely subsea based field where the hydrocarbons are exported directly into a seabed pipeline or subsea storage facility. This is an alternative for extremely deep waters or harsh conditions (for instance in the Barents sea).

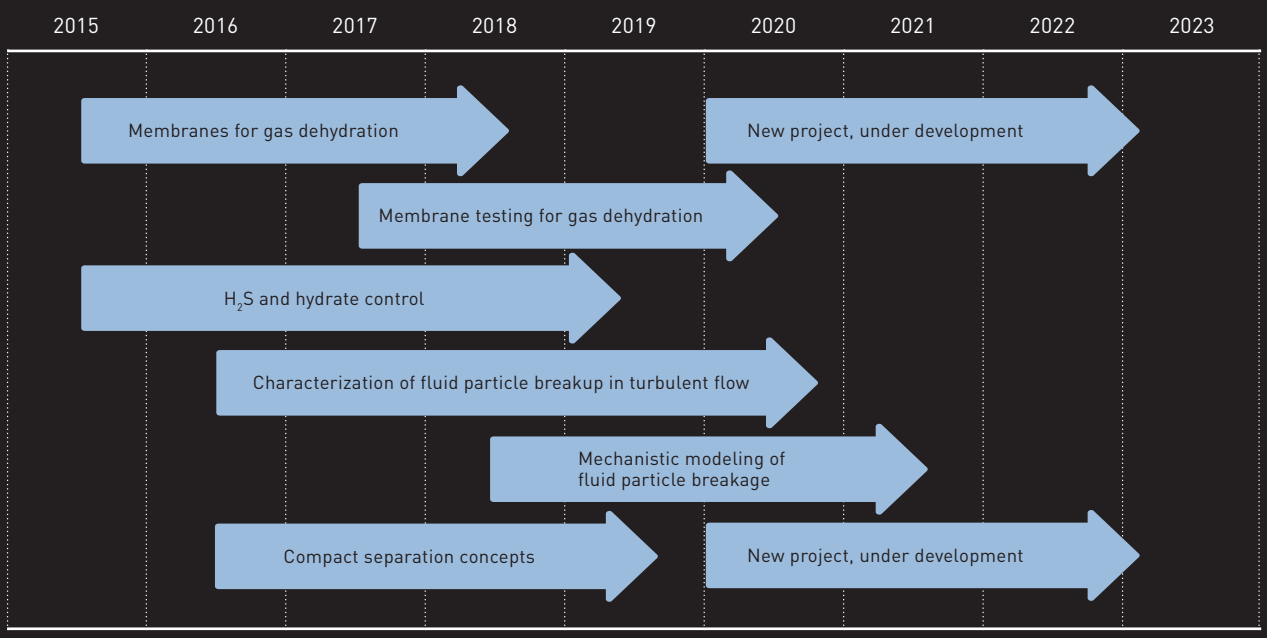
The process equipment used today topside, like the different absorbers for water and sour gases are not suitable for subsea use and there is need for new contacting devices that are not based on gravity and without rotating parts. Additionally they should be compact and have high reliability. The objective is thus to establish new separation equipment and concepts capable of running over long time periods without maintenance or intervention.

During 2018, one PhD project was completed; "Membranes for gas dehydration". The project is followed up by an experimental verification project "Membrane testing for gas dehydration".

The ongoing project "Characterization of fluid particle breakup in turbulent flow" is followed up by a new project from 2018; "Mechanistic modelling of particle breakage".

The figure to the right shows an overview of all projects within the research area.

Completed, current and planned projects



The Separation process concepts team. From the left: PhD student Mahdi Ahmadi, Postdoctoral fellow Hanieh Karbas, PhD student Eirini Skylogianni, Associate prof. Hanna Knuutila, professor Hugo Atle Jakobsen, PhD student Eirik Helno Hærø and researcher Nicolas La Forgia.
(PhD student Kristin Dalane and PhD student Håvard S. Skjefstad are not present in the picture).

Membranes for gas dehydration

Subsea dehydration with membrane technology can enable gas processing directly to export pipelines.

PhD student:
Kristin Dalane

Project manager and main supervisor:
Associate Prof.
Liyuan Deng

Co-supervisor:
Prof. Magne Hillestad

POTENTIAL BENEFITS OF SUBSEA DEHYDRATION

Natural gas in the reservoir is saturated with water, which may condense during transportation, causing flow assurance problems such as hydrate formation and corrosion. The gas needs to be dehydrated to meet the pipeline specifications for water content (-18°C at 70 bara). Moving the dehydration process subsea gives possible advantages, such as no need for continuous injection of chemicals to prevent hydrate formation and direct feeding of gas to the export pipelines without further topside treatment.

The objective of the project is to evaluate membrane technology for subsea natural gas dehydration through modeling and process simulation. Membrane technology enables high modularity, flexible operation, and compact design, and may therefore have a great potential for subsea operation.

BUILDING A MATHEMATICAL MODEL OF A MEMBRANE CONTACTOR PROCESS

The performance of a proposed membrane-based natural gas dehydration process was evaluated through a model, considering the subsea separation conditions. A membrane contactor was used as the absorber with triethylene glycol (TEG) as the solvent in combination with thermopervaporation for regeneration of the TEG (see illustration). To predict the separation performance of the dehydration process, mathematical models of the membrane units have been developed and implemented in Aspen HYSYS for an overall process design evaluation and optimization.

MODEL SIMULATION SHOWS POTENTIAL FOR MEMBRANE CONTACTORS IN GAS DEHYDRATION

The membrane contactor shows potential for subsea dehydration of natural gas. A dense membrane layer on top of the porous support is recommended to ensure long-term stable operation and prevent wetting of the membrane, which significantly would reduce the separation performance.

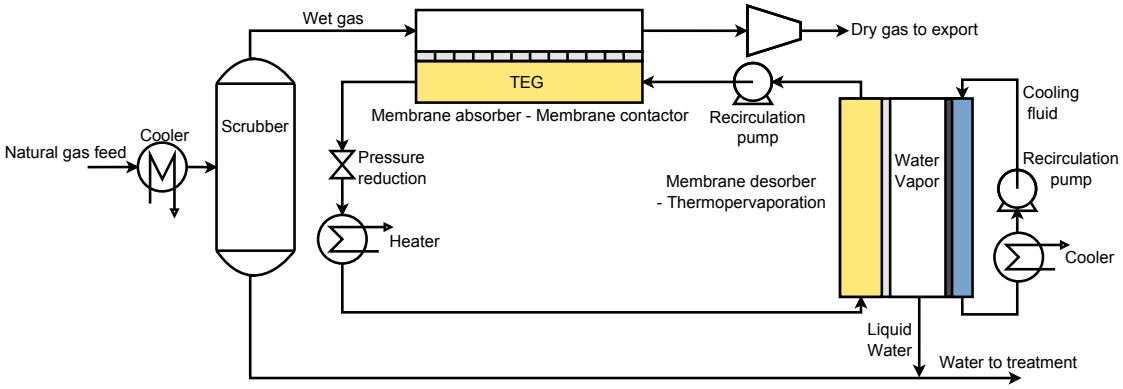
Thermopervaporation shows a potential for the solvent regeneration (dehydration of the water-rich TEG). The main limitation is the temperature drop of the liquid feed due to evaporation and heat transfer between the hot and cold liquids, which reduces the separation efficiency. Therefore, the air gap is found to be a critical parameter in the design of the thermopervaporation module.

It is preferable to stage the solvent regeneration step with several thermopervaporation units and heating between each stage, as this reduces both the size of the membrane units, the TEG flow rate, and the energy demands.

The developed MATLAB Cape-Open Unit Operation models can be used by the industry for further investigation of the technology and for process optimization.

The PhD project will be continued by a new experimental PhD project to evaluate the proposed membrane technology empirically. There are, however, still important modeling topics to be explored, such as to extend the models including mass transport of more components, alternative module configuration of the thermopervaporation unit, and to further optimize the process design.

The project was completed in 2018 and Kristin Dalane is now working as a process engineer in the oil and gas process consulting company Origo Process, Stavanger, Norway



Simplified illustration of the proposed subsea natural gas dehydration system with membrane technology and triethylene glycol (TEG). Water from wet natural gas is absorbed into the glycol in a membrane contactor and is removed from the water-rich glycol through thermopervaporation.

Membrane testing for gas dehydration

Subsea natural gas dehydration using membrane technology gives an energy saving and green process.

PhD student:
Mahdi Ahmadi

Project manager and main supervisor:
Associate Prof.
Liyuan Deng

Co-supervisor:
Prof. Magne Hillestad

EXPERIMENTAL TESTING OF MEMBRANE CONTACTORS

The goal of this project is to test membranes for natural gas dehydration experimentally. The project is a follow up of the modelling work in the project "Membranes for gas dehydration". A closed loop process was designed to dehydrate natural gas using glycols as solvent, including a membrane absorption unit to absorb water from natural gas and a thermopervaporation unit for the glycol regeneration. A liquid mixture of glycol and water at a higher temperature (ranging from 30 to 70°C) flows through the upstream side of the membrane, where the water evaporates and passes through the membrane. The water vapour is then condensed in the air gap by contact with a cooling plate at a lower temperature, similar to sea water temperature at the sea floor (down to 4°C).

Assessment of different membrane materials with respect to the compatibility with the solvent and natural gas as well as the membrane separation performance is the primary stage in the evaluation. A thermopervaporation module for glycol regeneration has been designed and built in house (see Figure 1.).

Compatibility of the membrane materials with glycol together with their long-term chemical and mechanical stability are of critical importance for subsea application. Membrane materials should also be stable and compatible with all components available in natural gas at high pressure and operating temperature. In addition to compatibility and stability, a highly selective and permeable membrane is required in order to reduce the capital and operating costs. Tests on membrane performance are on-going.

PERFORMANCE TEST RESULTS

The performance of the thermopervaporation process depends on operating parameters including temperature and composition of the feed, temperature of the cooling water, and flow rates of the feed and cooling water. Moreover, design parameters including thermal resistance of the condensation plate and membrane, air gap thickness, and the geometry of the membrane module are also affecting the performance of the process. In order to optimize the aforementioned parameters for a specific membrane material and improve the performance, more experiments will be performed in the continuation of the project. The diagram in Figure 2. shows permeate flux of water through a hydrophobic membrane as a function of feed temperature and concentration. The separation performance data obtained from glycol concentration in the permeate side show that the water mole fraction in the permeate is above 99,99%, which means that the water can be discharged directly to the sea.

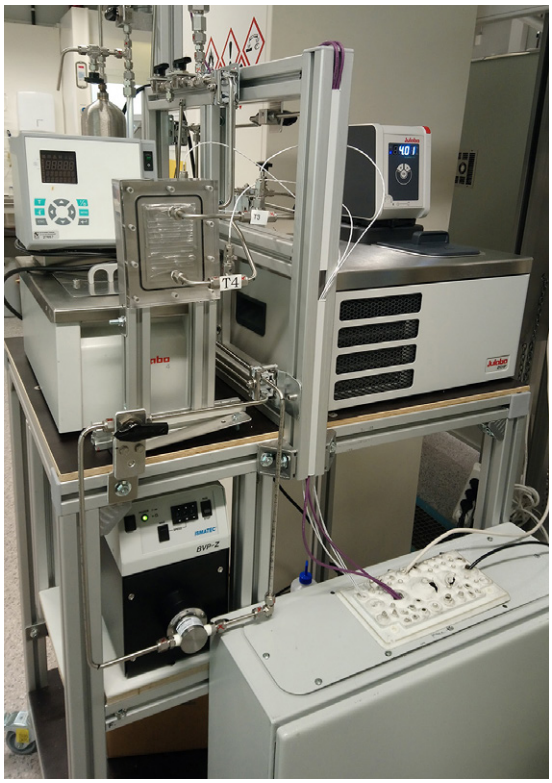


Figure 1. Thermopervaporation test rig for glycol regeneration.

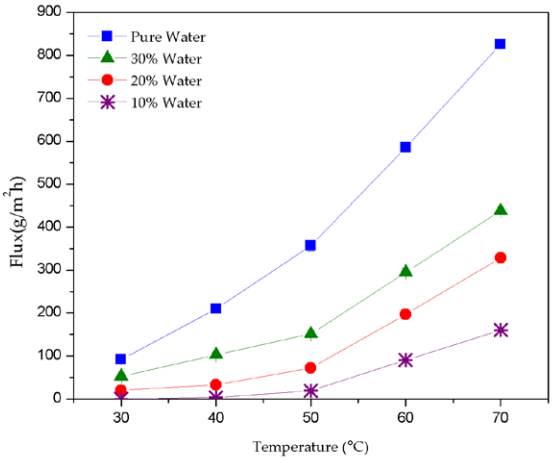


Figure 2. Permeate flux of water through a hydrophobic membrane as a function of feed temperature and concentration.

H_2S and hydrate control

A new regenerative process allows subsea gas processing for wells with high H_2S concentration.

PhD student:
Eirini Skylogianni

Project manager and main supervisor:
Associate Prof.
Hanna K. Knuutila

SIMPLIFICATION OF CHEMICAL SYSTEMS FOR H_2S AND HYDRATE CONTROL

Stringent requirements related to the content of water, carbon dioxide (CO_2), hydrogen sulfide (H_2S), and heavy hydrocarbons must be satisfied when produced gas is delivered to export pipelines. Today, typical topside absorption processes utilize amines and glycols for the removal of acid gases and water respectively. In addition, glycol is injected into the gas lines for hydrate control, giving in total three different chemical systems.

The objective of this project is to move processing equipment to subsea and simplify the chemical systems by proposing a single chemical for the simultaneous control of hydrogen sulfide and water content in the gas. This could ensure higher energy efficiency and better utilization of resources.

DEVELOPMENT AND EXPERIMENTAL TESTING OF A NEW COMBINED PROCESS

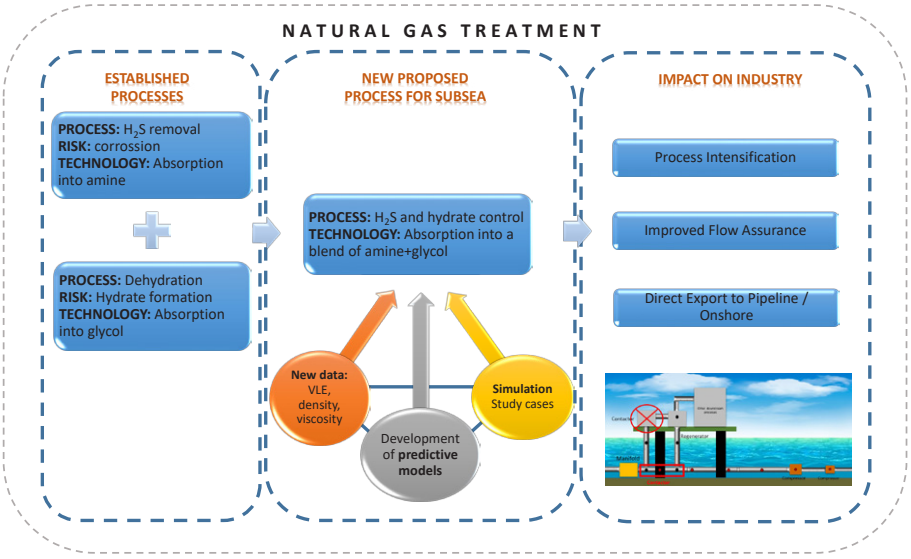
The project has performed the characterization of a solvent suitable for the regenerative process whereby both H_2S is removed and hydrate formation is controlled subsea. Since this will be a regenerative process, significantly higher concentrations of H_2S could be treated than what is normally the case today. A blend of a glycol (monoethylene glycol, MEG) and an amine (methyldiethanolamine, MDEA) was selected as a promising chemical solvent for this process. Knowledge of the thermodynamic behavior of the proposed system is necessary for the successful process design, development and optimization. The available models used by the industry for design and simulation of process plants today cannot predict accurately the behavior of this combined system, due to lack of experimental data.

Experimental testing of the combined system was performed in collaboration with the School of Mines ParisTech in France, and its specialized Centre of Thermodynamics of Processes (CTP). The measurements show that the presence of methane, even at very high pressure, minimally affects the removal capacity of the proposed solvent. Moreover, it was found that the proposed solvent would be able to simultaneously remove H_2S and inhibit hydrate formation. However, the concentration of the components in the solvent should be carefully selected, since the amount of glycol influences the H_2S removal capacity. The development of a predictive model for the thermodynamic behavior of such system, based on the new data, is on-going.

The successful application of the proposed system subsea also depends on the physical properties of this system, especially at the low temperatures of the seabed. Therefore, density and viscosity studies were performed and predictive models were developed. Based on input from the industry, it was concluded that besides the viscous nature of the proposed system, it does not pose difficulties in its application subsea.

FACTS

- Hydrogen sulfide (H_2S) is a toxic gas that can cause severe corrosion problems and premature failure of pipelines and other equipment.
- In the course of production, the H_2S concentration in the natural gas reservoirs often increases, possibly due to water injection for increased recovery purposes.
- A new regenerative process would allow the continuation of safe and trouble-free operations as the reservoir H_2S concentration rises.



Characterization of fluid particle breakup in turbulent flow

Fundamental understanding of particle breakup in oil-water separators can help designing more efficient separators.

PhD student:
Eirik Helno Herø

Researcher:
Nicolas La Forgia

Project manager and main supervisor:
Prof. Hugo Atle Jakobsen

Understanding of phase separation processes, particularly separation of oil and water, is key to subsea processing. The design of oil-water separators is not simple, as it requires accurate models to predict droplet size distribution in oil-water mixture. The particle size distribution is affected by droplet coalescence (merging) and droplet breakage processes, dependent on the flow conditions, which in most cases are turbulent.

The goal for the project is to study experimentally particle breakage processes under turbulent flow conditions.

The project has developed an advanced test rig for studying breakage of single oil droplets immersed in a continuous water phase and exposed to turbulent flow under controlled conditions. The particles are injected in a flow line and are passing a zone of turbulent flow induced by an uneven pipe wall geometry, causing the particles to break. The breakage is recorded by high-speed imaging and analysis software developed by the project, combined with Laser Doppler velocimetry (LDV) for detecting the turbulent flow condition. This is used to extract the relevant breakage information, including breakage probability, mother and daughter size distribution, breakage time, deformation prior to breakage, and turbulent flow condition, among other significant statistical quantities. The information is used to understand breakage mechanisms and to improve predictive models for turbulent flows.

The experimental project is followed by another project, "Mechanistic modelling of droplet breakage".

The results of the two projects might be used for designing internal geometry of separators and other processing equipment. Based on the new knowledge about the relation between turbulence and particle breakage, the improved design might provide better flow conditions, in order to reduce droplet particle breakage, and thereby contribute to more efficient separation.

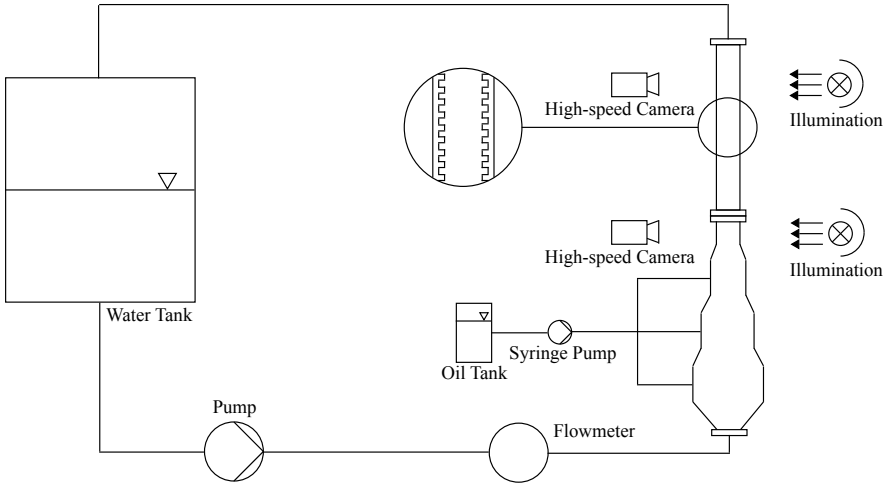


Figure 1. Schematic of test rig for studying particle breakage in turbulent flow conditions

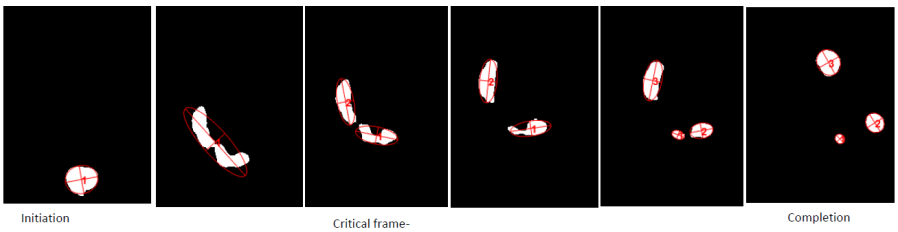


Figure 2. Pictures of an incoming single droplet, which splits to two droplets in the turbulent flow zone, and later into three smaller droplets.

Mechanistic modeling of fluid particle breakage

A complementary methodology for the prediction of fluid particle interface instability and its breakage.

Postdoctoral fellow:
Hanieh Karbas Foroushan

Project manager:
Prof. Hugo Atle Jakobsen

This project started in 2018 and builds on experimental data from the project "Experimental investigation and visual characterization of single particle breakup in turbulent flow conditions"

UNDERSTANDING PARTICLE BREAKAGE MECHANISMS IS ESSENTIAL FOR DESIGNING EFFICIENT SEPARATORS

Multiphase separators are recognized as the primary aid to separate the fluid components of wellbore multiphase flows for further processing. Insufficient separation efficiency can hinder the efficient performance of downstream processing equipment, whereas a proper design of separators can greatly assist to prevent adverse operational events. The design of separators essentially requires careful considerations of underlying physical phenomena, one being accurate quantification of fluid particle breakage and coalescence mechanisms. Separation efficiency is not only affected by separator vessel configuration and operational conditions, but also by the particle break-up and coalescence processes within the internal sectors. Thus, proper characterization of particle breakage is essential for enhancement of separator designs and, consequently, effective control of separation efficiency.

DEVELOPMENT OF AN ENHANCED MODEL FOR PARTICLE BREAKUP, SUPPORTED BY EXPERIMENTAL DATA

The present work focuses on studying the instability of the interface between the fluid particle and continuous phase and aims to improve the existing models by providing a complementary instability model for an oscillator fluid particle in turbulent flow. The model will be coupled with conventional particle breakage models previously developed and its influence on the predictions will be evaluated. Moreover, in conjunction with the project "Characterization of fluid particle breakup in turbulent flow", a statistical analysis of experimental data previously gathered will be performed. The existing particle breakup models will be evaluated and new improved models will be proposed. To further test the proposed models, Computational Fluid Dynamics (CFD) simulations will be performed, using Population Balance Method (PBM) with the new models. Furthermore, the applicability of the proposed models coupled with the instability analysis will be examined.

Compact separation concepts

A new concept for subsea bulk-water separation, securing increased energy efficiency, production optimization, lifetime extension and better tie-in/infrastructure utilization.

PhD student:
Håvard S. Skjefstad

Project Manager and and main supervisor:
Associate Prof.
Milan Stanko

THE NEED FOR SUBSEA SEPARATION OF PRODUCED WATER

The main objective of this project is to design and develop an innovative solution for separating produced water at the seabed, and perform experimental and numerical investigations of separator-concept performance. Development focus is on robustness, efficiency and compactness.

For mature oil fields, produced water is gradually taking over as the main extracted reservoir fluid, causing challenges in production. On the Norwegian Continental Shelf, 181 million standard cubic meters of produced water was reported for 2016. This accounts for more than twice the amount of produced oil. Today, produced water is transported topside where it is separated, cleaned and ultimately re-injected for pressure support or discharged to sea. Over time, the design water-treatment capacity of topside installations will be reached. This causes a bottleneck in production, and would leave a substantial part of the hydrocarbon processing capacity left unused. In addition, the high amount of water in the well stream will cause loss of pressure in transportation, lowering production rates.

By removing produced water at the seabed, more energy efficient processing systems can be developed, and spare topside capacity can be better utilized by new tie-ins to existing facilities. In addition, production rates can be increased, and the need for new subsea transport lines reduced.

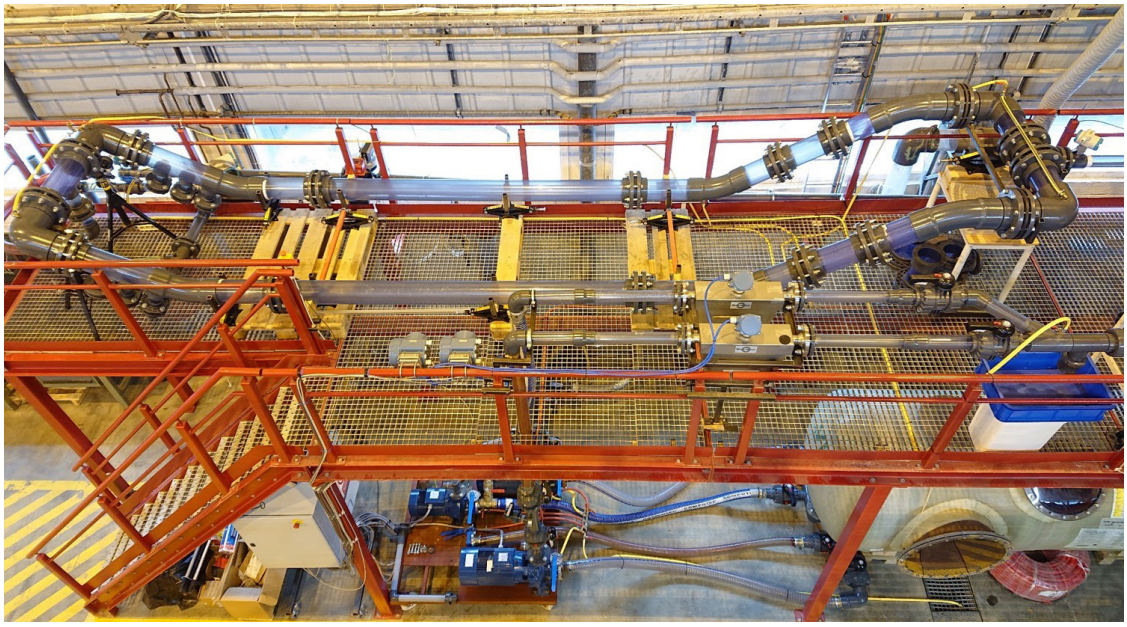
A NEW CONCEPT FOR COMPACT SUBSEA SEPARATION

In this project, a new multi-pipe based subsea oil-water separator has been designed, manufactured and tested. The design has been given the name Multiple Parallel Pipe Separator, or MPPS for short. The compact design allows for faster separation, reduced weight, size and costs compared to a traditional vessel type separator. Having several pipes in parallel allows separation at low fluid velocities, easy system scalability, and a large operational envelope compared to a single-pipe solution. The design aims to target identified shortcomings in existing technologies, and lower the cost of subsea produced water separation, making the business case more attractive.

PROJECT RESULTS

Project deliverables are an experimentally and numerically evaluated separator concept, which will be available to partners for further development and future subsea application. The concept has been presented in two publications, most recently in the Journal of Petroleum Science and Engineering, where detailed performance data is included. The experimental data and observations gathered during this project can be used to improve other oil-water separator designs, and to validate numerical models for oil-water separation.

As part of this project, a two-phase oil-water test rig has been designed and constructed. The facilities are used to experimentally validate the designed compact separator concept. Experiments are carried out on a two pipe 150 mm ID prototype.



The Multiple Parallel Pipe Separator prototype, installed in an oil-water separation test rig.

PROFESSOR
SIGURD SKOGESTAD

RESEARCH AREA
MANAGER

RESEARCH AREA

System control

Automatic control systems and digital twins contribute to digitalization, enabling smart, safe and optimal operation of subsea production and processing systems.

Subsea production and processing installations are not easily accessible and should be autonomous. This means that the equipment should regulate itself, hence reducing the need for human interaction and monitoring. To reach the goal of autonomous operation, mathematical models are needed,

- to develop digital twins to test alternative system designs and operation strategies
- to design model-based controllers for operation
- to estimate and predict uncertain states and parameters
- for production optimization to increase recovery from the reservoir

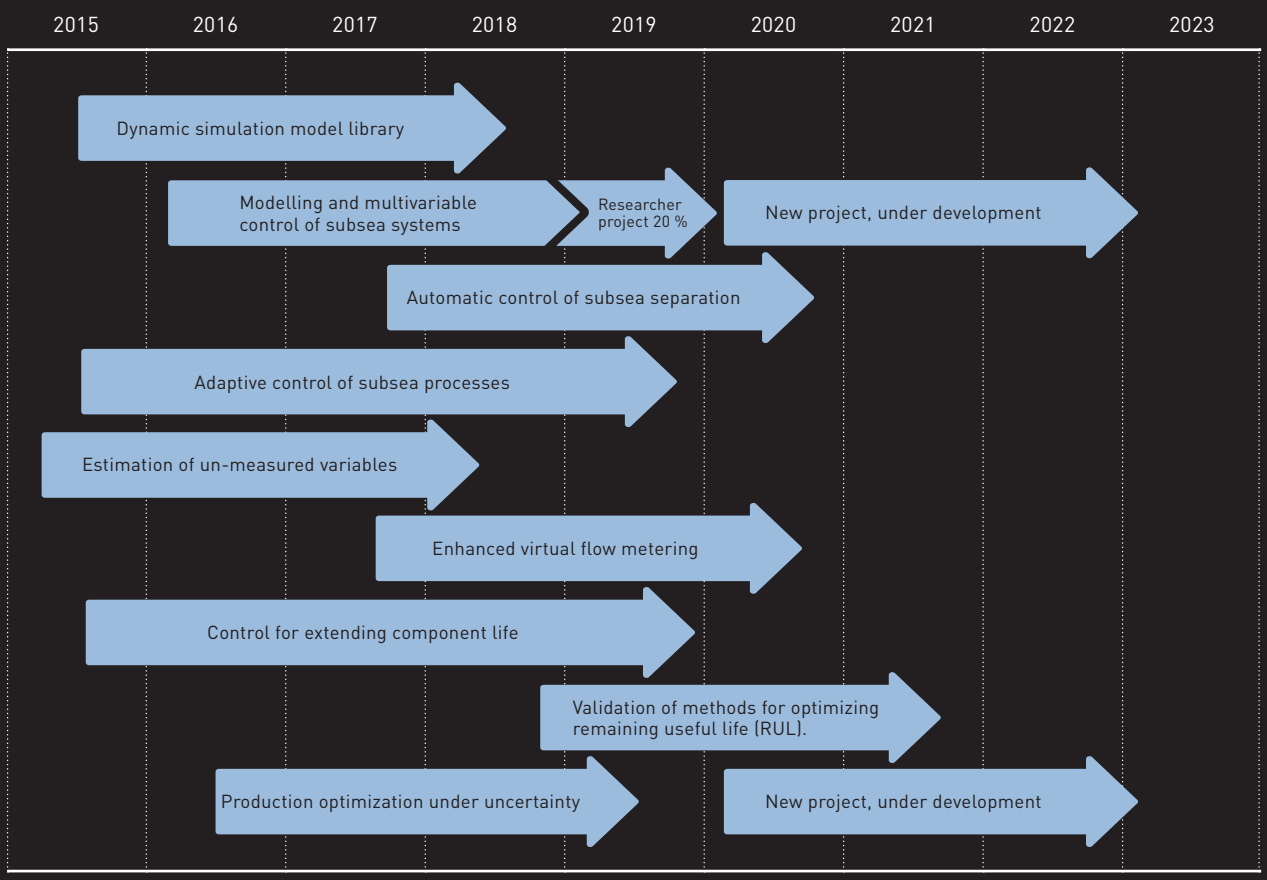
The models are based on first-principles physics as well as empirical observations. Controller, estimator and optimization algorithms are developed using state-of-the-art methods as well as further enhancements.

The focus is on subsea separation processes. In addition, multiphase pumping and wet- and dry-gas compression is included. The overall aim is to develop tools and methods that are simple and robust enough for use in real subsea applications.

During 2018, two projects were completed; "Dynamic simulation library" and "Estimation of un-measured variables" and one new project started up; "Validation of methods for optimizing remaining useful life (RUL)" .

The figure to the right shows an overview of completed, ongoing and future projects.

Completed, current and planned projects



System control team, work session. Front row from the left: PhD student Dinesh Krishnamoorthy, PhD student Adriaen Verheyleweghen and Post-doctoral fellow José O. A. Matias. Back row, from the left: PhD student Torstein Kristoffersen, Associate professor Christian Holden, PhD student Mishiga Vallabhan, Professor Sigurd Skogestad and PhD student Sveinung Ohrem. (Associate professor Johannes Jäschke, Postdoctoral fellow Christoph J. Backi, PhD student Timur Bikmukhametov and PhD student Tamal Das are not present in the picture).

Dynamic simulation model library

Development of simple mathematical models for simulation purposes as well as design of controllers and observers / estimators for the use in oil and gas production and processing

Postdoctoral fellow:
Christoph J. Backi

Project manager:
Prof. Sigurd Skogestad

THE NEED FOR SIMPLE MODELS FOR OPTIMIZATION AND CONTROL

Good, yet simple mathematical models of processes are required for improved operation utilizing automatic control, estimation and data integration. The objective for the project is to develop a model library for subsea processes which is suited for optimization and control. The models will be more detailed than those presently used by industry for optimization and control, but less detailed than design models, which often involve computational flow dynamics (CFD) calculations.

DEVELOPMENT OF THE MODEL LIBRARY

The following models have been developed:

- A simple gravity separator model, which can predict separation efficiency and be used for controller and observer design.
  The model has been extended to predict the build-up of emulsion layers between the oil- and water-continuous layers and ultimately to control these layers' thicknesses by adding demulsifiers to the inlet stream.
  The model was used to design virtual metering approaches, to estimate inflows to the separator as soft-sensors.
  The gravity separator model was subject to a predictive controller design, which can protect downstream equipment (e.g. hydro cyclones) from severe slugging events – a so called "Virtual harp".

- A novel method for parameter identification and state estimation in systems, where observability is limited

- An extension to a Greitzer surge model for compression systems based on actuation by a close-coupled valve (CCV) as well as the drive torque. This model was subject to the design of control- and estimation-structures, such as a nonlinear, robust feedback linearizing controller and a model predictive controller in combination with a moving horizon estimator.

The model library is written in Matlab, and it can be (and partly has been) ported to other software platforms, like Modelica.

INDUSTRY COOPERATION

The most useful cooperation for the project came out of input from and discussions with Equinor, who provided data for the validation of the gravity separator model and furthermore expert knowledge and the company's viewpoint on the model itself and its extension for emulsion layer modeling and control.

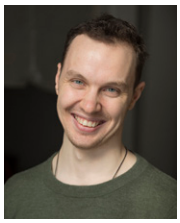
The gravity separator model in combination with virtual metering ("soft sensor") and predictive control for slug avoidance ("virtual harp") can be useful in the oil and gas industry. These software solutions can potentially replace hardware and be implemented in brown as well as green fields, leading to a reduction in CAPEX investments.

The project was completed in 2018.

Christoph J. Backi is now working as Automation Engineer for Advanced Process Control in in the chemical company BASF, Ludwigshafen, Germany.

Modelling and multivariable control of subsea systems

Digital twins based on mathematical models are important for cost-efficient operation



PhD student:
Torstein Thode Kristoffersen

Project manager and main supervisor:
Associate Prof. Christian Holden

The oil and gas industry has visualized a complete subsea factory for production of oil and gas in remote areas and deep waters. Cost-efficient operation is essential for the realization of the subsea factory. A digital twin of the subsea factory is a digital replica that emulates the physical behavior of the subsea processing system, based on measurements and mathematical models. The digital twin allows for development of software tools for cost-efficient operation through:

- safe and optimal operation, enabling reduced down-time and increased product quality and throughput
- estimation of unmeasured variables, enabling reduced need for instrumentation and additional insight
- simulation of various scenarios enabling testing of process changes and operator training.

The focus of this project is the development of mathematical models of separation and boosting processes, based on first-principles.

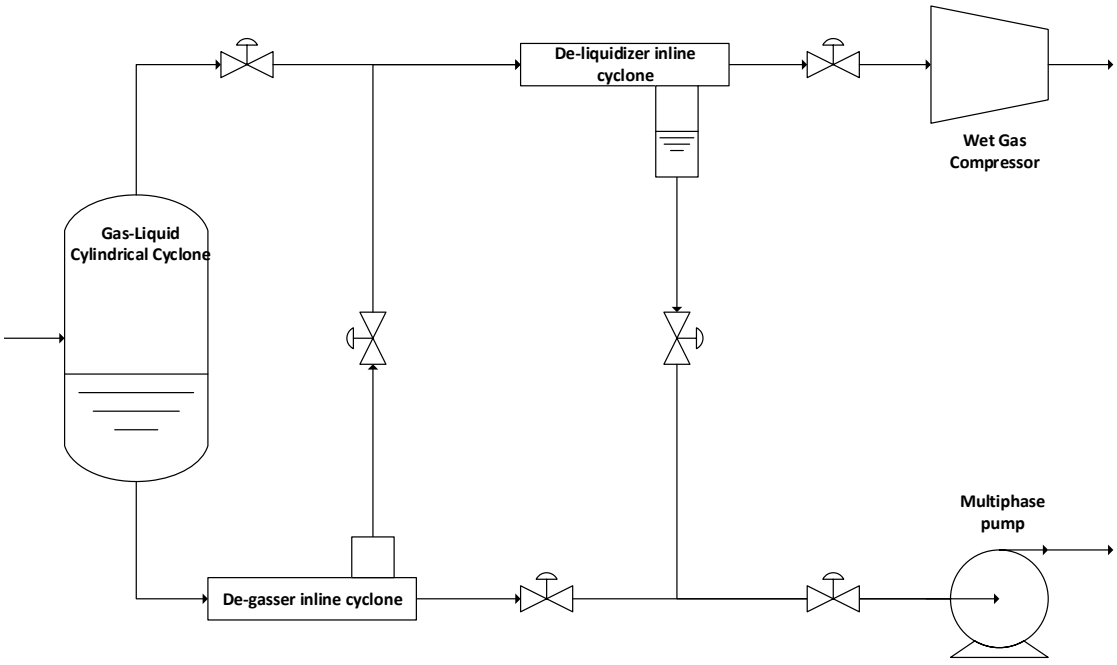
The project has resulted in the development of mathematical models of:

- Gas-Liquid Cylindrical Cyclone (GLCC) separator
- Wet gas centrifugal compressor.

The potential of software for estimation of unmeasured variables, and for safe, efficient and optimal process control has been demonstrated based on these models.

However, all mathematical models have model errors due to incorrect and un-modelled dynamics which can make control and optimization of the process difficult. Therefore, we are currently developing a machine learning Model Predictive Control (MPC) algorithm for adapting to the local model and measurement uncertainties enabling robust, optimal control in the presence of uncertainties.

Planned future work includes modification of the wet gas compression model for development of a mathematical model of a Multiphase Pump (MP) system.



The generic separation and boosting process described by the mathematical models which have been developed in the project.

Automatic control of subsea separation

Digital solution to ensure efficient operation and reduce environmental foot print.

PhD student:
Mishiga Vallabhan

Project manager and main supervisor:
Associate Prof.
Christian Holden

Co-Supervisors:
Prof. Sigurd Skogestad and Prof. Olav Egeland

Subsea production and processing units need to be compact in order to reduce wall thickness and weight. While huge gravity or 3 phase separators are used for first stage separation topside, it is not feasible to bring such huge equipment to water 3000 meters deep. Compact separation is thus inevitable in a deep water subsea environment. A possible subsea solution could be to use compact first stage separators like pipe separators, and then use a series of hydro cyclones. When the equipment becomes compact, there arises a need for advanced control technologies to optimize the operation.

The goal for this project is to:

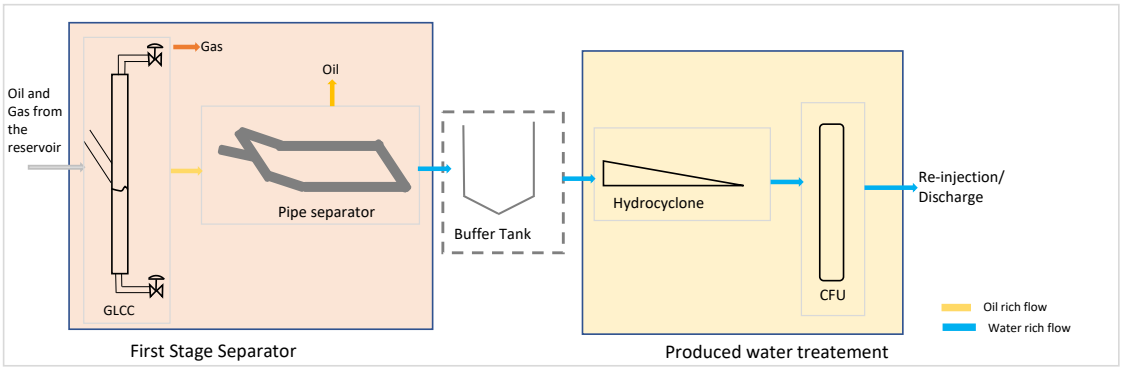
1. Develop mathematical models and virtual metering estimators for compact separation systems (hydro cyclones, compact flotation units, gas liquid cylindrical cyclones).
2. Improve and automate the control of compact separators by using advanced modeling techniques.

The development is based on results from the SUBPRO projects "Modelling and multivariable control of subsea systems " and "Adaptive control of subsea processes". Present focus is on produced water treatment, where the water from first stage separators such as a gravity separator or a pipe separator is further processed by hydro cyclones or compact flotation units. Purified water from this stage can be used for water re-injection or on a longer term be discharged to sea, if oil contents can be reduced to the required level. Discharge of produced water to the sea is regulated internationally by the OSPAR commission, which has specified the limit as 30 mg of dispersed oil per liter of produced water. Hence it is important to maintain the efficiency of water treatment equipment in all operating environment.

The efficiency of the water treatment process can be improved by designing model-based controllers. In this project, we are deriving mathematical models for hydrocyclones. Later, the models will be used to develop advanced control algorithms which can handle the unforeseen process disturbances in the field and automatically stabilize the system with minimal human intervention.

A steady-state model for the hydrocyclone based on droplet trajectories is under progress. The separation efficiency is calculated by tracking the oil droplets of different sizes ranging from 5 to 100 microns. This model can estimate the pressure drop ratio (PDR) for a given inflow rate and underflow and overflow valve opening.

The compact separation laboratory has entered the final phase of construction. With the help of SINTEF, we have designed a pump system with a control valve to emulate a first stage gravity separator. This system is expected to deliver the same oil droplet size and oil content in water as a real gravity separator. Discussions with the industry partners helped us to select the right control valve for the system, and GLCC design was by Equinor.



A flow diagram of a plausible compact separation system.

Adaptive control of subsea processes

Adaptive control solutions increases autonomy and paves the way to the digitalized future.

PhD student:
Sveinung Ohrem

Project manager and main supervisor:
Associate Prof.
Christian Holden

HOW TO CONTROL A DYNAMIC SUBSEA PROCESS?

With improved control, oil and gas companies can increase the recovery of hydrocarbons, increase the lifetime of fields and equipment, and take the step into the digitalized future.

In the production and processing of oil and gas, operational conditions are often changing. The pressure in the wells decreases, the temperatures fluctuate, unforeseen situations occur, and equipment degrades and fails. All of this affects the quality and quantity of the products and the environmental impact of the production. It is not trivial to describe these dynamic, complex and non-linear phenomena occurring inside the subsea equipment with simple mathematic equations. The central question in this project is; how can we best control a process like this?

USE OF ADAPTIVE CONTROL ALGORITHMS

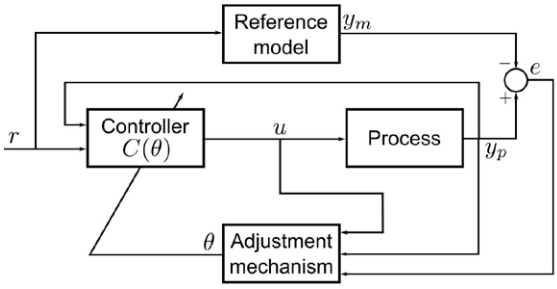
The goal of this project is to find an answer to this question. We believe the answer lies in the use of adaptive control algorithms. These algorithms are capable of self-tuning, i.e., they change their internal parameters automatically based on changes in the process they are controlling. They require little to no intervention from operators, which leads to a more autonomous operation of the processes. Last, but not least, it can be proven mathematically that the controllers will work even when the process parameters change.

So far, we have developed an adaptive control algorithm for a gas liquid cylindrical cyclone and we have implemented an adaptive control solution for anti-slug control of a pipeline-riser system. We have also developed a new adaptive controller and observer scheme where the controller enforces a certain dynamic response on the system and these known dynamics are used in the observer. The results show that a detailed model of the system is unnecessary when designing an observer and hence, we can simplify the design.

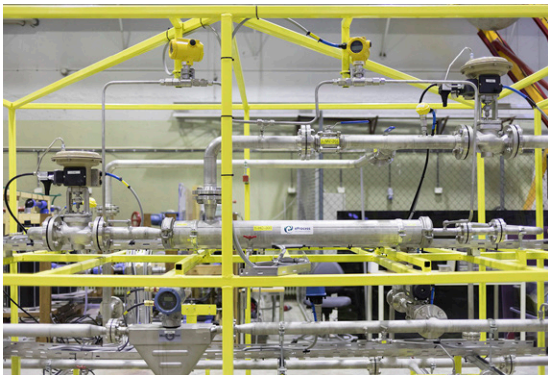
A collaborating study with the project "New safety and control philosophy for subsea systems" found that adaptive control can decrease the amounts of hazards caused by human operators. Currently, we are collaborating with the project "Compact subsea separation" on developing controllers for the new separator concept. We are investigating different control structures and use both adaptive and conventional control algorithms.

ADAPTIVE CONTROLLERS CAN IMPROVE AUTONOMY AND PROCESS PERFORMANCE

The project has shown that adaptive controllers can replace or cooperate with traditional controllers in a process/production facility and help increase the level of autonomy and improve the overall stability and performance of a process.



The basic structure of an adaptive control system.



Subsea Process Control Laboratory for testing new control algorithms and simulation models.

Estimation of un-measured variables

Model based estimation of process variables can substitute missing physical measurements subsea.

PhD Student:
Tamal Das

Main Supervisor:
Associate Prof.
Johannes Jäschke

Co-supervisor:
Prof. Sigurd Skogestad

THE NEED FOR ESTIMATION OF UNMEASURED VARIABLES

A challenge for subsea control systems is accurate and reliable process measurements. Sensors and automation systems that are qualified for topside use are not necessarily qualified for subsea use and are prone to malfunctioning in subsea conditions. To alleviate this problem, this project has found ways to estimate variables that are difficult or impossible to measure subsea. Additionally, the project developed simple methods to keep a low computational delay for real time decisions.

DEVELOPMENT OF MODELS FOR ESTIMATION AND CONTROL

The project has developed the following methods for estimation and control:

- Models for estimation of oil and water concentration for four different separator types;
  - Three layer based gravity separator
  - Coalescence based gravity separator
  - Inline de-oiling hydrocyclone
  - Compact flotation unit
- Study of control for optimal operation of
  - Inline de-oiling hydrocyclone
  - Compact flotation unit
  - Subsea separation system consisting of coalescence based gravity separator, inline de-oiling hydrocyclone and compact flotation unit
- Estimation results
  - Inflow estimation in gravity separator using three layer gravity separator model
  - Reducing online computational delay using pathfollowing method applied to moving horizon estimation problem

Equinor provided data for gravity separator validation

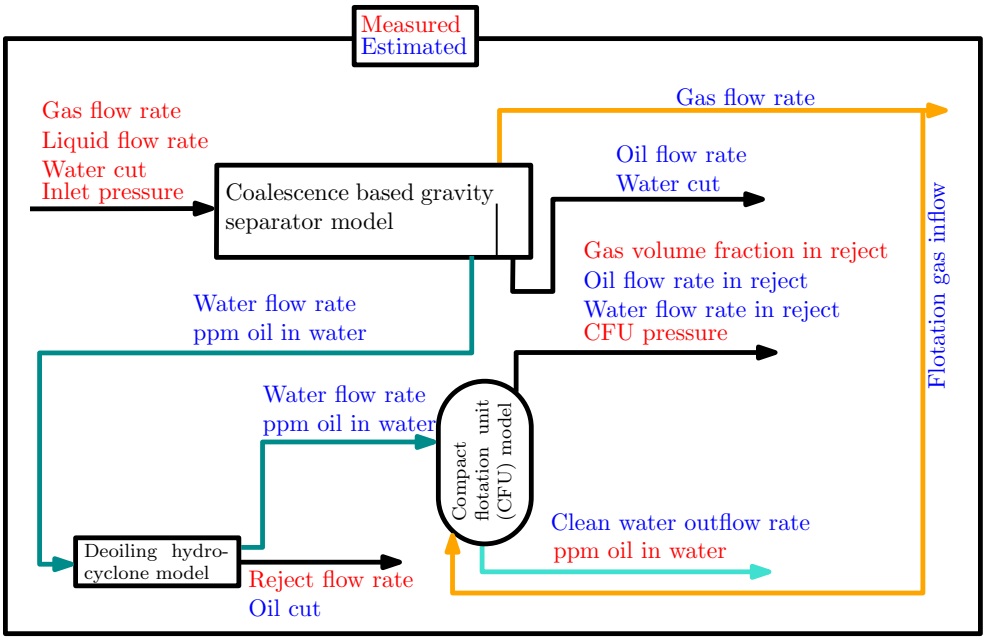
The project has given a new insight: Analysis of an integrated processing system is much more valuable than of a single unit, because single units are never operated standalone. Any analysis that does not include the interaction between different units in a system is largely inadequate.

INNOVATION

The models developed in the project can be easily integrated in the existing infrastructure of models used by the industry for simulation studies, operator training and process control. The models are implemented in MATLAB/Simulink, and some of the models have been converted to the Modelica platform, to enable easy use by Equinor and other industry partners.

Possible further work includes model validation and testing against real data and use of methods for production optimization.

The project was completed in 2018 and was followed up by a new project from 2017, "Enhanced virtual flow metering". Tamal Das is now working as a project engineer at ABB AS, Oslo, Norway.



Results from optimal operation of the separation system studied in this project. All models in this system were developed in the project.

Enhanced virtual flow metering

PhD student:
Timur Bikmukhametov

Project manager and main supervisor:
Associate Prof.
Johannes Jäschke

THE NEED FOR VIRTUAL FLOW METERING

In subsea field development, multiphase flowrate measurements play an important role in production optimization, rate allocation and reservoir management. Apart from the technical side, it is important for fiscal reasons to know the flowrates from satellite fields feeding into a field center with a different ownership. This is a common case when smaller fields are tied-in to an existing infrastructure. Usually, flowrates are measured by hardware multiphase flow meters, which are expensive, have a limited operational envelope and are exposed to erosion and failures.

Virtual Flow Metering (VFM) is a method for estimating oil, gas and water flowrates produced from wells without measuring them directly. The method uses the data from the field such as pressure and temperature measurements as well as choke position to estimate the flowrates.

PROJECT RESULTS

This project is dedicated to improving the understanding of this technology and development of new methods for accurate and robust multiphase flowrate estimation. The project has a close collaboration with Equinor through developing and testing the models on real field data.

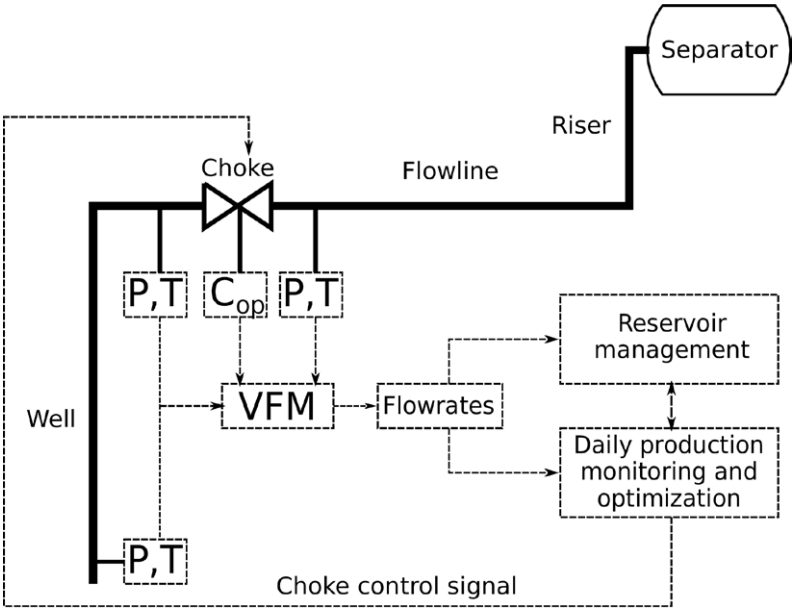
So far, the following has been done:

- A first principles Virtual Flow Metering software based on OLGA and MATLAB has been developed
- Influence of sensor degradation on flowrate estimates based on statistical methods has been studied
- A study of applying machine learning algorithms for Virtual Flow Metering has been performed

The ongoing work and future plans include:

- Reveal the potential of machine learning in Virtual Flow Metering including:
  - development of models with high accuracy and optimal structure
  - evaluation of flowrate estimation uncertainty
  - combining machine learning with first principles models, data validation and reconciliation methods
- Use machine learning approaches in Virtual Flow Metering for production optimization under uncertainty

The results from this project can be used in subsea production including planning and optimization, rate allocation and reservoir management.



Virtual Flow Meter (VFM) estimates multiphase flow rates based on available measurements and models. The estimates can be further used in production optimization and reservoir management to control and optimize the well production.

Control for extending component life

A new method for safe and economical operation.

PhD student:
Adriaen Verheyleweghen

Project manager and main supervisor:
Associate Prof.
Johannes Jäschke

In subsea oil and gas production, unexpected stops result in the loss of valuable production time. Additionally, the cost of intervention in the case of a module breakdown is very high due to the need for specialized intervention vessels and remotely operated vehicles. It is for these reasons that the equipment is designed and operated in such a fashion that the chance of failure becomes marginally small. However, this approach can lead to very conservative operation.

Our idea is to combine health monitoring and control of available degrees of freedom to find the optimal operation strategy. The goal is to ensure that the remaining useful life of the equipment is longer than the time to the next planned maintenance stop, while maximizing production. In other words, we want to make sure that the system does not become unavailable due to avoidable adverse operating conditions. We are using model predictive control to find the optimal input trajectory, given a mathematical description of the system behavior.

So far, the following has been developed:

- A MATLAB model for compressor degradation and the optimal control of a compression station
- A MATLAB model for choke erosion and the optimal operation of a gas network
- Methods for systematic handling of model uncertainty
- A method for optimal scheduling of production and maintenance
- A controller algorithm for control of a Greitzer compressor model, subject to surge/oscillation-induced degradation
- An extension to a Greitzer model based on actuation by a close-coupled valve (CCV) as well as the drive torque applied to the compressor shaft (in collaboration with the projects "Dynamic simulation model library" and "Production optimization under uncertainty").

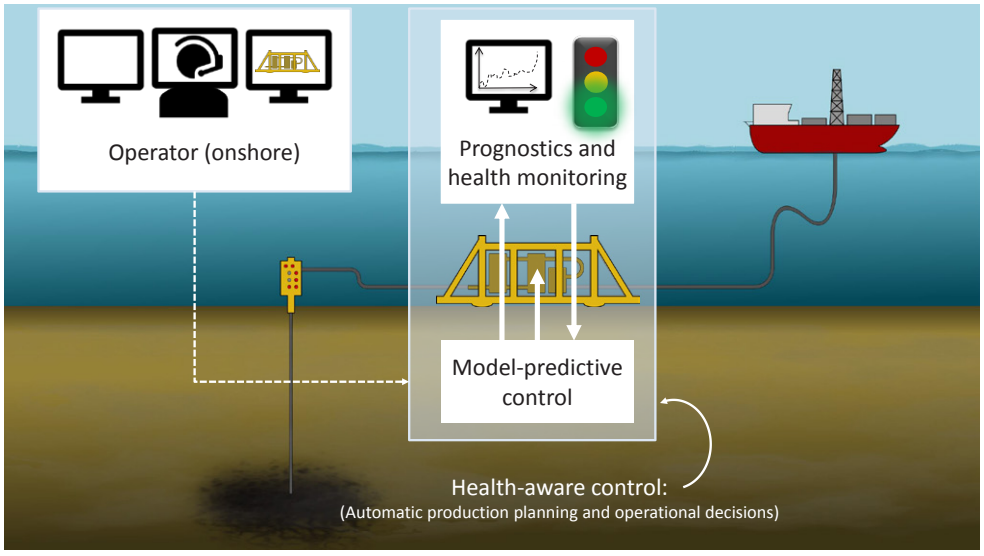
In order to verify the developed methods and make industrial adoption easier, we are designing and building a test rig for accelerated wear with sand erosion. The rig is designed in cooperation with the projects "Automatic control of subsea separation" and "Validation of methods for optimizing remaining useful life (RUL)". It will be in operation from summer 2019.

INDUSTRIAL APPLICATION OF RESULTS

The ideas developed in this project are applicable to all systems where reliability objectives are in conflict with control/production objectives or inspection/testing objectives. Some potential O&G-related use cases are:

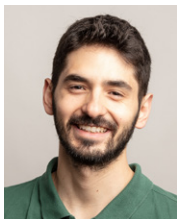
- Compressors and pumps
- System-wide production and maintenance optimization
- Scheduling of overhauls
- Test frequency for safety critical valves (see the project "Reliability and availability assessment in subsea design")

Equinor and DNV GL have contributed to the project by providing technical knowledge, industrial data for model testing, and discussions regarding relevance to industrial needs.



In health-aware control, prognostics and health monitoring is included in a model predictive control framework. This results in a controller that can automatically make operational decisions that optimize the trade-off between equipment degradation and hydrocarbon production.

Validation of methods for optimizing remaining useful life (RUL)



Postdoctoral fellow:
José Otavio Assumpcao Matias

Project manager:
Associate Prof.
Johannes Jäschke

THE POTENTIAL OF COMBINING OPTIMIZATION OF OPERATION AND MAINTENANCE

Unplanned maintenance interventions of subsea oil and gas production systems are very expensive. Unanticipated breakdowns can lead to long halts and large losses in the production. Equipment degradation is intensified by for example sand production. Key failure modes are related to erosion, sand accumulation, plugging and contamination by sand. Specifically, particle erosion can severely limit the remaining useful life of exposed equipment. Usually, the sand managing strategy is outlined early in the field development to ensure appropriate sizing and selection of equipment as well as instrumentation for monitoring, controlling and handling of sand production. Even with all these precautions, a very conservative operational strategy is often adopted. Typically, an acceptable sand rate is defined based on worst-case erosion scenarios, leading to sub-optimal operation and potential profit loss.

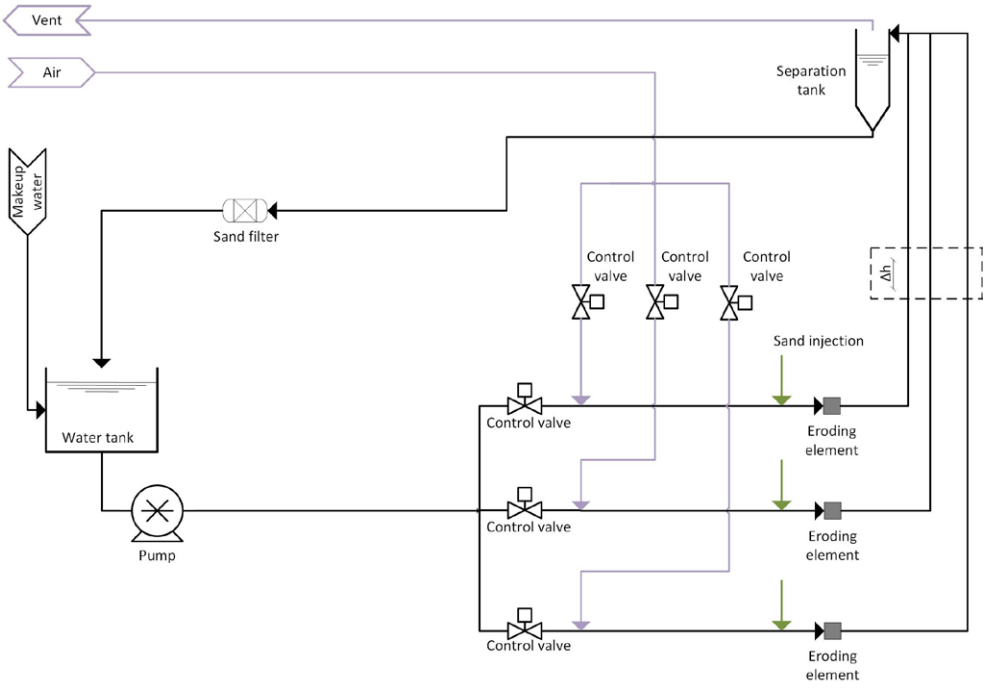
This conservativeness can be reduced by integrating equipment condition monitoring and prognostics into the control strategy. By applying a robust model predictive control approach that incorporates erosion models, we are able to steer plant degradation actively and prevent violation of health-critical constraints. This allows us to proactively control the system degradation, rather than simply reacting to it.

EXPERIMENTAL TESTING OF MODEL FOR EXTENDING REMAINING USEFUL LIFE

This project aims at developing methods for optimizing production from an oil field, while simultaneously avoiding unplanned production stops due to equipment degradation. In its first stage, which is currently undergoing, the objective is to design and set up a small lab rig for production optimization and accelerated life testing of critical components in oil production systems. The idea is to verify the methods proposed by the ongoing SUPRO project "Control for extending component life", which were only tested in simulations since erosion data is rarely presented in the open literature. The second stage will be to develop these methods further, and also to study how machine-learning techniques can be used to develop data-driven diagnostic and prognostic models for the lab system.

USE OF RESULTS

By integrating condition monitoring and prognostics into the control strategy, the developed method has the potential to maximize the economic profit, while ensuring that the subsea facilities remain operational until the next planned maintenance, with no unplanned shutdowns due to premature equipment failures occurring. Furthermore, this project is especially appealing, because it could be used for validating models and optimization/control strategies developed in other SUBPRO projects.



Preliminary design of the lab rig for accelerated wear testing with sand erosion. A mixture of water, mud/sand slurry and air is used for degrading the eroding elements in three "wells" in parallel. By continuous monitoring of the degradation of these elements, the flow loop can be used for testing and validating the proposed control strategies for extending component life.

Production optimization under uncertainty

Digital solutions to assist daily production optimization under uncertain conditions.

PhD student:
Dinesh Krishnamoorthy

Project manager and main supervisor:
Prof. Sigurd Skogestad

THE ROLE OF UNCERTAINTY IN PRODUCTION OPTIMIZATION

Daily production optimization is an important aspect throughout the production phase of any field, where the objective is to maximize the operational profits on a day-to-day basis. Currently, commercially available tools are commonly used for production optimization. These tools are based on steady-state models that are updated at irregular intervals. Due to lack of knowledge, model simplification and sparsity of well test data, the production optimization problem is subject to a wide range of uncertainties, which affects the decision making process.

SIMPLE TOOLS MAY SOLVE THE PROBLEM, WITHOUT USE OF ADVANCED MODELS

In this project, we develop different software tools and methods in order to optimize production from a field under uncertain conditions. One way to handle uncertainty is to use the production data to characterize and adapt to the uncertainty. This project focuses on developing tools where real-time production data can be efficiently utilized in the real-time decision making process. One of the main challenges with data utilization is that the production data contains transient measurements for significant periods, which typically are discarded today. We have developed different algorithms that can use such transient measurements efficiently and thereby increase the potential of real time production data.

We have also developed a framework for optimal operation using simple feedback control loops that do not require complex models or additional software tools to be implemented, where we show that we can achieve optimal operation using simple PI controllers implemented in existing process control systems (PCS), which are easy to tune and maintain by production engineers and operators.

In some cases, sufficient measurements may not be available for handling uncertainty. In such cases, robust optimization tools can be used to seek robustness against the uncertainty. In particular, this project focuses on scenario optimization approaches, where the evolution of uncertainty in the future is explicitly taken into account in the optimization problem. This method was shown to be less conservative than other robust approaches whilst ensuring robust constraint satisfaction.

RESULTS SO FAR

- Daily production optimization strategy using simple feedback control loops implemented in existing process control system (PCS)
- An optimization workflow that uses transient measurements to incorporate real-time data into real-time decision making.
- A model-free data-driven optimization approach for network optimization that effectively uses transient measurements.
- A scenario optimization tool to optimize production over several possible scenarios to account for the uncertainty.

The results from this project can be used for automated production optimization to increase daily operating income and reduce operator workload in the production optimization process, resulting in safe and optimized production. Implementation of the results does not require any changes in the configuration of production and processing systems.

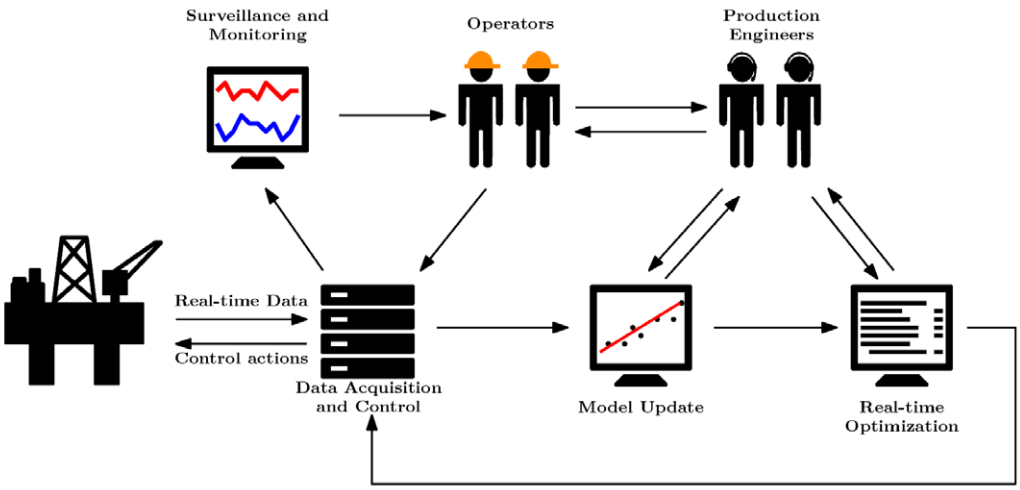


Illustration of the automated production optimization workflow for an oil and gas production network.

A model builder's work place; PhD student Adriaen Verheyleweghen developing models for extended remaining useful life of equipment.

PhD education

Being a PhD student in a Centre for research-based innovation is a very different experience from working in a traditional stand-alone PhD project.

In SUBPRO it is a goal that the students shall not only become specialists in their own field, but also learn about implementation of their project results in the industry, project planning, working in teams, sharing of knowledge across disciplines and participate in international networks. This will prepare the students for jobs both in the industry and academia.

INDUSTRIAL EXPOSURE
The SUBPRO PhD students are exposed to an industrial context from day one. The students present their work and project results for industrial reference groups twice a year, where they participate in discussions about industrial relevance and possible applications of their scientific achievements.

Some of the students have case projects based on field data from the industry partners.

Once a year they go for an excursion to one of the industry partner's industrial sites.

The PhD students present their work at industrial conferences like Subsea Valley Conference and Underwater Technology Conference.

CROSS DISCIPLINE WORK
SUBPRO is a cross disciplinary project, involving three departments and two faculties at NTNU. The industry urges the researchers to stick their heads together and create synergies between the projects. Gradually, this has become the working culture of SUBPRO. The PhD students arrange colloquia at regular intervals, and many of the projects collaborate on common development tasks.

INTERNATIONAL COLLABORATION
The PhD students have the opportunity to visit or work for periods at other universities and research institutions around the world. SUBPRO/NTNU is collaborating with Brazilian universities through the INTPART project Brazilan- Norwegian Subsea Operations Consortium

SOCIAL EXPERIENCE
Through social events and excursions, the PhD students and NTNU staff get to know each other also outside work.

PhD student Yun Zhang presenting her project for industry partners at a reference group meeting.

In 2019 SUBPRO has the responsibility for arranging the subsea session of the Subsea Valley Conference, including 3 presentations from SUBPRO. The picture shows the SUBPRO presentation group on Subsea Valley Conference in 2017.

SUBPRO PhD colloquia are arranged at regular intervals.

From a seminar in Trondheim, Norway, for the INTPART project Brazilan- Norwegian Subsea Operations Consortium.

Master students at SUBPRO

Every year approximately 20 students do their master thesis in association with SUBPRO research centre.

NTNU is the major supplier of Master candidates to the oil and gas industry in Norway. During the period of low oil prices, the number of students taking their master thesis within oil and gas was drastically reduced. SUBPRO has motivated the master students to keep on studying petroleum related subjects, pointing at future field developments, technological challenges and the prospected job market. In 2017, 17 master students had a thesis connected to SUBPRO. Some of these were also hired by SUBPRO for summer internships.

The master students in 4th grade meet the SUBPRO industry partners at an annual spring term meeting at NTNU, where the industry partners present subsea technology projects. Some of the students choose to do their master projects in cooperation with the SUBPRO industry partners.

SUBPRO and the industry partners invite graduate students at NTNU to an annual meeting for informing about job and master project opportunities within subsea technology.

Experts in Teamwork

Training for work in multidisciplinary teams

Associate Professor at NTNU Department of Chemical Engineering, Brian Arthur Grimes has conducted the SUBPRO village the last 4 years.

The unique feature of Experts in Teamwork is that the students not only work on their technical project, but also evaluate the way they work together as a team. Experts in Teamwork is compulsory for all master students at second-degree level at NTNU.

SUBPRO is providing industry relevant topics and involvement from industry partners and faculty at NTNU to one of the EiT Villages every year.

What was the topic of the EiT village this year?

- The village title is "Challenges in Subsea Production and Processing". This year we have a focus on Digitalization and Green Solutions in the Petroleum Industry. We have the following projects:

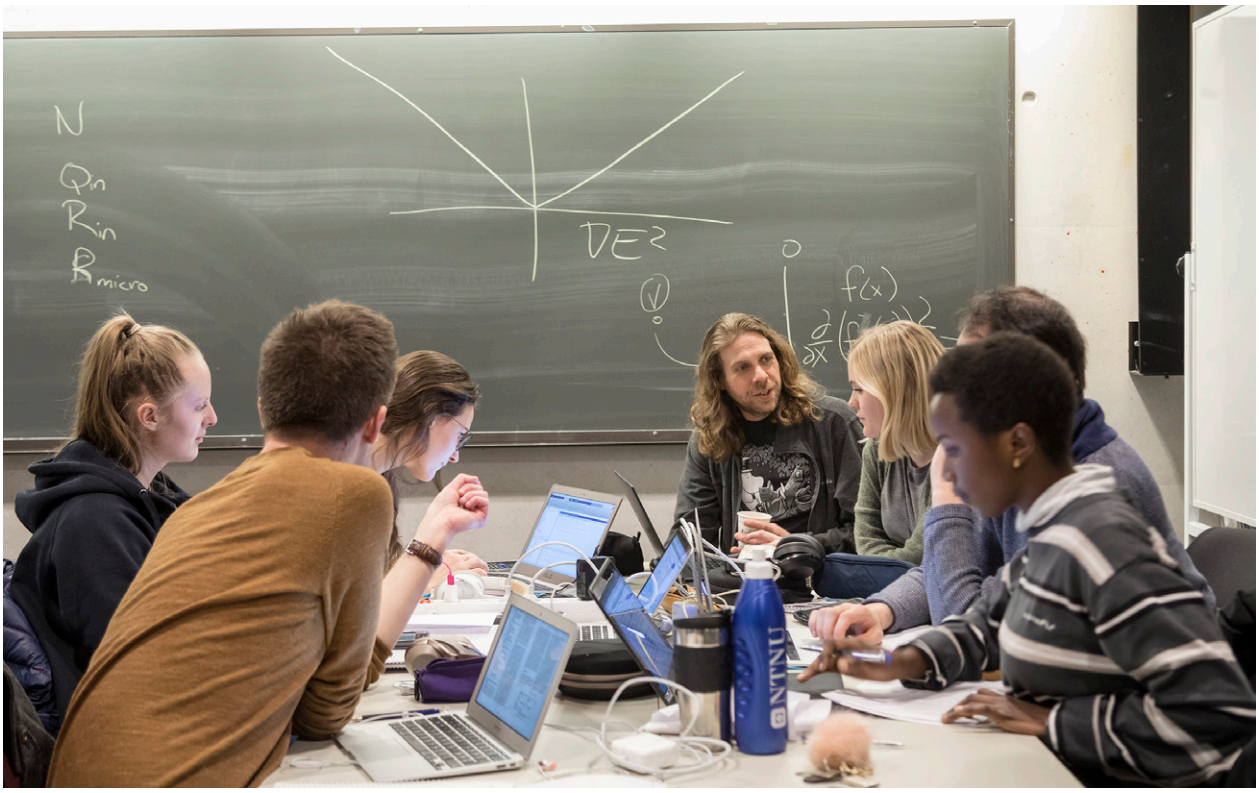
- Digitalization in the petroleum industry
- Green RAMS (Reliability, Availability, Maintenance and Safety)
- Technical, economic, and CO_2 emission aspects of produced water treatment
- New concepts in liquid-liquid separation

How do the Industry sponsors from SUBPRO contribute?

- Equinor has contributed every year with a project mentored by researchers from their RDI Centre. In the past, ABB has mentored 3 projects for the students and hosted presentations on the mid-term day. Additionally, the RAMS group at NTNU/ SUBPRO have contributed all three years to the village with a RAMS focused project.

What kind of background do the students have?

- The students are mainly from the Departments of Petroleum Engineering, Chemical Engineering, Mechanical and Industrial Engineering and Marine Technology; Every once in a while we'll get one or two students from the Departments of Physics, Chemistry, Material Science, or Energy and Process Engineering. These are all in the engineering faculties. However, this



Group session In Experts in Teamwork. Group facilitator, Associate Professor Brian Arthur Grimes in the background.
Students from left around the table: Anders Runningen, Siri Wetjen, Carita G. Ranvik, Kristine Maria Nettum, Martin Sanden and Rehema Kivuyo.

year we got our first student from the Department of Industrial Economics and Technology Management.

How is the work organized?
- The students are organized in "villages" with about 25-30 students working on a common broad topic, and groups of about 7 students focusing on specific problems.

How do they work?
- The students work on their projects in groups during the class hours. The class runs all day, every Wednesday during the semester. I chat with all the groups each week about their progress and my assistants facilitate their team work with team exercises and spontaneous discussions about their team behavior.

What will they learn (hopefully)?
- Foremost, they will learn about themselves and how they work in teams. Hopefully, through that experience they can improve their team skills through the process. Additionally, they will learn the basics of subsea production and processing and get a detailed introduction to their specific project topic.

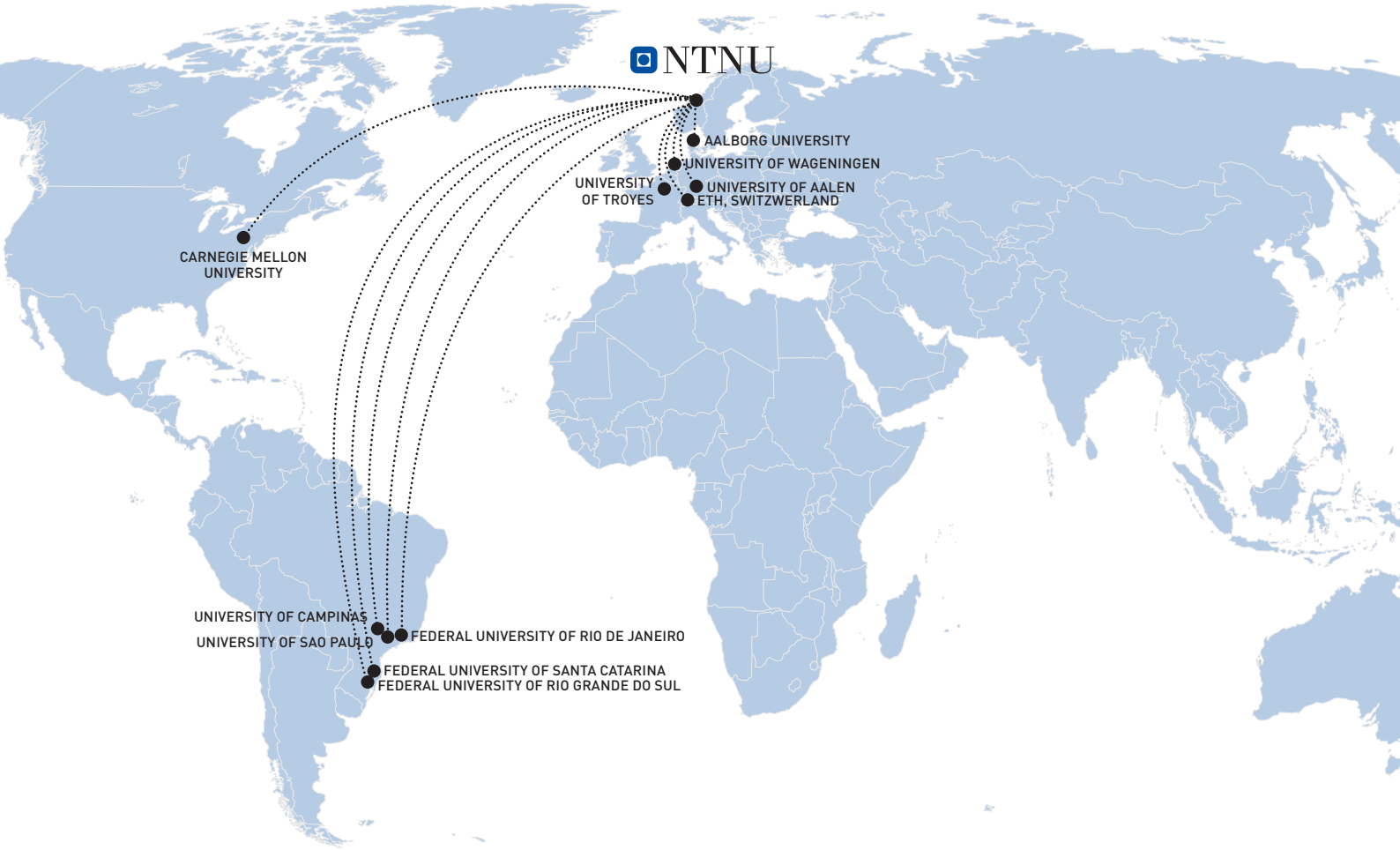
What will they deliver?
- The students will deliver a project report of about 25-50 pages.

Do they have fun?!!
- Of course they have fun! This varies by group and year, but they are usually having a good time.

International Collaboration

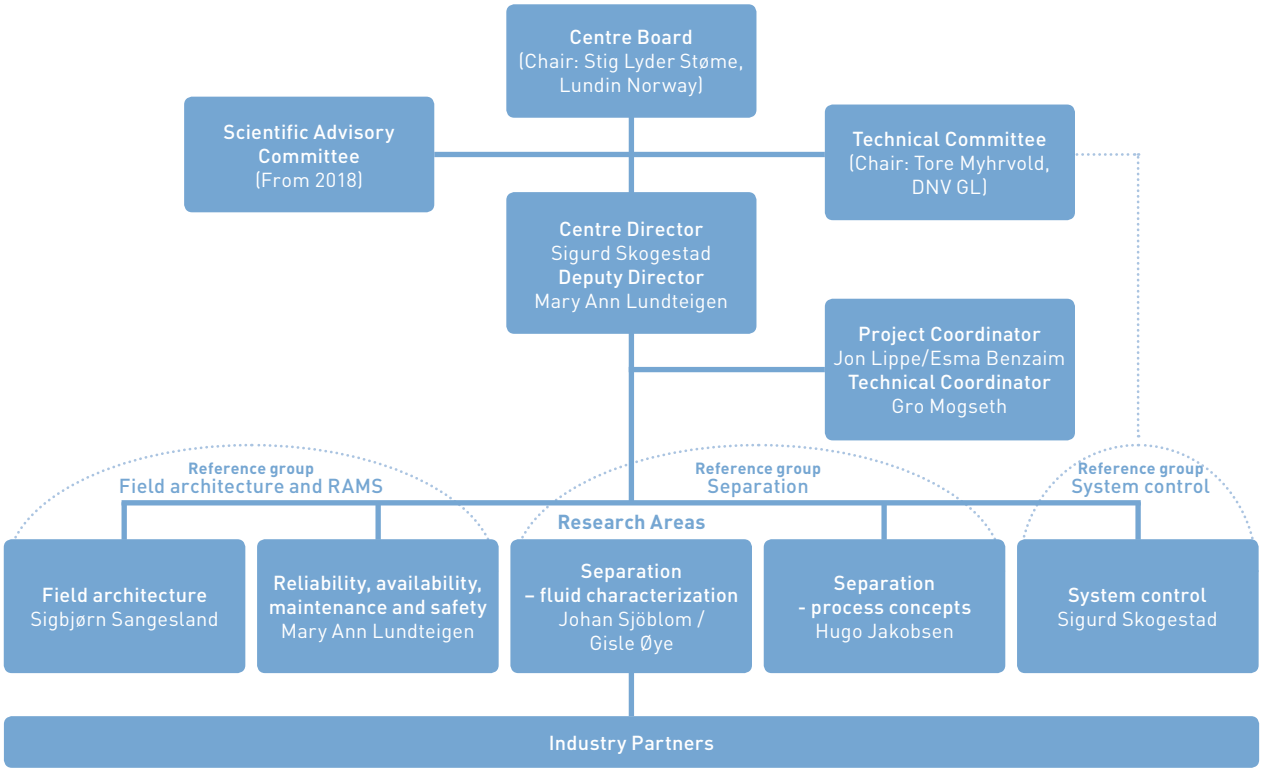
In 2018 and 2019, SUBPRO participates in research collaboration with 11 renowned international universities. The collaboration involves mutual exchange programs for professors, PhD students and Master students and co-authoring of scientific papers etc.

- Brazilian –Norwegian Subsea Operation Consortium and Brazil - Norway Production Optimization Consortium (two INTPART projects); exchange of PhD and Master students, guest lecturing, annual workshops in Brazil and Norway
  - Federal University of Rio de Janeiro/COPPE
  - Federal University of Santa Catarina
  - University of Sao Paulo
  - University of Campinas
- Federal University of Rio Grande do Sul and Petrobras/ CENPES research centre; PhD student Fabio C. Diehl, 8 months visit to NTNU regarding production optimization.
- University of Aalen, Germany, Professor Marcus Grazer, Collaboration on reliability of subsea systems. 6 months sabbatical stay at NTNU.
- University of Troyes, France.
  - PhD student Nan Zhang; Collaborative research on data analytics for prognosis, using Equinor data (2018)
  - Professor Antoine Grall, collaboration on reliability, availability, maintenance and safety
- University of Wageningen (Netherlands) and 5 other European university groups, 2 research institutes, 4 companies; Submitted MCSA application for Innovative Training Network. Topic: HPHT microfluidic studies of multiphase dispersions
- ETH, Switzerland; Exchange visit Postdoctoral fellow Marcin Dudek.
- Carnegie Mellon university, USA, Professor Lawrence Biegler, Exchange visit, PhD Student Dinesh Krishnamoorthy.
- Aalborg University, Denmark, PhD candidate Leif Hansen, research visit to SUBPRO/NTNU, Advice for design of subsea separation test rig.



Organization of the Centre

GOVERNANCE STRUCTURE



CENTRE BOARD 2018-2019

Stig L. Støme
Lundin Norway
Chair of the Centre board

Audun Faanes
Equinor

Frank Børre Pedersen
DNV GL

Angeles Yackow
Neptune Energy Norge

Lars Katteland
VNG Norge (Until merger with Neptune Energy Norway in 2019)

Camilla Leon
Aker BP
(up to 01.09.2018)

Håkon Skofteland
Aker BP
(from 01.09.2018)

Lars-Erik Svabø
Kongsberg Digital
(from 01.01.2019)

Jostein Kolbu
Aker Solutions
(from 01.01.2019)

Kimberly C. Mayes
Research Council of Norway, observer

Øyvind Weiby Gregersen
NTNU

Sigurd Skogestad,
NTNU,
Centre director
Secretary of the Centre board

Organization of the collaboration between NTNU and industry partners

CENTRE BOARD
The Centre board has one representative from each partner. The board adopts goals and strategies for the Centre and makes decisions about the project portfolio and annual budgets.

TECHNICAL COMMITTEE
The Technical Committee has typically 1–2 members from each partner. It monitors the technical quality and industrial relevance of the Centre activities and gives technical advice to the Centre board.

REFERENCE GROUPS
Three different project reference groups, one for each of the major research areas of SUBPRO, meet the researchers twice a year, for presentation of projects results and giving feedback to continued activities, with special emphasis on innovation .

SCIENTIFIC ADVISORY COMMITTEE
The Scientific Advisory Committee was established in 2018. It consists of 1 international expert for each of the five research areas. The committee shall assess the quality of the ongoing research activities and give advice for further planning of research projects.

TECHNICAL CONTRIBUTIONS TO THE RESEARCH ACTIVITIES
The industry partners contribute directly to the research projects through industrial cases, field data, technical knowledge and advice and co-supervision of PhD projects.

ADJUNCT PROFESSORS FROM THE INDUSTRY PARTNERS WORKING FOR SUBPRO
From 2018, two Adjunct professors from the industry partners (Audun Faanes and Gunleiv Skofteland from Equinor R&D) have been assigned at SUBPRO/NTNU, to enhance the collaboration between the Centre and the industry.

RESEARCHERS FROM SUBPRO WORKING WITH THE INDUSTRY PARTNER ORGANIZATIONS/INNOVATION PROJECTS
PhD student Yun Zhang has been working in DNV GL's and Equinor's organizations for 3 months in 2018, to implement a new user interface for condition based maintenance in their software tools. This is an example of a new type of activity in SUBPRO, called Innovation project, where PhD projects are extended in order to enable implementation of project results in the industry.
PhD student Diana Gonzales is working for six months in another Innovation project in 2019, to develop a software tool for decision support on field development optimization, in collaboration with Aker BP, Equinor and Lundin.
Two PhD students are working in 20 % position in Equinor/SUBPRO in parallell with/after their PhD project during 2019, enabling transfer of knowledge from SUBPRO to the industry partner and vice versa.

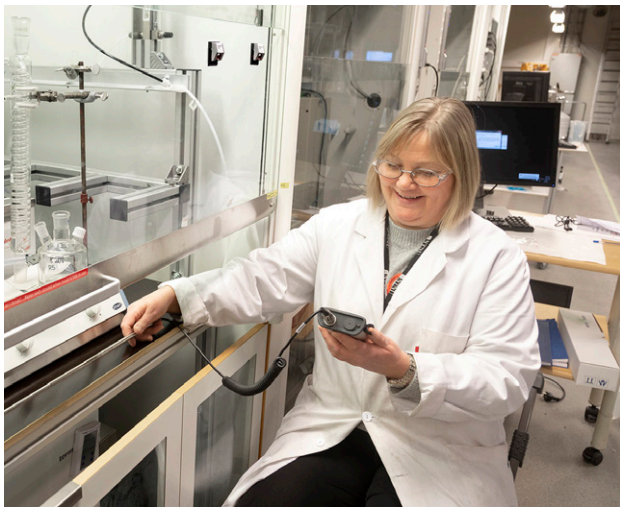
HSE

During 2018, 5 HSE related events have been reported within the SUBPRO laboratory projects. One of the events caused temporary, minor swelling of a finger. For the remaining 4 events, no personnel injuries or damage to equipment have been reported. All events have been systematically followed up with a post-event analysis and preventive mitigations.

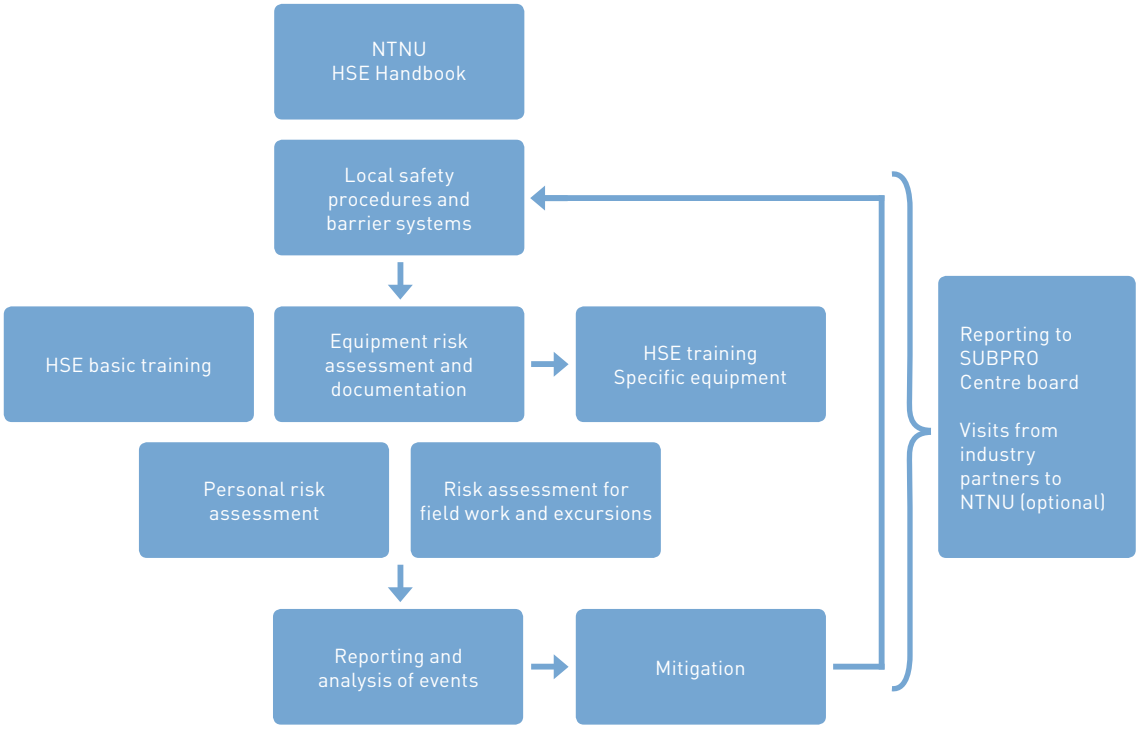
All PhD students, Postctoral fellows and Master students who work in laboratory projects in SUBPRO receive a two level safety training; basic HSE training and HSE training for specific equipment.

SUBPRO follows NTNU's HSE system, and reports possible events and mitigations to the SUBPRO Centre board twice a year. From 2018 an annual HSE learning report has been distributed to all personnel at SUBPRO who work in experimental projects. The report has also been distributed to the Centre board.

The industry partners have the right to visit the work sites whenever desired.



Gunn Torill Wikdahl, Senior HSE Engineer at NTNU, inspecting an extractor hood in the laboratory.

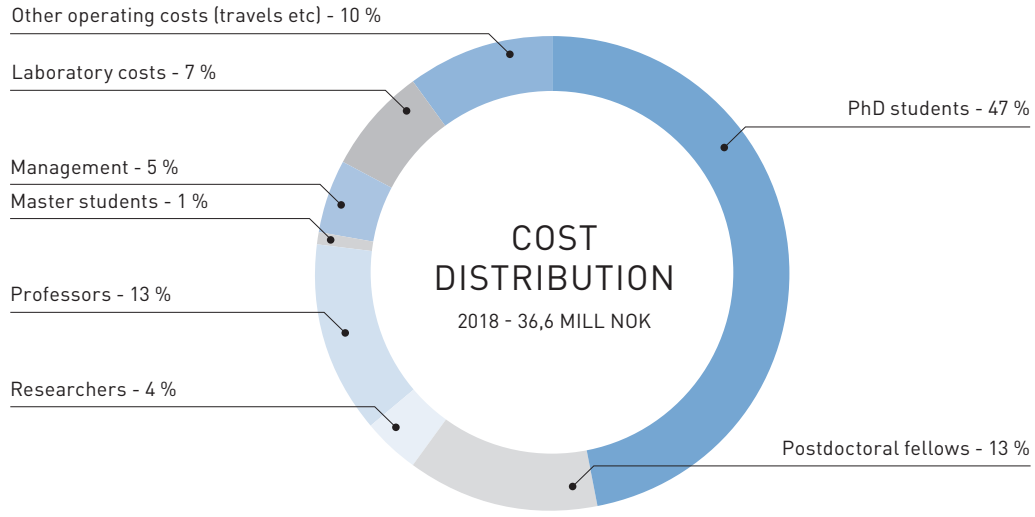


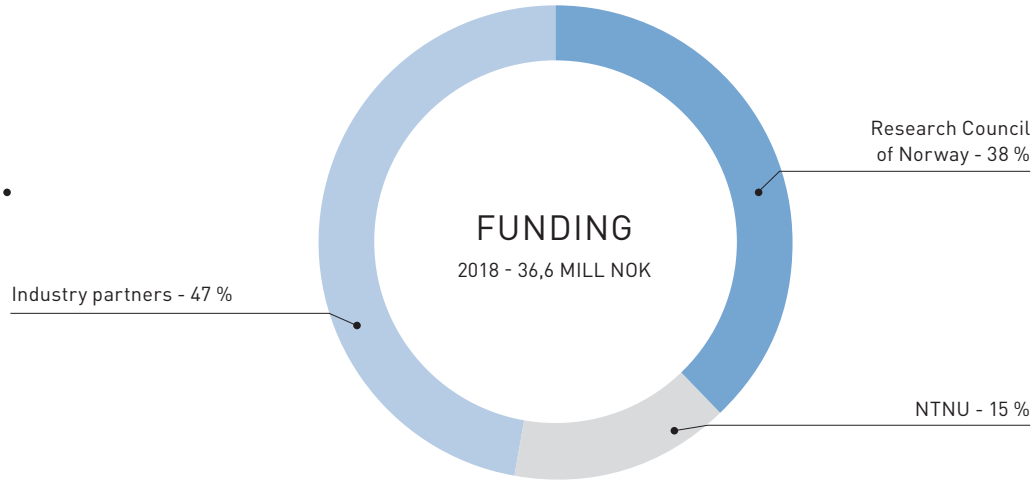
NTNU/SUBPRO HSE system

Key figures

PROJECT DURATION	AUGUST 2015 – AUGUST 2023		
Total annual budget (annual average, 2015-2023)	32 mill. NOK		
Personnel	Planned 2015-2023	Currently engaged 2018	Female percentage
PhD students	34[1]	21	24 %
Postdoctoral scholars	9[1]	7	29 %
Researchers (full or part time)	7[1]	6	17 %
Professors	22	21	19 %
MSc students (per year)	25	17	30 %

PUBLICATION 2018	
Journal and conference papers	51





Publications

Journal papers and conference papers published in 2018

FIELD ARCHITECTURE

Diaz Arias, Mariana JC; Stanko, Milan; Sangesland, Sigbjørn.
"Exploring New Concepts in Subsea Field Architecture".
Offshore Technology Conference; 2018-04-30 - 2018-05-03.

Diaz Arias, Mariana JC; Stanko, Milan; Sangesland, Sigbjørn.
"The subsea gate box: an alternative subsea field architecture".
SPE Norway the First Magazine 2018; Volume 1. pp.38-43.

Gonzalez Rengifo, Diana Carolina; Stanko, Milan; Golan, Michael.
"Numerical Feasibility Study of a Wax Cold Flow Approach for Subsea Tie-In Flowlines Using a 1D Mechanistic Multiphase Flow Simulator".
Engineering 2018; Volume 10. (3) pp.109-123.

Gonzalez Rengifo, Diana Carolina; Stanko, Milan; Golan, Michael.
"Numerical Feasibility Study of Electric Heating Strategies for Subsea Tie-In Flowlines Using a 1-D Mechanistic Multiphase Flow Simulator".
Engineering 2018; Volume 10. (9) pp.531-571.

RELIABILITY, AVAILABILITY, MAINTENANCE AND SAFETY

Bucelli, Marta; Zhang, Juntao; Rauzy, Antoine; Sultana, Sharmin.
"How systems engineering may be useful in risk management – A systems engineering approach for framing reliability, availability, and maintainability in systems design."
Proceedings of the 28th International European Safety and Reliability Conference, ESREL 2018, Trondheim, Norway.

Kim, HyungJu; Lundteigen, Mary Ann; Hafver, Andreas; Pedersen, Frank Børre; Skofteland, Gunleiv.
"Application of System-Theoretic Process Analysis to the isolation of subsea wells: Opportunities and challenges of applying STPA to subsea operations".
Offshore Technology Conference 2018 (OTC 2018); 2018-04-30 - 2018-05-03.

Kim, Hyunglu; Lundteigen, Mary Ann.; Hafver, Andreas; Pedersen, Frank Børre; Skofteland, Gunleiv; Holden, Christian; Ohrem, Sveinung.
"Application of systems-theoretic process analysis to a subsea gas compression system".
Safety and Reliability - Safe Societies in a Changing World - Proceedings of the 28th International European Safety and Reliability Conference, ESREL 2018, 2018, Trondheim, Norway.

Srivastav, Himanshu; de Azevedo Vale, Guilherme; Barros, Anne; Lundteigen, Mary Ann; Pedersen, Frank Børre; Hafver, Andreas; Oliveira, Luiz F.
"Optimization of periodic inspection time of SIS subject to a regular proof testing."
Safety and Reliability - Safe Societies in a Changing World - Proceedings of the 28th International European Safety and Reliability Conference, ESREL 2018, Trondheim, Norway.

Wu, Shengnan; Zhang, Laibin; Barros, Anne; Zheng, Wenpei; Liu, Yiliu.
"Performance analysis for subsea blind shear ram preventers subject to testing strategies".
Reliability Engineering & System Safety, 2018; Volume 169.

Zhang, Yun; Rauzy, Antoine; Barros; Anne; Lunde, Erling.
"A modelling methodology for the assessment of preventive maintenance on a compressor drive system".
Safety and Reliability - Safe Societies in a Changing World - Proceedings of the 28th International European Safety and Reliability Conference, ESREL 2018, Trondheim, Norway.

Zhang, Juntao; Haskins, Cecilia; Liu, Yiliu; Lundteigen, Mary Ann.
"A systems engineering–based approach for framing reliability, availability, and maintainability: A case study for subsea design".
Systems Engineering 2018; Volume 21. (6) pp.576-592.

Zhang, Nan; Fouladirad, Mitra; Barros, Anne. (2018).
"Optimal imperfect maintenance cost analysis of a two-component system with failure interactions".
Reliability Engineering & System Safety, 2018; Volume 177.

SEPARATION – FLUID CHARACTERIZATION

Bertheussen, Are; Simon, Sebastien Charles; Sjøblom, Johan.
"Equilibrium Partitioning of Naphthenic Acid Mixture, Part 1: Commercial Naphthenic Acid Mixture".
Energy & Fuels 2018; Volume 32. (7) pp.7519-7538.

Bertheussen, Are; Simon, Sebastien Charles; Sjøblom, Johan.
"Equilibrium Partitioning of Naphthenic Acid Mixture Part 2: Crude Oil-Extracted Naphthenic Acids".
Energy & Fuels 2018; Volume 32. (9) pp.9142-9158.

Dudek, Marcin; Bertheussen, Are; Dumaire, Thomas; Øye, Gisle.
"Microfluidic tools for studying coalescence of crude oil droplets in produced water".
Chemical Engineering Science 2018; Volume 191. pp.448-458.

Dudek, Marcin; Muijlwijk, Kelly; Schroën, Karin; Øye, Gisle.
"The effect of dissolved gas on coalescence of oil drops studied with microfluidics".
Journal of Colloid and Interface Science 2018; Volume 528. pp.166-173.

Dudek, Marcin; Øye, Gisle.
"Microfluidic Study on the Attachment of Crude Oil Droplets to Gas Bubbles".
Energy & Fuels 2018; Volume 32. (10) pp.10513-10521.

Ruwoldt, Jost; Kurniawan, Muh; Oschmann, Hans-Jörg.
"Non-linear dependency of wax appearance temperature on cooling rate".
Journal of Petroleum Science and Engineering 2018; Volume 165. pp.114-126.

Ruwoldt, Jost; Subramanian, Sreedhar; Simon, Sebastien Charles; Oschmann, Hans-Jörg; Sjøblom, Johan.
"Asphaltene fractionation based on adsorption onto calcium carbonate: Part 3. Effect of asphaltenes on wax crystallization".
Colloids and Surfaces A: Physicochemical and Engineering Aspects 2018; Volume 554. pp.129-141.

Skartlien, Roar; Bertheussen, Are; Simon, Sebastien Charles; Sjøblom, Johan.
"Development of electrochemical DPD molecular simulations for oil/water partitioning of organic acids at varying pH".
Journal of Dispersion Science and Technology 2018; Volume 39. (9) pp.1367-1375.

SEPARATION - PROCESS CONCEPTS

Dalane, Kristin; Svendsen, Hallvard Fjøsne; Hillestad, Magne; Deng, Liyuan.
"Membrane contactor for subsea natural gas dehydration: Model development and sensitivity study".
Journal of Membrane Science 2018; Volume 556. pp.263-276.

Herø, Eirik Helno; La Forgia, Nicolas; Shi, Jing; Solsvik, Jannike; Jakobsen, Hugo Atle.
"On the turbulent dissipation rate in experimental investigation of single droplet breakage in fluid-fluid system".
6th International Conference on Popu-lation Balance Modelling; 2018-05-07 - 2018-05-09.

La Forgia, Nicolas; Herø, Eirik Helno; Solsvik, Jannike; Jakobsen, Hugo Atle.
"Dissipation rate estimation in a rectangular shaped test section with periodic structure at the walls".
Chemical Engineering Science 2018; Volume195. pp.159-178.

Skjefstad, Håvard Slettahjell; Stanko, Milan.
"An Experimental Study of a Novel Parallel Pipe Separator Design for Subsea Oil-Water Bulk Separation".
SPE Asia Pacific Oil & Gas Conference and Exhibition; 2018-10-23 - 2018-10-25.

SYSTEM CONTROL

Assumpcao Matias, Jose Otavio; Le Roux, Galo AC; Jaeschke, Johannes.
"Modifier adaptation for real-time optimization of a gas lifted well network".
IFAC-PapersOnLine 2018; Volume 51. (8) pp.31-36.

Backi, Christoph Josef; Gravdahl, Jan Tommy; Skogestad, Sigurd.
"Simple method for parameter identification of a nonlinear Greitzer compressor model".
IFAC-PapersOnLine 2018; Volume 51. (13) pp.198-203.

Backi, Christoph Josef; Grimes, Brian Arthur; Skogestad, Sigurd.
"A Control- and Estimation-Oriented Gravity Separator Model for Oil and Gas Applications Based upon First-Principles".
Industrial & Engineering Chemistry Research 2018; Volume 57. (21) pp.7201-7217.

Backi, Christoph Josef; Krishnamoorthy, Dinesh; Skogestad, Sigurd.
"Slug handling with a virtual harp based on nonlinear predictive control for a gravity separator".
IFAC-PapersOnLine 2018; Volume 51. (8) pp.120-125.

Backi, Christoph Josef; Krishnamoorthy, Dinesh; Verheyleweghen, Adriaen; Skogestad, Sigurd.
"Combined nonlinear moving horizon estimation and model predictive control applied to a compressor for active surge control".
2nd IEEE Conference on Control Technology and Applications; 2018-08-21 - 2018-08-24.

Backi, Christoph Josef; Skogestad, Sigurd.
"Virtual inflow estimation with simplified tuning using cascaded and Kalman-like least squares observers".
Computer-aided chemical engineering 2018; Volume 43. pp.1153-1158.

Bikmukhametov, Timur; Milan Stanko, Johannes Jäschke .
"Statistical Analysis of Effect of Sensor Degradation and Heat Transfer Modeling on Multiphase Flowrate Estimates from a Virtual Flow Meter".
SPE Asia Pacific Oil and Gas Conference and Exhibition, 23-25 October 2018, Brisbane, Australia. SPE 191962.

Bonnowitz, Harro; Straus, Julian; Krishnamoorthy, Dinesh; Jahanshahi, Esmaeil; Skogestad, Sigurd.
"Control of Steady-state Gradient of an Ammonia Reactor using Transient Measurements".
Computer-aided chemical engineering 2018; Volume 43. pp.1111-1116.

Das, Tamal; Jäschke ,Johannes.
"Modeling and control of an inline deoiling hydrocyclone".
IFAC-PapersOnLine 2018 , Volume 51. (8) pp. 138-143. ISSN 2405-8963.

Krishnamoorthy, Dinesh; Aguiar, Marco Aurelio; Foss, Bjarne Anton; Skogestad, Sigurd.
"A Distributed Optimization Strategy for Large Scale Oil and Gas Production Systems".
Proceedings of the IEEE Conference on Control Applications 2018pp.521-526.

Krishnamoorthy, Dinesh; Foss, Bjarne Anton; Skogestad, Sigurd.
"A Distributed Algorithm for Scenario-based Model Predictive Control using Primal Decomposition".
IFAC-PapersOnLine 2018; Volume 51. (18) pp.351-356.

Krishnamoorthy, Dinesh; Foss, Bjarne Anton; Skogestad, Sigurd.
"Steady-State Real-time Optimization using Transient Measurements".
Computers and Chemical Engineering 2018; Volume 115. pp. 34-45.

Krishnamoorthy, Dinesh; Jahanshahi, Esmaeil; Skogestad, Sigurd.
"Gas-lift Optimization by Controlling Marginal Gas-Oil Ratio using Transient Measurements".
IFAC-PapersOnLine 2018; Volume 51. (8) pp.19-24.

Krishnamoorthy, Dinesh; Suwartadi, Eka; Foss, Bjarne Anton; Skogestad, Sigurd; Jäschke, Johannes.
"Improving Scenario Decomposition for Multistage MPC using a Sensitivity-based Path-following Algorithm".
Proceedings of the IEEE Conference on Decision & Control, including the Symposium on Adaptive Processes 2018.

Krishnamoorthy, Dinesh; Suwartadi, Eka; Foss, Bjarne Anton; Skogestad, Sigurd; Jäschke, Johannes.
"Improving Scenario Decomposition for Multistage MPC using a Sensitivity-based Path-following Algorithm".
IEEE Control Systems Letters 2018; Volume 2. (4) pp.581-586.

Krishnamoorthy, Dinesh; Thombre, Mandar; Skogestad, Sigurd; Jäschke, Johannes.
"Data-driven Scenario Selection for Multi-stage Robust Model Predictive Control".
IFAC-PapersOnLine 2018; Volume 51. (20) pp.462-468.

Kristoffersen, Torstein Thode; Holden, Christian.
"Modelling and nonlinear control of a wet gas centrifugal compressor".
IEEE Conference on Control Technology and Applications 2018; 2018-08-21- 2018-08-24.

Kristoffersen, Torstein Thode; Holden, Christian.
"Nonlinear state and parameter estimation of a gas-liquid cylindrical cyclone".
IEEE Conference on Control Technology and Applications 2018; 2018-08-21 - 2018-08-24.

Kristoffersen, Torstein Thode; Holden, Christian.
"State and parameter estimation of a gas-liquid cylindrical cyclone".
European Control Conference 2018; 2018-06-12 - 2018-06-15.

Ohrem, Sveinung Johan; Holden, Christian.
"Controller and observer design for first order LTI systems with unknown dynamics".
The 6th International Conference on Control, Mechatronics and Automation; 2018-10-12 - 2018-10-14.

Ohrem, Sveinung Johan; Kim, HyungJu; Lundteigen, Mary Ann; Holden, Christian.
"A Comparison of Hazards and Efficiencies of Conventional and Adaptive Control Algorithms using SystemsTheoretic Process Analysis".
European Stamp Workshop and Conference; 2018-10-31 - 2018-11-02.

Ohrem, Sveinung Johan; Kristoffersen, Torstein Thode; Holden, Christian.
"Model-Based and Model-Free Optimal Control of a Gas Liquid Cylindrical Cyclone".
IFAC-PapersOnLine 2018; Volume 51. (8) pp.113-119.

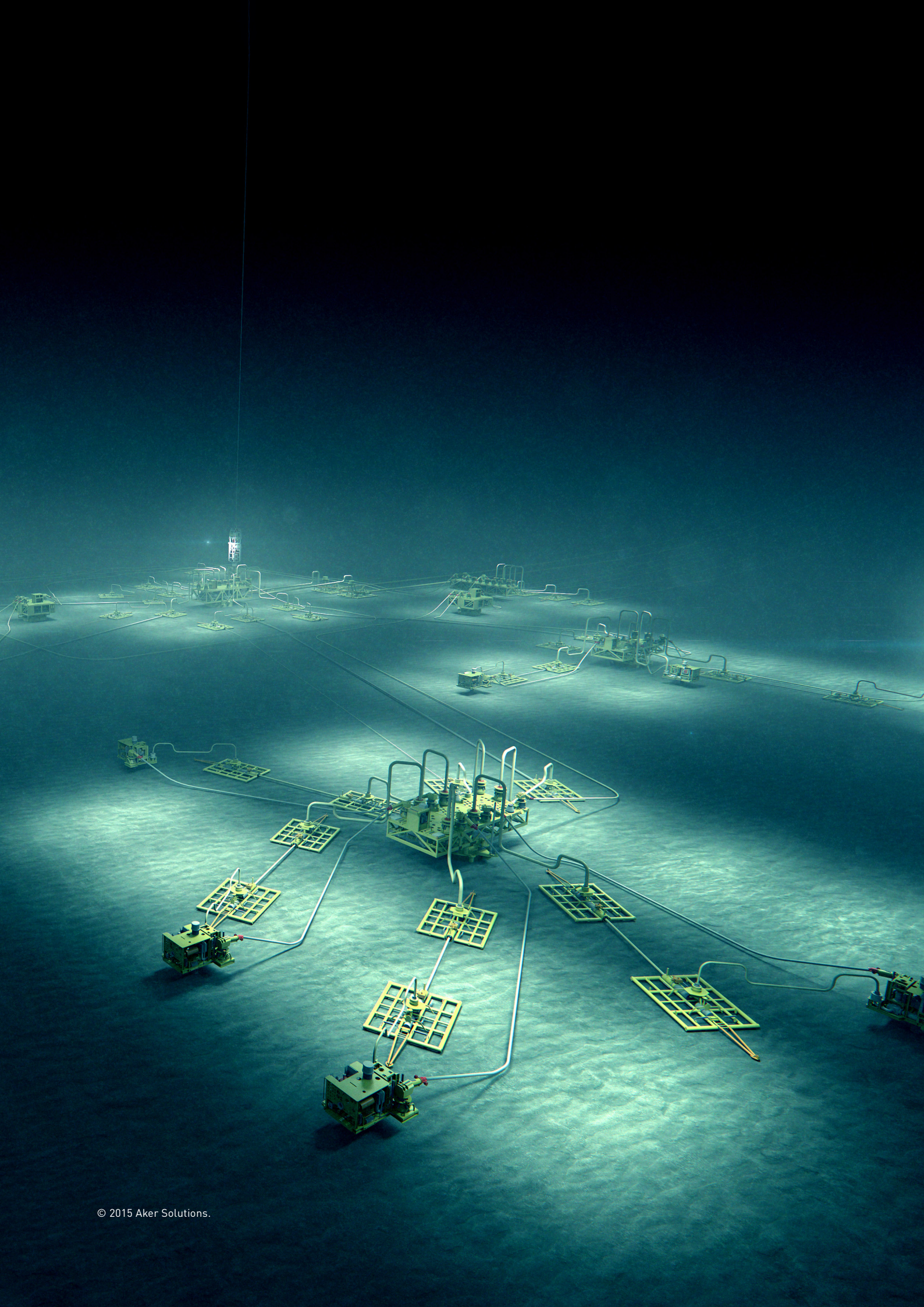
Reyes Lua, Adriana; Backi, Christoph Josef; Skogestad, Sigurd.
"Improved PI control for a surge tank satisfying level constraints".
IFAC-PapersOnLine 2018; Volume 51. (4) pp.835-840.

Stechlinski, Peter; Jaeschke, Johannes; Barton, Paul I.
"Generalized sensitivity analysis of nonlinear programs using a sequence of quadratic programs".
Optimization 2018, Volume 0. pp 1-21. DOI:10.1080/02331934.2018.1517159.

Tengesdal, Njål; Kristoffersen, Torstein Thode; Holden, Christian.
"Applied Nonlinear Compressor Control with Gain Scheduling and State Estimation".
IFAC-PapersOnLine 2018; Volume 51. (8) pp.151-157.

Verheyleweghen, Adriaen; Jäschke, Johannes; Gjøby, Julie Marie.
"Health-Aware Operation of a Subsea Compression System Subject to Degradation".
European Symposium on Computer Aided Process Engineering; 2018-06-10 - 2018-06-13.

Verheyleweghen, Adriaen; Johannes Jäschke.
"Oil production optimization of several wells subject to choke degradation".
IFAC-PapersOnLine 2018, Volume 51 (8), pp. 1-6. ISSN 2405-8963.



People in SUBPRO

CENTRE MANAGEMENT

Prof. Sigurd Skogestad
Centre Director

Prof. Mary Ann Lundteigen,
Centre co-director

Jon Lippe,
Project coordinator
(Until 01.06.2019)

Esma Benzaim,
Project coordinator
(From 01.06.2019)

Gro Mogseth,
Technical coordinator

RESEARCH AREA MANAGERS/CORE TEAM

Prof. Sigbjørn Sangesland,
Field architecture

Prof. Johan Sjöblom,
Separation – Fluid characteristics

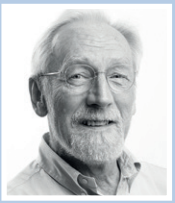
Prof. Gisle Øye,
Co-manager
Separation – Fluid characteristics

Prof. Hugo Atle Jakobsen,
Separation – Process concepts

PROJECT MANAGERS

Associate Prof. Milan Stanko, Field development concepts, Compact separation concepts

Postdoctoral fellow Jesus De Andrade, Multiphase booster models



Prof. Tor Berge Gjersvik, Methods for minimizing costs and risks in subsea field development

Prof. Anne Barros, Condition based maintenance models, Optimizing condition monitoring

Associate Prof. Brian Arthur Grimes, Modelling of coalescence, Digital twin library for multiphase separation and transport processes

Associate Prof. Liyuan Deng, Membranes for gas dehydration
Membrane testing for gas dehydration

Associate Prof. Hanna Knuutila, H_2S and hydrate control

Associate Prof. Christian Holden, Modelling and multivariable control, Control of subsea separation, Adaptive control of subsea processes

Associate Prof. Johannes Jäschke, Estimation of unmeasurable variables, Enhanced virtual flow metering, Control for extending component life, Validation of methods - Remaining Useful Life

ADJUNCT PROFESSORS

Adjunct professor Audun Faanes, (Equinor)

Adjunct professor Gunleiv Skofteland, (Equinor)

PHD STUDENTS


Diana Gonzalez


Gilberto Nunez


Juntao Zhang (Completed 2018)


Yun Zhang (Completed 2018)


Himanshu Srivastav


Haoge Liu


Jost Ruwoldt (Completed 2018)


Are Bertheussen (Completed 2018)


Kristine Dalane (Completed 2018)


Mahdi Ahmadi


Eirini Skylogianni


Eirik Helno Herø


Håvard Slettahjell Skjefstad


Torstein Thode Kristoffersen


Mishiga Vallabhan


Sveinung Johan Ohrem


Tamal Das (Completed 2018)


Timur Bikmukha-metov


Adriaen Verheyleweghen


Dinesh Krishnamoorthy

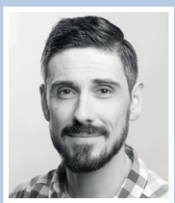

Nanda Anugrah Zikrullah (Associated project Safety 4.0)

POSTDOCTORAL FELLOWS


Mariana Diaz

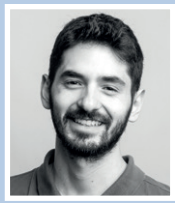

HyungJu Kim (Completed 2018)


Aleksandar Yordanov Mehandzhiyski (Completed 2018)


Christoph Josef Backi (Completed 2018)


Marcin Dudek


Hanieh Karbas Foroushan


José Otavio Assumpcao Matias

RESEARCHERS AND CO-SUPERVISORS


Prof. emeritus Michael Golan


Associate Prof. Yiliu Liu


Prof. Antoine Rauzy


Researcher Sebastien Charles Simon


Prof. Magne Hillestad


Postdoctoral fellow Luca Ansaloni


Researcher Nicolas La Forgia


Postdoctoral fellow Jannike Solsvik


Prof. Olav Egeland


Researcher Esmaeil Jahanshahi


Postdoctoral fellow Zhongde Dai

SUBPRO

SUBSEA PRODUCTION AND PROCESSING

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SUBPRO team at NTNU,
in front of a Subsea Distribution Unit
from the Njord field, Equinor.

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