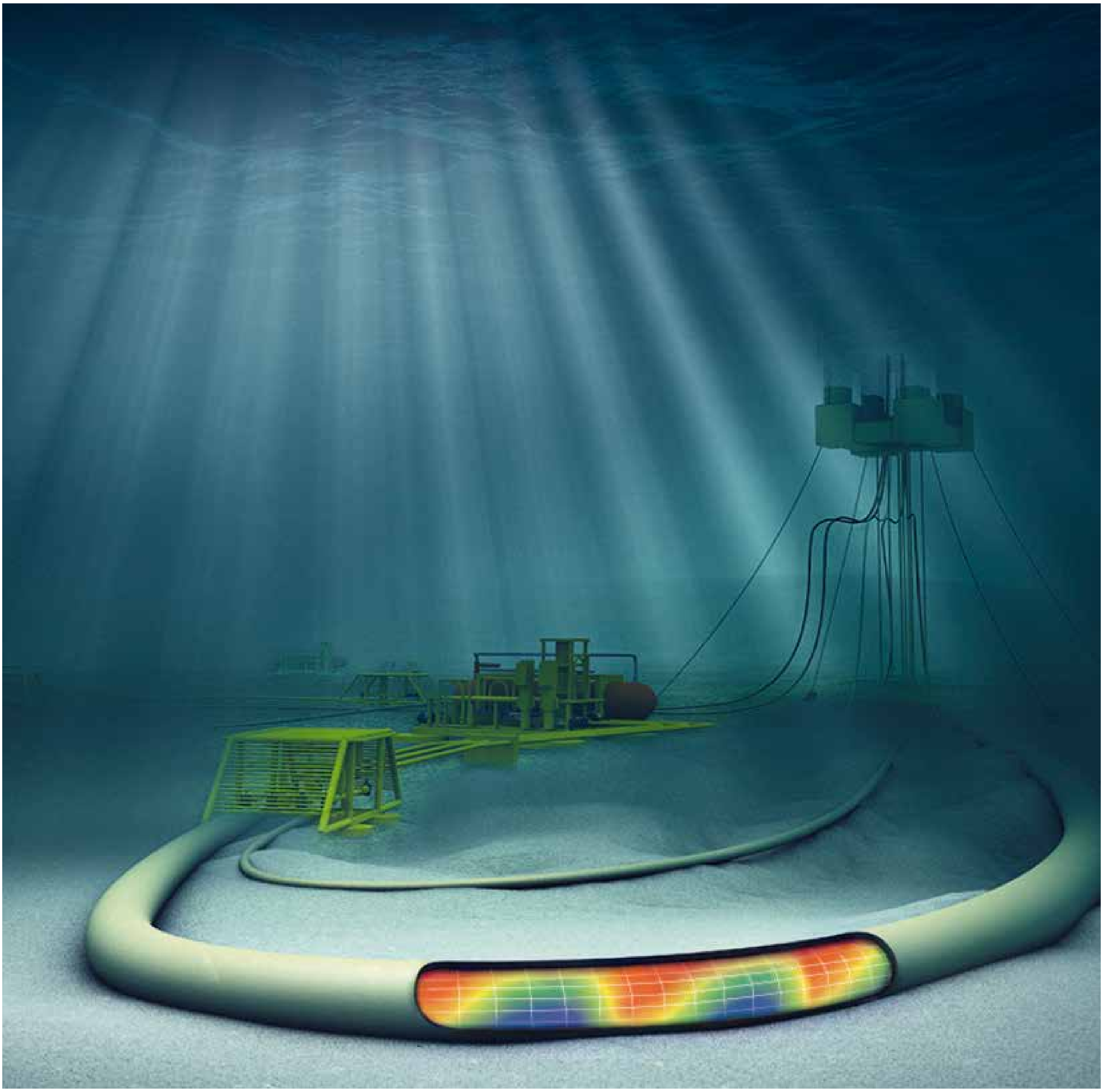
SUBPRO

SUBSEA PRODUCTION AND PROCESSING

Annual Report
2021
2022



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, nine industrial partners, and NTNU. Norwegian companies have been in the forefront of developing and implementing subsea technology for many years, and the reason for 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 (RAMS)
- Separation - Fluid characterization
- Separation - Process concepts
- System control

SUBPRO started up in August 2015, so we are now six and a half year into the planned eight 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 23 full time PhD students and Postdoctoral fellows during 2021. In addition, about 20 professors and associate professors, 2 researchers, and 5 advisors from the industry partners 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 energy industry. The direct transfer of knowledge through hiring of 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 exploited by the industry on a longer time perspective. 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 to improve the design of compact oil-water separators.

SUBPRO is the most comprehensive academic research programme in Norway within oil and gas and it is 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:

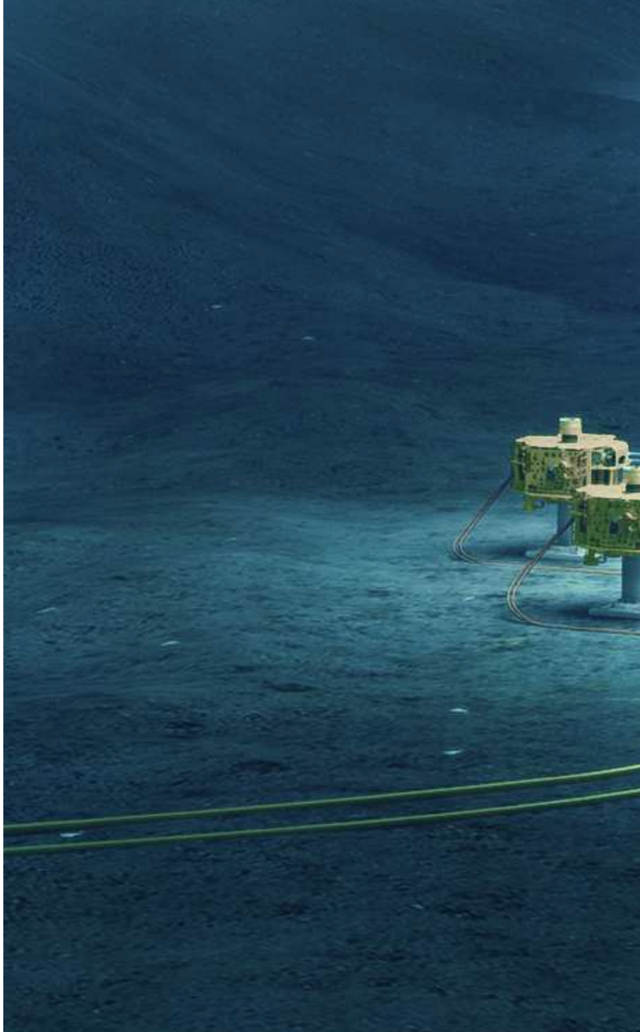
- reduce cost and complexity of subsea field developments
- enable development of new and more demanding oil and gas fields
- increase production and extend life of existing fields
- reduce environmental footprint of subsea field developments
- maintain safety levels

FUTURE CHALLENGES REQUIRE

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

Front page illustration: Subsea multiphase flow (LedaFlow).
Photo credit: Kongsberg Digital.

CONTENT



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**
- **Knowledge, methods, technology and system understanding – as a basis for industrial innovation**
- **Internationally high level of graduated PhD and Master students**

Illustration of subsea operation. Courtesy of DNV.

Chair of the Board

SUBPRO has managed to keep up the level of research during the pandemic, it has increased the focus on energy transition and sustainable development along with the oil and gas industry, and it is preparing a new project initiative - SUBPRO Zero, while it is entering the last two years of a successful research and innovation period.

TRINE BOYER
ENGINEER RESEARCH AND DEVELOPMENT, STAVANGER RESEARCH CENTRE, TOTALENERGIES E&P NORGE

CHAIR OF THE SUBPRO CENTRE BOARD

I will start by giving Frank Børre Pedersen our sincere thanks for his years as the chairman in SUBPRO, for his inspiring engagement, reflections and visions given to the project through the challenging years where unfortunately the pandemic has taken too much of our focus.

Who could imagine that we had to spend more than 2 years on this pandemic, on testing and keeping distance and not being able to travel nor spend time with our family and friends in the same degree as we were used to? These times have changed us all and we are now appreciating the freedom, the social life and just a normal day more than we did before.

It is therefore with the greatest respect and gratefulness we look at results achieved by the PhD students, the Post docs and the master students in SUBPRO these years. They have handled the time alone, kept the focus and worked hard - what a job performed through these challenging times that we hope will never come back!

We are glad to see that society is now being normalized, step by step are we getting back to living the life as before the pandemic. Maybe not everything will be the same, because the technology development has not been on pause. All companies have been and are now working more than ever on their innovations, on new business models, new ways of working and prioritizing, so maybe we don't have to travel to make decisions, can it be done through Teams? We can then save emissions in areas we did not do before.

Many companies have changed names, reorganized, changed strategies, and created roadmaps to prepare for the new energy transition and in line with the United Nations' sustainable development goals, the Paris agreement, and the acceptance that we must do something to stop climate change.

We have all had time to reflect and now it is time for action and to be future oriented.

In SUBPRO we have also started planning the continuation of SUBPRO. We will build on the knowledge and organization developed in SUPRO, define research and industry needs, important problems to solve, in line with the new OG21 strategy and create SUBPRO Zero – SUstainable Bridge PROjects towards ZERO emissions.

First, we have two upcoming exiting years left in the current SUBPRO project, where more outstanding work will be done. The Board is there to support, to discuss, follow and learn. We need to do our part on distributing and publishing the knowledge gained in the project, which is also part of the steps needed to reach a sustainable world.

Centre director

SUBPRO is now into the sixth year of its eight-year duration. The activity in 2021 reached a peak with 23 active projects (fulltime PhD and postdocs). Because we are approaching the end, we have only started up two new projects in 2021. Through the new initiative SUBPRO Zero, led by associate professors Johannes Jäschke and Milan Stanko, we are making plans to continue the activity by making a bridge to a zero-emission future.

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 academic excellence is well taken care of by the large number of PhD students and postdocs that we have in the program, who are producing excellent scientific results. I'm also very proud that almost all of the projects are running on time. Eight projects have been finalized this year (final project documentation is included in this report):

- Haoge Liu (PhD) Optimizing subsea production systems to minimize risk and cost (page 18)
- Himanshu Srivastav (PhD) Optimizing condition monitoring (see last year's annual report)
- Nanda Anugrah Zikrullah (PhD) Demonstrating safety of novel subsea technologies (page 29)
- Marcin Dudek (Postdoc) Influence of chemicals on produced water quality (page 42)
- Hanieh Karbas (Postdoc) Mechanistic modelling of fluid particle breakage (page 56)
- Eirik Helno Herø (PhD) Experiments on fluid particle breakage (page 59)
- Mishiga Vallabhan (PhD) Automatic control of hydrocyclones for produced water treatment (page 74)
- José Octavio Assumpcao Matias (Postdoc), Experimental validation of methods - Remaining Useful Life (page 78)

The two new projects that started last year are:

- Mehman Ahmadli (PhD) Valves and materials – design concepts for simplifications (page 16)
- Jie Liu (PhD) Digital Twin Qualification for Maintenance (page 26)

In addition to academic excellence, innovation is very important for SUBPRO. The innovation should happen with the partners, and to facilitate this we have introduced 3-6 months innovation projects with the aim of making the scientific results more directly usable for the partners. During the last year SUBPRO funded three innovation projects involving Jose Matias, Mishiga Vallabhan and Nanda Zikrullah. A new innovation project with Haoge Liu has just started up.

In the last two annual reports I have been writing about the Corona virus. It has not had a major impact on SUBPRO, except for seriously limiting our travelling for international cooperation. It has limited our participation in international conferences, and we have had much less exchange of people, for example, with Brazil, where we have been lucky to have an associated INTPART project for short-term exchange. Fortunately, the pandemic now seems to be coming to an end, and the phase 2 of the INTPART program can finally start up.

Another recurring effect outside our control is the oil price which keeps going up and down, and now up again. The oil price went down to less than 20 USD per barrel when the Corona crisis hit in April 2020, but it has since then climbed steadily and is presently close to 100 USD. The European natural gas price has shown an even more dramatic increase, with a large increase towards the end of 2021 because of an energy shortage in Europe. With Putin's invasion of Ukraine, it may reach even higher values. All of this means that the oil and gas companies have record profits.

It is of course difficult to predict the long-term future, but with the increased focus towards sustainability and zero emissions of CO2, it is likely that demand for oil will drop in the future. For natural gas the case may be different, because it is seen by many as a temporary replacement for coal.

Furthermore, by using natural gas to produce "blue" hydrogen (i.e., with CO_2 removal and storage), natural gas may have an even more long-term future as an energy source. The competence within SUBPRO is perfect for developing new technologies in this direction, in particular for offshore facilities.

As mentioned also in last year's report, the industrial partners are generally very happy with the SUBPRO project, and the plans for the new project SUBPRO Zero have progressed in 2021, including looking into research projects that can be the basis for a more sustainable and greener future.

Partners

AkerBP AkerSolutions DNV equinor KONGSBERG Lundin Energy Norway NEPTUNE ENERGY TechnipFMC TotalEnergies NTNU Norwegian University of Science and Technology The Research Council of Norway

STATEMENTS FROM TWO OF OUR INDUSTRY PARTNERS

OLAV DOLONEN

LEAD FIELD DEVELOPMENT ENGINEER, NO

PROJECTS & ENGINEERING NEPTUNE ENERGY

Subsea production and development of new subsea technology is high on the agenda for Neptune Energy. As SUBPRO is a cooperation between NTNU, supplier industry and oil companies, it represents an important arena for Neptune Energy to contribute in developing the latest subsea technology. Additionally SUBPRO educates PhD and Master recruits which are employed by the industry and bring along new and valuable ideas and competence to further improve the business. Being part of SUBPRO has improved our understanding and helped us prepare for future subsea technology development.

LARS-ERIK SVABØ

GLOBAL DEPARTMENT MANAGER, SW DEVELOPMENT PRODUCTION ASSURANCE

DIGITAL ENERGY KONGSBERG DIGITAL

Kongsberg Digital believes it is important to work together with academia to enhance and share knowledge to the benefit of both the industry and academia. Kongsberg Digital has a particular focus on dynamic modelling and utilization of novel technologies supporting dynamic digital twins for both subsea and onshore assets.

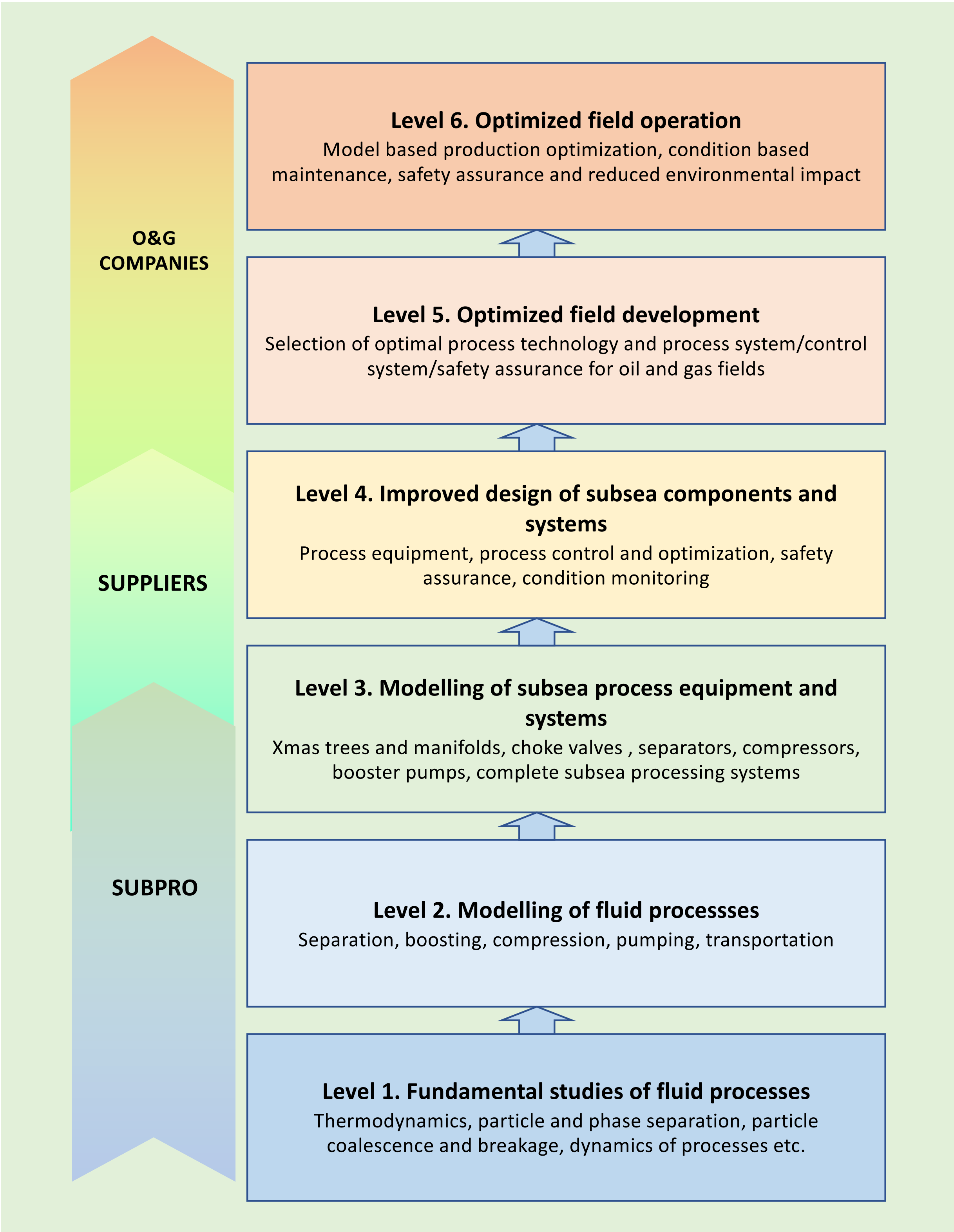
Many of the SUBPRO research areas and projects fit excellently with Kongsberg Digital's own subsea focus, and we see that by working with SUBPRO the industry will obtain innovative and improved concepts in the subsea domain.

SUBPRO will be an important contributor to ongoing and upcoming subsea developments and operations.

Åsgard Subsea Compression Phase II - compressor module. Courtesy of Aker Solutions/Equinor.

Scope of SUBPRO -

From fundamental research to industrial innovation



Project structure

RESEARCH AREAS

Field Architecture
Prof. Sigbjørn Sangesland

Reliability, Availability, Maintenance and Safety (RAMS)
Prof. Jørn Vatn

Separation – Fluid characterization
Prof. Gisle Øye

Separation – Process Concepts
Prof. Hugo Jakobsen

System Control
Associated Prof. Johannes Jäschke

PROJECTS

1.1 Subsea gate box
Postdoc Mariana Diaz
Prof. Sigbjørn Sangesland

1.1.b Superstructure optimization of subsea processing layouts
PhD Leonardo Sales
Assoc. Prof. Milan Stanko

1.1.c Enabling technology for low-cost subsea field development
Postdoc Lucas C. Sevilliano
Prof. Sigbjørn Sangesland

1.1.d Valves and materials - design concepts for simplifications
PhD Mehman Ahmadli
Prof. Tor Berge Gjersvik

1.2 Field development concepts
PhD Diana Gonzales
Assoc. Prof. Milan Stanko

1.3 Multiphase booster models
PhD Gilberto Nunez
Prof. Sigbjørn Sangesland

1.4 Subsea field layout optimization
PhD Haoge Liu
Prof. Tor B. Gjersvik

3.1 New safety and control philosophy for subsea systems
Postdoc Hyung Ju Kim
Prof. Mary A. Lundteigen

3.1.b Safety-critical systems for unmanned facilities
PhD Tae Hwan Lee
Prof. Mary A. Lundteigen

3.1.c Digital twin for safety demonstrations
PhD Ludvig Björklund
Prof. Mary A. Lundteigen

3.1.d Digital twin qualification for maintenance
PhD Jie Liu
Prof. Shen Yin

3.2. Reliability and availability in design
PhD Juntao Zhang
Prof. Mary A. Lundteigen

3.3. Condition and prognostic maintenance
PhD Yun Zhang
Prof. Anne Barros

3.3.b Optimizing condition monitoring
PhD Himanshu Srivastav
Prof. Anne Barros

3.3.c Estimation and optimization of remaining useful life
Postdoc Xingheng Liu
Prof. Jørn Vatn

SPINOFF: SAFETY 4.0 - Ensuring functional safety of novel technologies
PhD Nanda Zikrullah
Prof. Mary A. Lundteigen
Tore Myhrvold, DNV

Associated project Data-driven prognostics and health mgmt. in safety systems
PhD M. Gibran Alfarazi
Prof. Shen Yin

2.1 Produced water quality and injectivity
PhD Marcin Dudek
Prof. Gisle Øye

2.1.b Influence of chemicals on produced water quality
Postdoc. Marcin Dudek
Prof. Gisle Øye

2.1.c Re-Inj. of prod. water - disp. in porous media
PhD Ilgar Azizov
Prof. Gisle Øye

2.1.d Gas flotation for subsea produced water treatment
PhD Martina Piccioli
Prof. Gisle Øye

2.2 Modelling of wax crystallization and deposition
PhD Jost Ruwoldt
Prof. Johan Sjøblom

2.2.b Flow improvers for transport of waxy crudes
PhD George Claudiu Savulescu
Prof. Gisle Øye

2.3 Sequential separation
PhD Are Bertheussen
Prof. Johan Sjøblom

2.8 Modeling of coalescence
Postdoc Aleksandar Mehandzhiyski Yordanov
Assoc. Prof. Brian A. Grimes

2.8.b A digital twin library for oil/water emulsion separation and transport
PhD Moein Assar
Assoc. Prof. Brian A. Grimes

2.4 Membranes for gas dehydration - modeling
PhD Kristin Dalane
Prof. Liyuan Deng
Prof. Magne Hillestad

2.4.b Membrane testing for gas dehydration
PhD Mahdi Ahmadi
Prof. Liyuan Deng

2.4.c Natural gas dehydration with the use of membranes
Postdoc Mahdi Ahmadi
Prof. Magne Hillestad

2.5 Combined H2S and hydrate control
PhD Eirini Skylogianni
Prof. Hanna Knuutila

2.6 Particle breakup; turbulence and image analysis
Researcher Nicolás La Forgia
Prof. Hugo A. Jakobsen

2.6.b Mechanistic modeling of fluid particle breakage
Postdoc Hanieh Karbas
Prof. Hugo A. Jakobsen

2.7 Experiments on fluid particle breakage
PhD Eirik Helno Herø
Prof. Hugo A. Jakobsen

2.9 Compact separation
PhD Håvard S. Skjefstad
Assoc. Prof. Milan Stanko

2.9.b Subsea bulk oil-water separation
PhD Hamidreza Asaadian
Assoc. Prof. Milan Stanko

3.4 Dynamic simulation model library
Postdoc. Christoph Backi
Prof. Sigurd Skogestad

3.5 Modelling for control of subsea processes
PhD Torstein Kristoffersen
Assoc. Prof. Christian Holden

3.5.b Automatic control of hydrocyclones for produced water treatment
PhD Mishiga Vallabhan
Assoc. Prof. Christian Holden

3.5.c Energy-optimal subsea production and processing
PhD Asli Karacelik
Assoc. Prof. Christian Holden

3.6 Adaptive control of subsea processes
PhD Sveinung J. Ohrem
Assoc. Prof. Christian Holden

3.7 Estimation of unmeasured variables
PhD Tamal Das
Assoc. Prof. Johannes Jäschke

3.7.b Enhanced virtual flow metering
PhD Timur Bikmukhametov
Assoc. Prof. Johannes Jäschke

3.7.c High-accuracy virtual flow metering
PhD Md Rizwan
Assoc. Prof. Christian Holden

3.8 Control for extending component life
PhD Adriaen Verheyleweghen
Assoc. Prof. Johannes Jäschke

3.8.b Experimental validation of methods - Remaining Useful Life (RUL)
Postdoc José Matias
Assoc. Prof. Johannes Jäschke

3.9 Production optimization under uncertainty
PhD Dinesh Krishnamoorthy
Prof. Sigurd Skogestad

3.9.b Field-wide production optimization
PhD Risvan Dirza
Prof. Sigurd Skogestad

3.10 Digital Twins: Automatic calibration with uncertain/drifting sensors
PhD Halvor A. Krog
Assoc. Prof. Johannes Jäschke

Spin-off project: AutoPRO
PhD Evren Turan (SC)
PhD Emefon Dan (RAMS)
Assoc. Prof. Johannes Jäschke/Prof. Yiliu Liu/Ind. PhD Supervisor Edmary Altamiranda

Completed projects

Current projects

Associated projects/Spin-off projects

PROFESSOR
SIGBJØRN SANGESLAND

RESEARCH AREA MANAGER

RESEARCH AREA

Field Architecture

Improving 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:

- 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 subsea development and operations of 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.
- Fundamental requirements for Health, Safety and Environment (HSE) in a life-cycle perspective. How to implement principles for safety thinking, reevaluation of barrier philosophy to identify technical and economic opportunities for design simplifications of subsea trees and manifolds. Minimizing the use of resources (e.g., materials and energy consumption) for operations and installations while securing a responsible exploitation of the hydrocarbon over the life of the field.
- Exploiting the coming electrification of control systems and more fields being remotely operated to further develop new methods and systems for Condition and Performance Monitoring (CPM) for more effective scheduling and execution of necessary Inspection, Maintenance and Repair (IMR) operations.

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

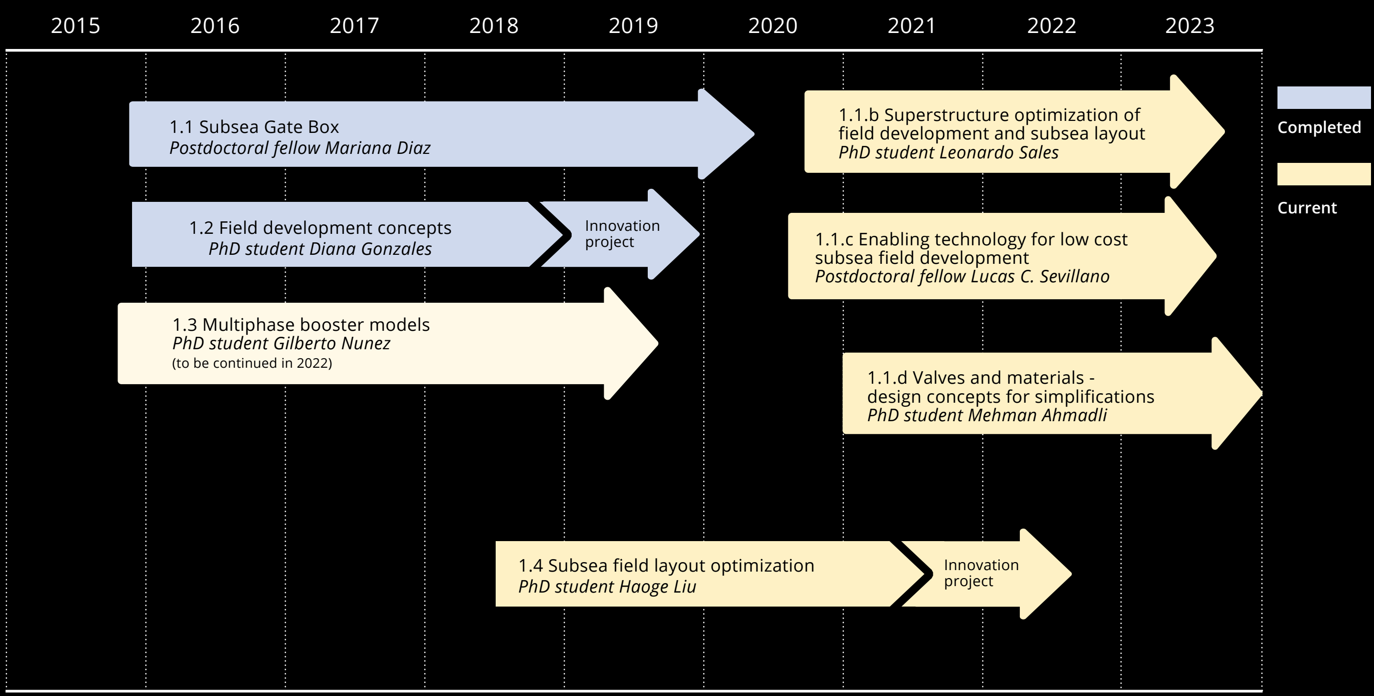
During 2021, one new project has been started:

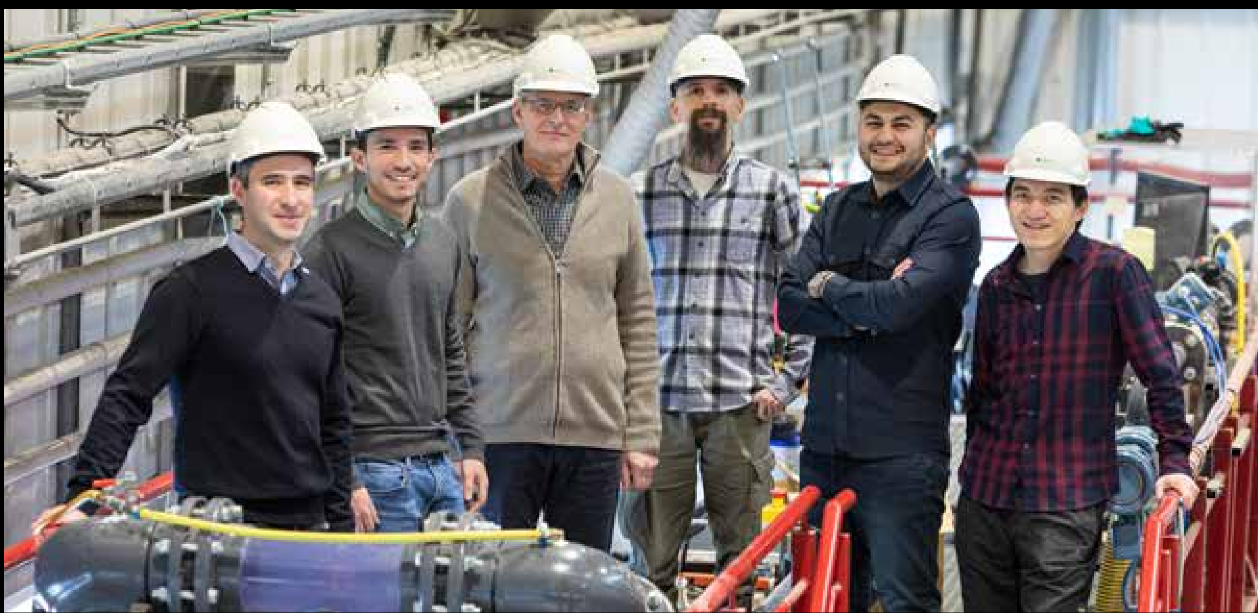
- 1.1.d Valves and materials - design concepts for simplification (PhD student Mehman Ahmadi)

Ongoing projects during 2021

- 1.1.b Superstructure optimization of subsea processing layouts (PhD student Leonardo Sales)
- 1.1.c Enabling technology for low-cost subsea field development (Postdoctoral fellow Lucas Cantinelli Sevillano)
- 1.4 Subsea field layout optimization (PhD student Haoge Liu)
  Followed up with Innovation project in 2022

Completed and current projects





The Field architecture team, in the laboratory of Department of Geoscience and Petroleum at NTNU
From the left: Associate Professor Milan Stanko, PhD student Leonardo Sales, Professor Sigbjørn Sangesland, Postdoctoral fellow Lucas Cantinelli Sevillano, PhD student Mehman Ahmadi and PhD student Haoge Liu. Professor Tor Berge Gjersvik was not present when the photo was taken.

1.1.b Superstructure optimization of subsea processing layouts

Developing methods and obtaining insights for optimization of subsea processing systems.

PhD student
Leonardo Sales

Project manager and main supervisor:
Associate Professor
Milan Stanko

Co-supervisor:
Associate Professor
Johannes Jäschke

1. SUBSEA LAYOUT OPTIMIZATION

The use of subsea processing creates new requirements and challenges that did not exist in earlier offshore projects. Determining the optimal layout of the subsea processing system, including location, type and number of equipment, operating conditions and capacity, are some of them. While manual methods require a wide range of expertise and effort, computer assisted optimization techniques can thoroughly explore the search space and determine designs that provide the largest profit, provide insights, and ensure the efficient use of resources. While most of the previous studies have focused on topside or field development, this project develops different layout optimization methods to maximize project net present value (NPV) considering subsea processing equipment.

2. APPROACHES TO THE PROBLEM

Firstly, we proposed a mixed-integer non-linear (MINLP) method to optimize subsea production system design using superstructures. The subsea layout, equipment capacity, oil and gas production rates, and system pressures are optimized, while NPV is maximized. A paper documenting this work will be submitted to a journal.

Secondly, we proposed a hybrid method, using a genetic algorithm combined with a gradient search method. The genetic algorithm is formulated to optimize the structure of the production system, while the gradient method solves the continuous non-linear variables related to flow rates, reservoir deliverability, equipment capacities, and others.

The two above methods were compared as they were applied to a synthetic case, based on the Goliat field. A paper was submitted to OMAE 2022 (The American Association of Mechanical Engineers) based on this study.

The project builds on three earlier research projects within SUBPRO; "Superstructure Optimization of Early Stage Offshore Oil Field Development with Subsea Processing" (Master project, Dag Krogstad), "1.1 Subsea gate box" (Mariana Diaz), and "1.2 Optimization of subsea layout" (Diana González).

We are working together with Equinor and Aker BP through master student projects. With Equinor, we are expanding the superstructure model and adding maintenance and reliability aspects. With Aker BP, we are considering uncertainties and guaranteeing optimality while using heuristics with an integrated modeling approach. TotalEnergies has provided feedback and suggestions to the work.

3. PROJECT RESULTS, DEMONSTRATION OF FINDING BEST SUBSEA PROCESSING DESIGN FOR A USE CASE

The two proposed models successfully find the best subsea processing design for the synthetic field (shown as structure A in Figure 1). For small-sized problems, the performance of the MINLP is superior to that of the hybrid method. However, as the number of variables of the problem is increased, the convergence time of the MINLP method grows rapidly and becomes much larger than the one required by the hybrid method.

The two other best solutions (obtained by the MINLP method) are also shown in Figure 1, as structure B and C. In the sensitivity analysis shown in Figure 2, we notice that structures A and B, which use subsea separation and boosting, are more robust to changes (i.e., less impact on NPV) in uncertain parameters such as oil price, oil-initially-in-place (OIIP) and gas-oil ratio than structure C, which only uses subsea boosting.

4. POSSIBLE APPLICATION OF RESULTS

The MINLP method guarantees global field layout optimality, although it can only be used for smaller problems. The hybrid method quickly obtains optimum solutions for larger problems, thus allowing analysis such as Monte Carlo simulation. Both methods ensure the highest value for the project and the efficient use of resources.

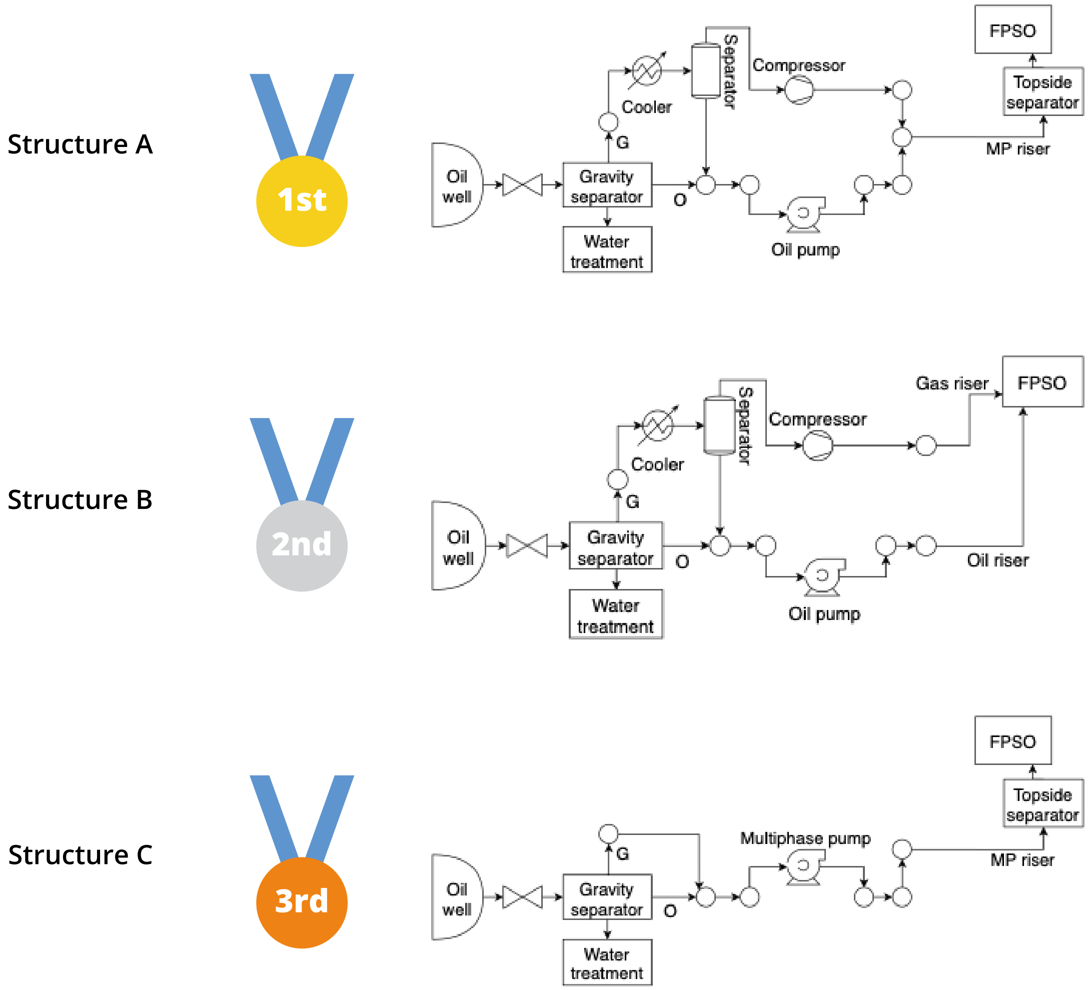
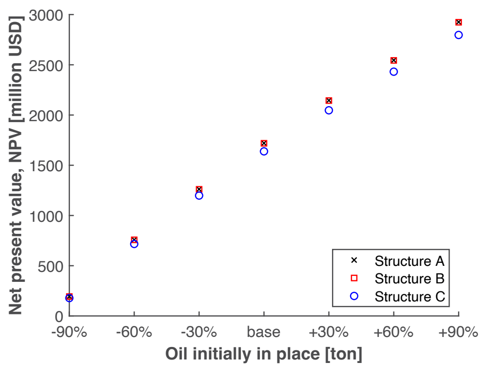
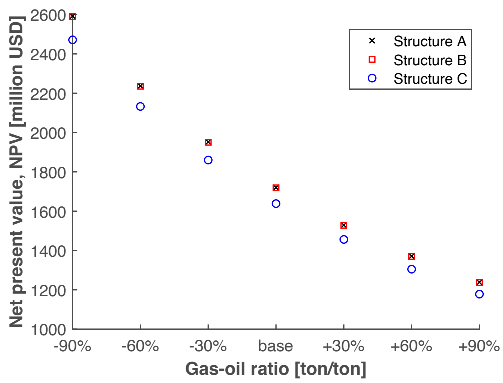


Figure 1. Best structures found by applying the MINLP optimization model to the synthetic case based on the Goliat field. The arrows point to the flow direction between the units. The nodes represent mixing or splitting points.





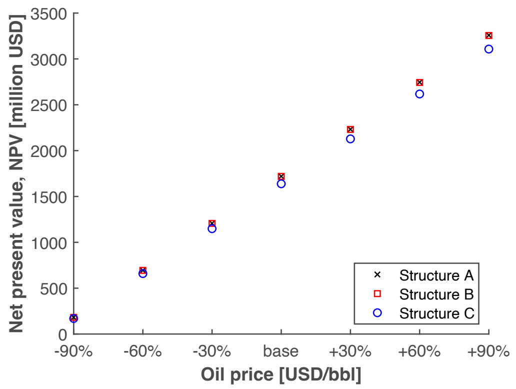


Figure 2. Sensitivity analyses of net present value by varying three parameters: oil initially in place, gas-oil ratio and oil price. The base is the original synthetic use case, while the increase or decrease in the variable is given by the percentage values.

1.1.c Enabling technology for low-cost subsea field development

Investigating the impact of new technologies and proposing novel designs to subsea production systems. Formalizing a suitable set of metrics for evaluating technical, environmental, and economic benefits of alternative designs when compared to conventional solutions applied to subsea developments, particularly marginal fields.

Green shift impact: New technologies and novel designs can reduce the carbon footprint of subsea production systems by enabling leaner systems and improving well maintenance.

Postdoctoral fellow:
Lucas Cantinelli Sevillano

Project manager and main supervisor:
Professor
Sigbjørn Sangesland

Co-supervisors:
Professor
Tor Berge Gjersvik
Adjunct Professor
Audun Faanes (Equinor)

1. BACKGROUND

Despite the ongoing green shift, the oil and gas industry will still be a major energy provider during the next decades. Nonetheless, the industry must address climate change and declining oil prices by reducing carbon emissions and costs related to field development.

As offshore oil and gas industry moves to marginal and deep-water fields, subsea production systems (SPS) have become the norm to overcome technical and economic challenges. A SPS consists of completed wells with seabed wellhead, subsea Xmas trees, tie-ins to a flowline system, and equipment for production, processing and control. It can range in complexity from a satellite well to several wells connected to a manifold.

The overall footprint and costs of a SPS are associated with manufacture, handling, and installation of individual components, and the resources needed to operate, monitor, and maintain the system.

Deep-water SPSs already present low energy consumption/carbon emissions per barrel produced, yet improvements are feasible. The solution envelope for a SPS is restricted by industry guidelines and practices, but ongoing technological developments make it possible to challenge practices and rethink the solutions applied to subsea field development.

The concept of Technology Readiness Level (TRL) is used by the oil and gas industry to characterize the status of new technologies. TRL 0 refers to unproven concept stage while TRL 7 refers to field proven technology. This research aims to use recent technological developments (TRL 3 to 7) to generate new design concepts up to TRL 1 (proven concept), which could be further developed together with industry partners.

2. RESEARCH ACTIVITIES AND DELIVERABLES

The objective of this research is to perform structural and fundamental analysis of SPSs and address the question:

- How may the design of SPSs be improved regarding technical, economic, and environmental aspects?

To address this question the project focuses on the subsea Xmas tree and ongoing technological developments which may represent opportunities for design simplifications of SPSs, while still maintaining the integrity of the system.

Main concepts investigated, and their impact on the design and operation of SPSs, will be:

- All-electric control
- Chemical storage
- Resident subsea vehicles
- Modular architecture

We are studying modularization of the Xmas tree. Dividing the tree into modules can require more materials, but the manufacture process can become simpler. Modularization could also, for instance, reduce the costs of interventions by enabling smaller vessels to retrieve just the defective modules instead of the whole tree. This could:

1. Reduce carbon emissions, by employing smaller vessels.
2. Reduce maintenance costs, by employing vessels with cheaper rates.
3. Reduce non-productive time, by simplifying retrieval operations.
4. Increase field life, by enabling additional interventions to be carried out.

Starting from a base-case scenario, we aim to propose alternative SPS solutions and then determine the impact on field development of modular architecture, and other design concepts, from manufacture to abandonment, by estimating expenses reduced, additional income, and overall emissions and materials consumed. The figure below illustrates this approach and the parameters selected for evaluating the generated solutions.

Figure 1. The combined concepts when applied to a subsea field may provide different design options for the production system. The research aims to identify the feasible solutions and rank them based on technical, operational, and environmental parameters.

Individual milestones reached during the research will be submitted for publication in conference and journal papers. Study cases shall present findings and main conclusions of the research, with the future goal towards applying technical solutions with low carbon footprint and reduced costs to actual field data.

The research project works closely with another SUBPRO project titled "1.1.d Valves and materials – design concepts for simplifications" (Mehman Ahmadli). As such, the proposal of new designs for valves, particularly those used in the Xmas tree will also be addressed by the project.

3. INDUSTRY PARTICIPATION

Currently, Equinor has provided valuable feedback to the concepts promoted in this project, and additional collaboration with other industry partners is under exploration within SUBPRO.

Results of this research can be used in the development of new subsea fields or the extension of old ones, particularly by improving the decision-making process regarding the potential of reducing cost/carbon emissions in oil and gas production.

Figure 2. Postdoctoral fellow Lucas Cantinelli Sevillano and PhD student Leonardo Sales, both from Brazil, discussing new methods to develop more efficient subsea fields with lower CO_2 emissions.

1.1.d Valves and materials - design concepts for simplifications

Investigating new possibilities for valves and actuators assuming all-electric control system and exploiting alternative designs (valve types, materials, and placements)

Green shift impact: Reduction in carbon footprint will be achieved by minimizing the power consumption of subsea valves and valve control systems, optimizing subsea valve design, and simplifying the maintenance operations.

PhD student:
Mehman Ahmadli

Project manager and supervisor:
Professor
Tor Berge Gjersvik

1. BACKGROUND

In a situation where the oil and gas industry now more strongly than ever before, asks for research and technology development towards systems, methods, and equipment to reduce CAPEX, OPEX and the environmental footprint, the ongoing "electrification" of subsea functions through a transition from electrohydraulic to all-electric control systems constitutes an important contribution. However, merely changing the control system platform without simultaneously challenging the design of mechanical parts, system interphases and current design practices, leaves out a significant potential for further improvements:

- Making currently non-retrievable components and systems like Christmas trees (XTs) designed for 20-30 years of life, more easily retrievable and replaceable at low cost using smaller vessels and fewer marine operations.
- Moving/shifting functionalities from XTs towards and onto separate bridging modules and/or manifolds, reducing unit size and weights of XTs
- Replacement of steel with other and lighter materials
- Re-design of Fail-Safe-Close (FSC) valves and actuators for low power operations and easier and less costly retrievability

2. RESEARCH ACTIVITIES AND RESULTS

- Develop and verify a Finite Element Method/Analysis (FEM and FEA) model for gate valves that calculates loads and displacements in form of contact- and friction forces and power (torque and speed) during valve operations.
- Investigate and propose use of alternative materials and material combinations (e.g., aluminium bodies with internal steel linings) in XTs.
- Investigate and propose concept design for easy subsea replacement of critical components like valve actuators; possibly also the valve itself.
- Challenge design margins – current margins being based on non-retrievability and lack of control of forces in actuators (with spring) over the lifetime for the XT. All electric systems allow such control.
- Investigate and calculate effects on loadings from removing the mechanical spring (potentially up to 80%).
- Investigate use of possible low-friction materials like polycrystalline diamond compact (PDC) and other materials for valve seats.

3. INDUSTRIAL PARTICIPATION

TotalEnergies is actively involved in the project alongside with other SUBPRO partners. As the project progresses further, more involvement and contribution from the industry partners is expected, since the industry is investing continuous efforts for improving HSE performance and subsea production sustainability, which are within the scope of the project.

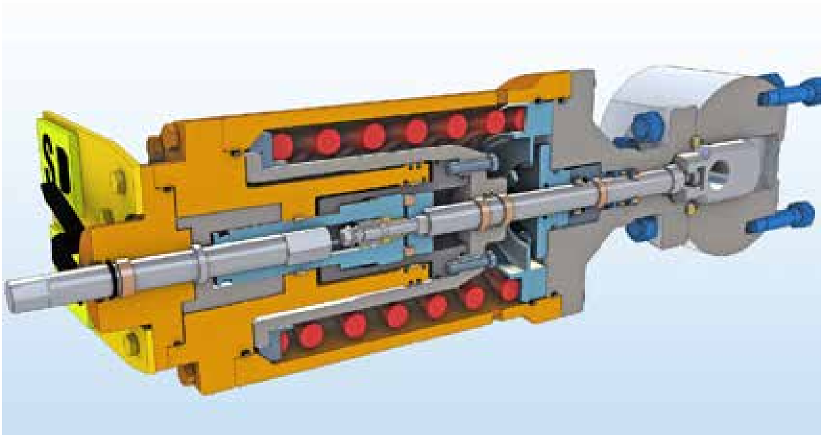


Figure 1 Fail-Safe-Close (FSC) subsea valve. Valve is in closed position (Courtesy of Aker Solutions)

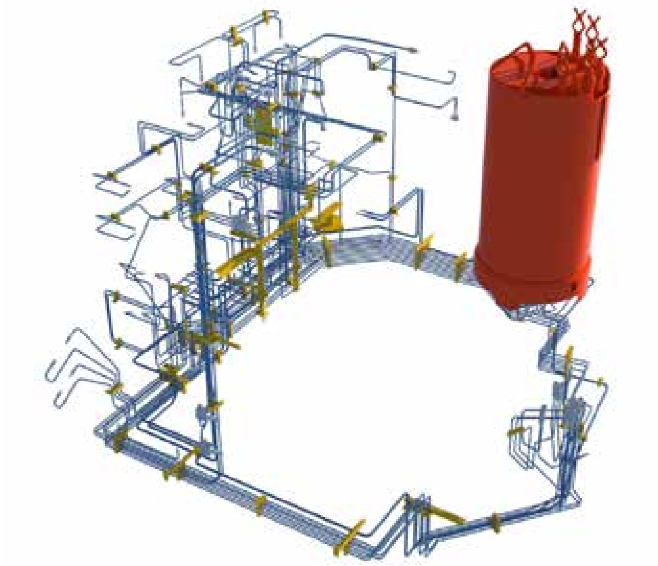


Figure 2: Small Bore Tubing on Christmas tree [TechnipFMC]

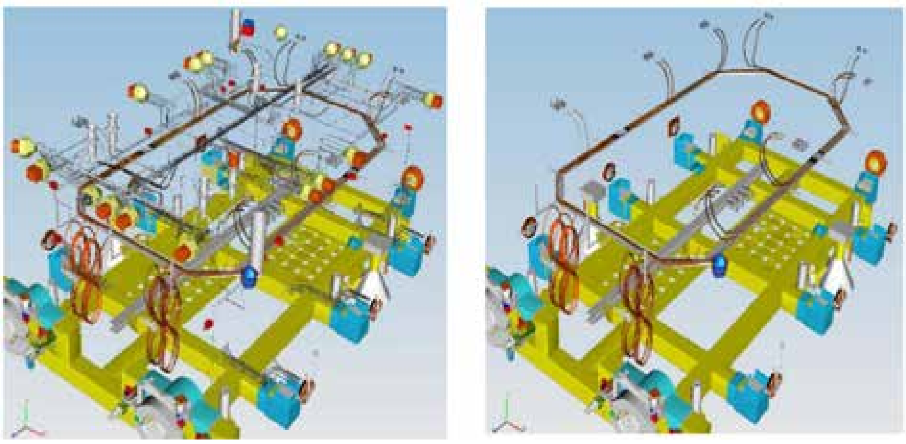


Figure 3: Four-slot manifold with electro-hydraulic controls (to the left), and with electric controls (to the right) [TechnipFMC]

1.4 Subsea field layout optimization

A systematic method for solving the “k-sites-n-wells” problem, boosting computational efficiency drastically with global optimum guaranteed.

Postdoctoral fellow:	**Haoge Liu**
Start date:	09.11.2018
Thesis defense date:	08.02.2022
Title of thesis:	Subsea Field Layout Optimization
Thesis committee members:	Professor Bernt S. Aadnøy, University of Stavanger, Norway Professor Juliana Baioco, Federal University of Rio de Janeiro, Brazil (2. opponent) Professor Sigbjørn Sangesland, NTNU
Main supervisor:	Professor Tor Berge Gjersvik, Department of Geoscience and Petroleum, NTNU
Co-supervisor:	Adjunct Professor Audun Faanes (Equinor)

1. BACKGROUND FOR THE PROJECT

At present, finding the optimal field layout is a trial-and-error process based on the engineers’ experience. Such a process is tedious and time-consuming, additionally, it cannot guarantee the global optimum, i.e., the minimum cost with risks and engineering constraints taken into consideration. Therefore, we have aimed to develop a global optimal method with high efficiency for subsea field layout optimization to reduce the overall cost under various engineering constraints.

2. WHAT I HAVE DONE

This year, we have combined the “3D Dubins Curve” method for the directional well trajectory design and the reduced binary linear programming (BLP) method for the continuous spaced location-allocation problem to solve the “k-sites-n-wells” problem. As the name indicates, the “k-sites-n-wells” problem not only requires us to determine the optimal location of the drilling site for a cluster of wells, just as “1-site-n-wells” does, but also requires us to determine the optimal number of clusters if it is not manually constrained and the optimal combination of the wells.

Two field tests have been done in cooperation with Equinor. The feedback is very positive: our method “can save their two weeks’ effort within just a coffee break” (quote from Equinor field development specialist).

3. MAIN RESULTS

The results of the project include three parts:

- The first is the reduced BLP method for the continuous spaced location-allocation problem, which was introduced in the SUBPRO Annual Report 2019/2020.
- The second is the “3D-Dubins Curve” method for the “1-site-n-wells” problem, which was introduced in the SUBPRO Annual Report 2020/2021.
- The last is the systematic combination of the two methods above to solve the complex “k-sites-n-wells” problem. The full process is shown in the flowchart below:

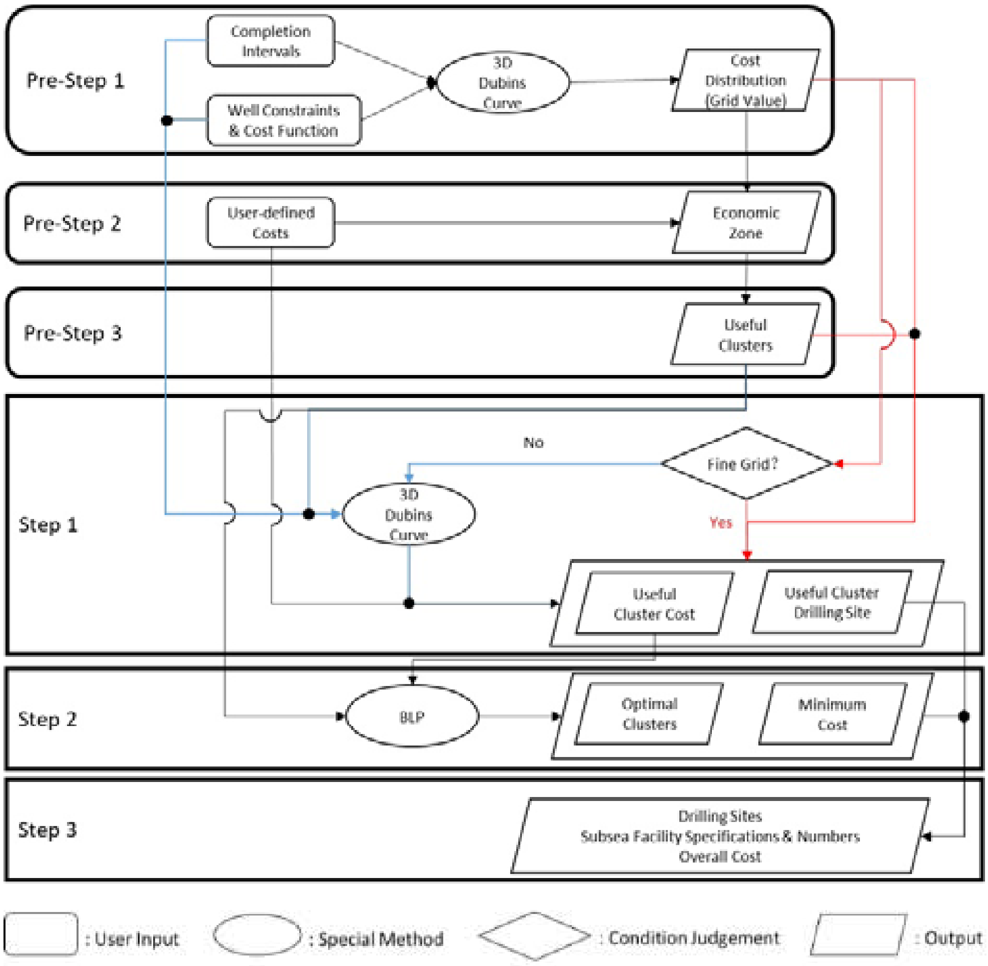


Figure 1. Flowchart of Full Process

The following two figures show the different layout under different constraints. Our method can handle user-defined costs or cost functions under various constraints. Hence, it becomes very easy to do the cost sensitivity analysis.

4. INNOVATION

The advantage of the method developed in the project is that it guarantees the global optimum with extremely high efficiency. Hence, it becomes practically feasible to find the global optimal layout for a much larger field. We no longer need to compromise on the optimality for the sake of computing time limitations. Both the capital cost and the time cost will be reduced during the early-phase design for subsea field layout.

5. FURTHER WORK, INNOVATION PROJECT

The PhD project will be extended by an innovation project funded by SUBPRO, where we will cooperate with SUBPRO industry partners to develop our method into a user-friendly software. We will also perfect the details for the application in more practical scenarios.

As a popular phrase goes -- "rubbish in, rubbish out" -- no matter how good our method is, if the user-defined costs are not accurate, we will still lose the global optimality. Therefore, we would also like to explore a method to help users to acquire the accurate costs.

6. COMPLETE LIST OF PUBLICATIONS AND REPORTS

A series of three papers has been published in the Journal of Petroleum Science and Engineering, which is the highest-ranking journal in petroleum engineering according to Clarivate's Journal Citation Reports (JCR).

Haoge Liu, Tor Berge Gjersvik, Audun Faanes,2021, Subsea field layout optimization *(Part I) — directional well trajectory planning based on 3D Dubins Curve*, Journal of Petroleum Science and Engineering.
https://doi.org/10.1016/j.petrol.2021.109450

Haoge Liu, Tor Berge Gjersvik, Audun Faanes, 2021, *Subsea field layout optimization (part II) — the location-allocation problem of manifolds*, Journal of Petroleum Science and Engineering.
https://doi.org/10.1016/j.petrol.2021.109273

Haoge Liu, Tor Berge Gjersvik, Audun Faanes, *Subsea field layout optimization (part III) — the location-allocation problem of drilling sites,* Journal of Petroleum Science and Engineering.
https://doi.org/10.1016/j.petrol.2021.109336

7. MY NEW JOB

Organization: Department of Geoscience and Petroleum, NTNU
Position: Researcher, SUBPRO innovation project.
Job description: Continue developing our method into a user-friendly tool, with the support from SUBPRO industrial partners such as Equinor, TotalEnergies, etc.

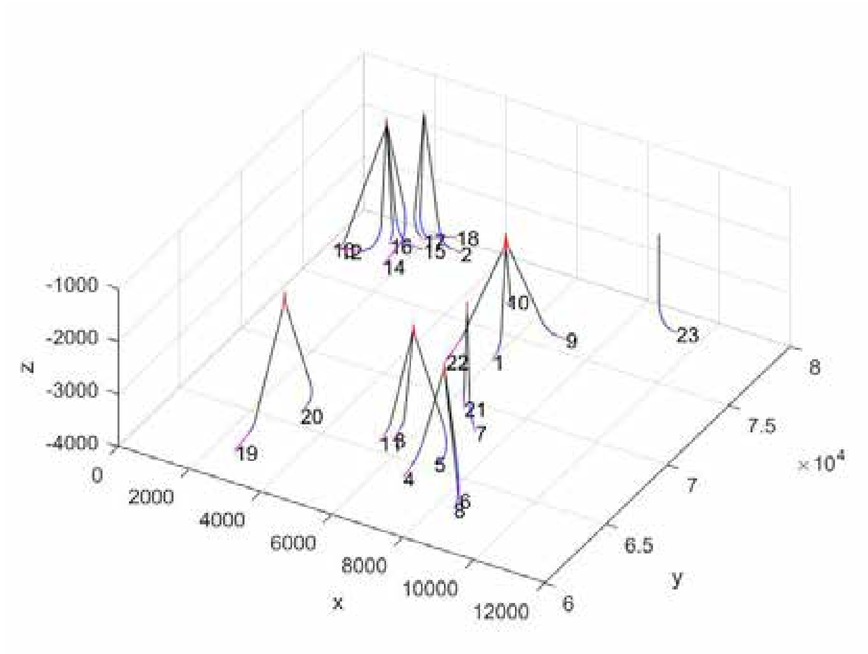


Figure 2. Optimal well layout without drilling site number constraint

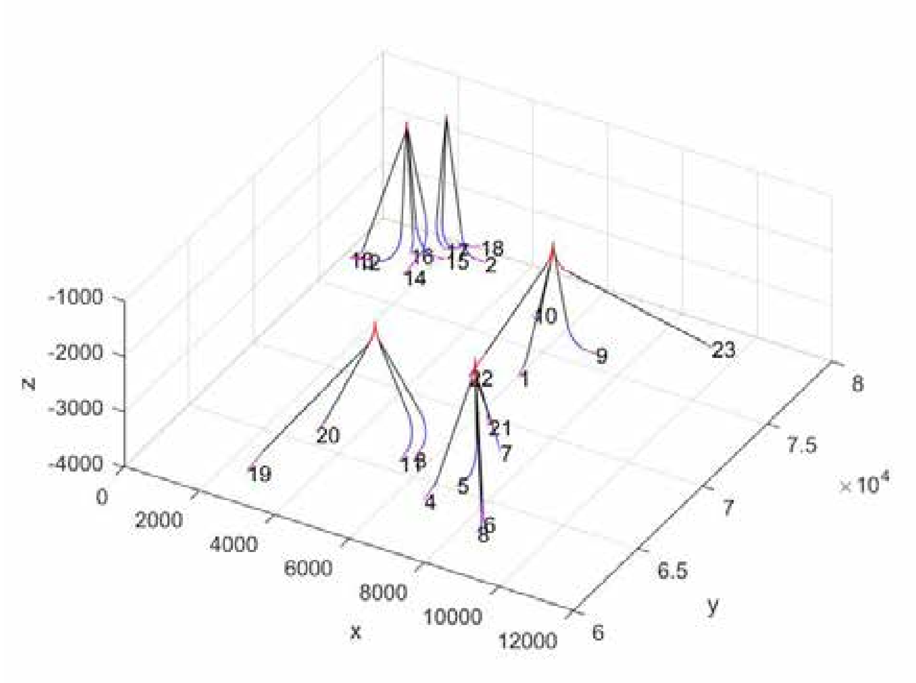


Figure 3. Optimal well layout with maximum number of drilling sites = 5

PROFESSOR
JØRN VATN

RESEARCH AREA
MANAGER

RESEARCH AREA

Reliability, Availability, Maintenance and Safety (RAMS)

Cost efficient solutions without compromising safety and environment.

2021 was a year for the continuation of ongoing research within the established topics of the RAMS research area. As a result of the SUBPRO Digital Twin webinar in November 2020 a new PhD project on Qualification of Digital Twins for Maintenance was granted and Jie Liu was recruited for this position. Covid-19 restriction caused delays, but from autumn 2021 she has been part of the team.

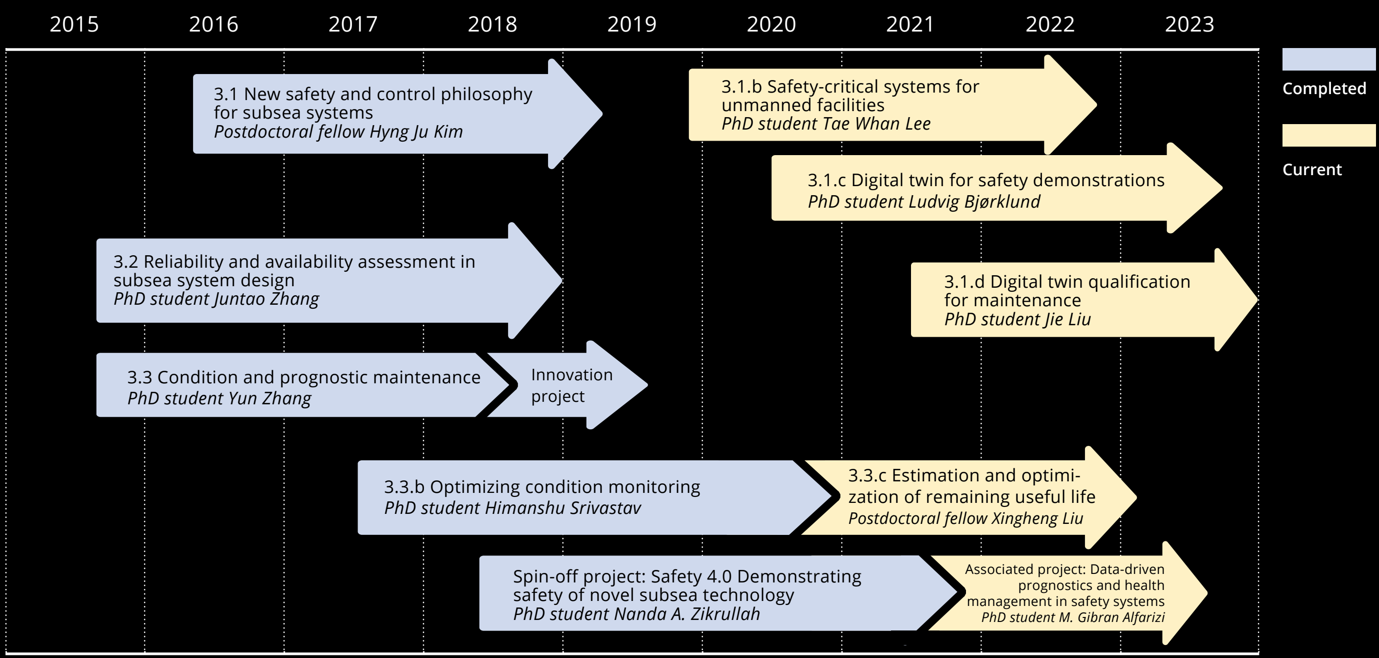
Within the RAMS field there are synergies between SUBPRO and the BRU21 program, both at NTNU. In 2020 SUBPRO hosted "The Digital Twin-webinar", whereas in 2021 BRU21 hosted "The Predictive Maintenance Workshop". From SUBPRO we had presentations from Muhammad Gibran Alfarizi (Machine Learning in RUL Estimation for Subsea Choke Valve: An Experimental Study) and Xingheng Liu (Choke valve erosion modeling and remaining useful life prediction: a data driven approach). Visit the following link to see all the presentations.

SUBPRO is aiming to continue the research beyond the original time frame of the SFI. We consider the knowledge achieved so far valuable for the green shift with emphasize on "Zero emission" both during production and use of the Norwegian oil- and gas resources. RAMS is seen as crucial in a continuation of SUBPRO. For example production of blue hydrogen is seen as a promising technology where safety and risk perspective will play an important role. This applies both with respect to the need for analytical methods, and in order to design novel technology qualification methods together with the petroleum safety authority (PSA). During 2021 the RAMS research area has contributed to the design of the project proposal for SUBPRO Zero. The green shift implication for the various PhD and Postdoctoral projects are emphasized in the following.

Predictive Maintenance Workshop program:

The presentations:

Completed and current projects



The Reliability, Availability, Maintenance and Safety team
From the left, around the clock: PhD student Tae Hwan Lee, Profesor Jørn Vatn, PhD student Jie Liu, Professor Mary Ann Lundteigen, Postdoctoral fellow Xingheng Liu and PhD student Muhammad Gibran Alfarizi. Professor Shen Yin, Adjunct Professor Gunleiv Skofteland (Equinor), Professor Markus Glaser (Aalen University), Senior principal Researcher Tore Myhrvold (DNV), PhD student Nanda Anugrah Zikrullah and PhD student Ludvig Bjørklund were not present when the picture was taken.

3.1.b Performance management of safety-critical systems at unmanned facilities with restricted access

A decision support system based on machine learning to enable better situational awareness on unmanned facilities

Green shift impact: Unmanned oil and gas facilities have a great potential for reduced carbon footprint, and the development of a SIS performance management system that satisfies new requirements for unmanned facilities will greatly support early adaptation of such technology.

PhD student:
TaeHwan Lee

Project manager and main supervisor:
Professor
Mary Ann Lundteigen

Co-supervisor:
Adjunct Professor
Gunleiv Skofteland
(Equinor)

1. BACKGROUND

Performance management of safety instrumented systems (SIS, automatic control systems to ensure safe condition of process systems in accidental situations) is a vital part of the major accident risk management for oil and gas processing facilities. The requirements to performance management are provided in national regulations and governing standards for SIS, such as IEC 61508 and IEC 61511, and cover the need for regular testing and inspection, online diagnostics, failure registration and analysis, and implementation of corrective measures upon performance deviations. Many of these tasks are resource demanding, carried out manually, and dependent on local presence of humans at the facilities. For unmanned oil and gas facilities offshore, it is necessary to move to a higher level of automation and autonomy in performance management. This includes the utilization of artificial intelligence (AI) to determine the ability of the SIS to respond to demands under various operating conditions, based on real-time data and event data from multiple monitoring systems.

2. RESEARCH ACTIVITIES AND RESULTS

The key purpose of the project is to study how data analytics and other techniques can be utilized to improve SIS performance management systems for unmanned facilities.

An advisory system (SIS Advisor) has been developed to support operator's decision in case of emergency as well as ordinary tasks such as normal operation or maintenance work. The SIS Advisor classifies current operating condition as normal or dangerous. The normal operating envelope is established by analyzing large amounts of historical operating data, using machine learning. The overall architecture and procedure for measuring the performance of SIS advisor was published and presented at ESREL 2021 conference.

In 2021, research activities were focused on following items:

- Literature survey on domain adaptation algorithm to overcome imbalanced data issue when applying data analytics.
- Building a K-SPICE (Dynamic process simulation system provided by Kongsberg Digital) model for experiment.
- Identifying various hazardous scenarios for simulation.
- Generation of data both from simulation and emulation.

During 2022, which is the final year for the project, implementation of a data analysis algorithm and validation of the solution will be performed.

3. INDUSTRY PARTICIPATION

Currently, Equinor and DNV are participating actively in this project, and collaboration is established with Kongsberg Digital on utilizing K-SPICE as a platform for model development. The license for K-SPICE was provided as an in-kind contribution for SUBPRO, and a basic training course for K-SPICE was also provided. K-SPICE plays a critical role in this research by generating simulation data and emulated field data of an oil and gas platform.

Moreover, to stimulate closer collaboration with industry partners in SUBPRO, two Tech-Lunch events were coordinated by inviting DNV and Kongsberg Digital. An open simulation platform and K-SPICE were introduced to NTNU students and professors for discussing how such products can be utilized in their research.

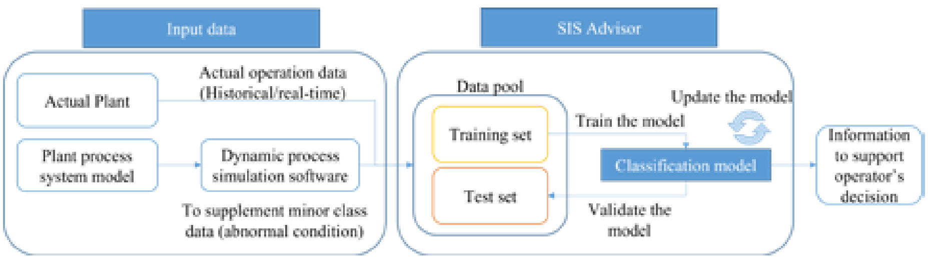


Figure 1. SIS Advisor framework

3.1.c Digital Twin for Safety Demonstrations During the Complete Life Cycle

A new method for safety demonstrations of safety-critical systems. The method will be evaluated on a case study of an all-electric control system.

Green shift impact: A shift to all-electric control system for subsea safety valves removes the need for hydraulic power systems in deep waters, and the risk of leaking hydraulic oil into the sea. This project may contribute to this shift, by improving the way safety demonstrations of novel systems are performed.

PhD student:
Ludvig Bjørklund

Project manager and main supervisor:
Professor
Mary Ann Lundteigen

Co-supervisors:
Adjunct Professor Gunleiv Skofteland (Equinor)
Professor Markus Glaser (Aalen University)

1. BACKGROUND

The shift from hydraulic-based actuation systems to all-electric would enable several benefits such as:

- CAPEX reduction (reduced umbilical cost, reduced system cost)
- Environmental impact (pollution free technology, no hydraulic power units)
- OPEX reduction (reduced maintenance, improved diagnostics)

The case study for this project is an all-electric control system that operates the safety valves in a X-mas tree, i.e., valves that are part of primary and secondary well barriers. Demonstrating the safety of the system is crucial. Research will be conducted to utilizing a digital twin for these safety demonstrations, to mitigate costs and effort.

2. RESEARCH ACTIVITIES AND DELIVERABLES

The digital twin mirrors the components and behavior we want to capture, e.g., the valve, the batteries etc., referred to in the Figure 1 as the Physical Asset. One major task of this research is to build the digital twin and additional modules to ensure sufficient coverage of the subsea valve(s) and the all-electric control system. A focus in 2021 has been defining an approach to construct the digital twin and the supporting modules to enable its utility throughout the physical asset's lifecycle. Figure 1 identifies three stages of how we envision this progression. In the left, the digital twin is modeled, based on, and validated against, the specifications of the physical asset. During the testing stage, the digital twin is interfaced with software modules, such as the control and diagnostics, to enable verification and validation of the functional safety. Experimental data and representations of reliability and degradation models are to be used to increase and optimize the coverage of the test cases and improve the accuracy of the digital twin. During operation stage the digital twin can be utilized for verification and validation of software updates. The digital twin is complemented by additional modules to generate tests and analyze the results.

In 2021 an article was presented at the 31st ESREL Conference, highlighting current realizations of virtual validation and verification of software reliant safety-critical systems. The collaboration with Professor Markus Glaser's research group in Aalen University has been active, including a research stay in Aalen from fall of 2021 and spring of 2022. The research stay aims to develop a strategy for interfacing software with a Digital Twin and a testing environment, involving expertise at Aalen University. This includes:

- Researching possibilities enabling co-simulation with selected subsystems modelled on field-programmable gate array (FPGA) boards with models running on the CPU.
- Interface capabilities for FPGA-in-the-loop

The planned deliverables are:

- A prototype Digital Twin that:
  - Includes all safety relevant components and captures the behavior of the all-electric control system
  - Provides a suitable interface to connect to hardware modules.
- An analysis of the suitability, challenges, and limitations of the approach.
- A methodology for safety demonstrations.

3. INDUSTRY PARTICIPATION

A collaboration has been established with Equinor. Further, in 2021 an introductory meeting with DNV was conducted, increasing the knowledge of current state of verification and validation of safety critical systems.

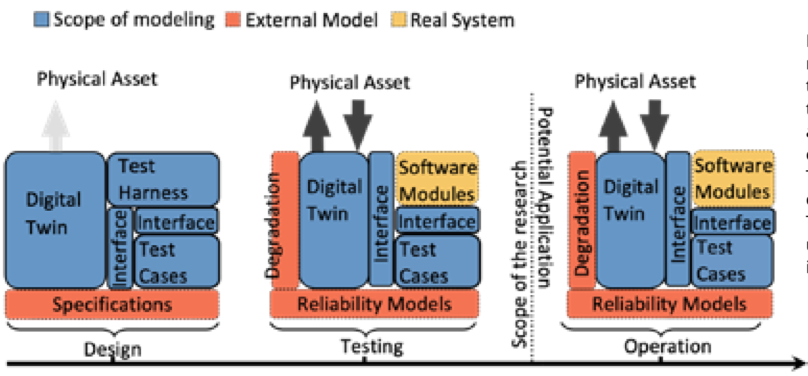


Figure 1: The illustration represents the utility of the Digital Twin during the phases of the physical asset's lifecycle, from design to operation. The blue blocks will be developed by the project. The dashed blocks will be utilized but not developed in the project.

3.1.d Digital Twin Qualification for maintenance

A new method to qualify and assure trustworthiness and performance of digital twins for maintenance.

Green shift impact: Digital twins for maintenance optimization may lead to reduced consumption of materials and transportation for maintenance, and hence contribute to reduced environmental footprints.

PhD student:
Jie Liu

Project manager and supervisor:
Professor Shen Yin

Co-supervisor:
Professor Jørn Vatn

1. BACKGROUND

This PhD project was proposed and supported during a Digital Twins seminar arranged by SUBPRO in November 2020. Digital twins are believed to play an important role in maintenance optimization and maintenance engineering, since they could continuously estimate the state and trend of process systems and help the optimization of maintenance plans. There are still some challenges to be met until digital twins may be implemented in the industry, such as ensuring the quality of models and assuring that the output from the models is continually trustable. DNV has published a Recommended Practice document "DNV-RP-A204 Qualification and assurance of digital twins" in 2020. The document gives a guideline to the designers and operators regarding the method and structure of qualification and assurance for digital twins. The document is a general instruction for a broad range of digital twins' applications, while digital twins for maintenance have their own specific properties different from other applications. Hence there is a need for a specialized method for qualification and assurance of such systems. Figure 1 shows the capability level for Digital Twin for maintenance [1].

There are three types/areas of maintenance models:

- Fault diagnosis
- Failure prognosis
- Maintenance planning/optimization

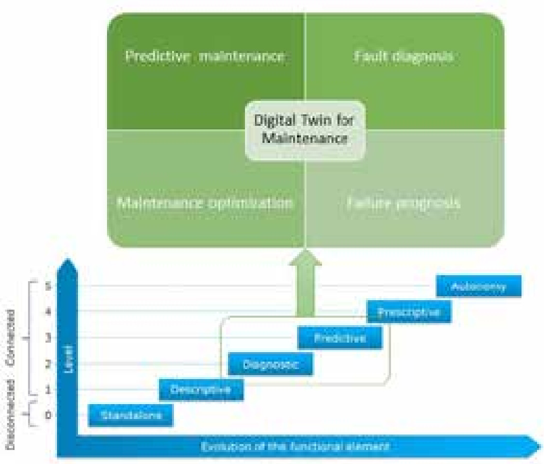


Figure 1: The capability level for Digital Twin for Maintenance [1]
Reference: [1] DNVGL-RP-A204. Qualification and assurance of digital twins. Recommended practice, DNV GL, October 2020.

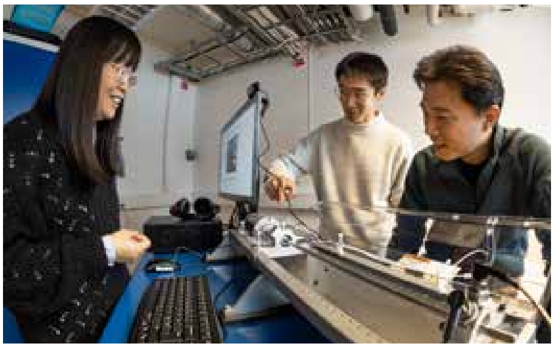


Figure 2. Test rig for condition monitoring of rotating equipment, used in PhD student Jie Liu's Master project, prior to the PhD project. From the left: PhD student Jie Liu, Postdoctoral fellow Xingheng Liu and PhD student Tae Hwan Lie.

All these models are designed based on probability theory, and the underlying algorithms for diagnosis and failure prediction are not visible to the user. Therefore, trustworthiness of the models is difficult to assess. The same goes for digital twins for maintenance which are based on such maintenance models. The purpose of the PhD project is to develop methods for qualification and assurance of digital twins for maintenance.

2. RESEARCH ACTIVITIES AND EXPECTED RESULTS

As a part of the PhD academic training, essential courses have been followed, such as System Resilience and Digital twins for sustainable manufacturing.

In addition, one paper has been prepared based on the candidate's master's thesis. The paper is a comparison study of prediction systems for remaining useful life of bearings. It compares standard stochastic approaches applied to digital twins created in Matlab with experimental data and discusses the advantages and disadvantages of the models.

In the continuation of the project, more assurance methods will be developed in the Matlab digital twin and tested to find efficient quality indicators for prediction of remaining useful life.

3. INDUSTRIAL PARTICIPATION AND USE OF RESULTS

The document published by DNV is the starting point for the PhD project. During the project, it is foreseen to cooperate with DNV and other industry partners who develop or use digital twins for maintenance, to discuss and verify the proposed methods and perform testing with field data.

3.3.c Prognostic health management for subsea systems

A new method for condition monitoring of choke valves.

Postdoctoral fellow:
Xingheng Liu

Project manager and supervisor:
Professor Jørn Vatn

1. BACKGROUND

Subsea systems are prone to degradation and failures since they are located in complex and harsh environments. Due to the inaccessibility, field inspections and maintenance on subsea systems are costly (often requiring replacement of whole subsea modules) and cannot be carried out without a certain delay. Thus, it is crucial to estimate a component's remaining useful life (RUL) with a specific confidence interval. By predicting the evolution of the component's degradation level over time, we can estimate the probable time to failure, thus offering a frame to support the decision-makers on whether or when to fix or replace a component or module.

2. RUL ESTIMATION FOR SUBSEA CHOKE VALVES

This project's first objective is to develop prototype simulators to estimate RUL for subsea choke valves that suffer from erosion due to sand production in mature fields. A health indicator of the erosion process is the difference between the initial (as new condition) and estimated actual *valve flow coefficients* (Cv), a relative measure of the efficiency to control the fluid flow. When the difference finally passes a predefined threshold, the choke cannot execute its function correctly and needs to be replaced.

3. MODEL ADVANTAGES

Unlike traditional models, which consider only the raw Cv deviation, our model takes into account the influences of the valve's operation process history, i.e., the records of valve openings. Based on least squares, it computes the Cv deviation curve's initial shape and accurately estimates the erosion rate at different valve openings. Most importantly, it reveals the "true" erosion state that can differ from the raw Cv measurement and gives alarms when the failure threshold is approached. The figure below presents a case study on the erosion data[1] of a fixed non-retrievable production choke. The orange points show the raw Cv deviation, which suggests that the erosion is far from the failure threshold. However, by using our model, we can include the effect of valve opening changes and estimate the "true" but hidden Cv deviation, as shown in blue. Clearly, the hidden Cv deviation in this valve is much closer to the failure threshold, and the corresponding RUL may be shorter than what the raw measurements suggest. Our model gives a more accurate estimation of the RUL, avoiding as much as possible false alarms and non-detection.

4. INDUSTRY PARTNER INVOLVMENT AND COLLABORATION WITHIN SUBPRO

The project is supported by Equinor, who provides field data and technical advice. Within SUBPRO, the RUL estimation is also the subject of the project "3.8.b Experimental validation of methods - Remaining Useful Life (RUL)" (José Octavio Assumpcao Matias), so I worked with Jose Matias to analyze choke valve erosion data collected from his experimental rig.

5. RESULTS AND DELIVERABLES

Last year we published one journal paper[2] and two conference papers[3,4]. This year, with the development of the new model, we intend to publish the results in two conferences. We will also deliver a toolbox for choke valve erosion estimation and RUL prediction for industry partners.

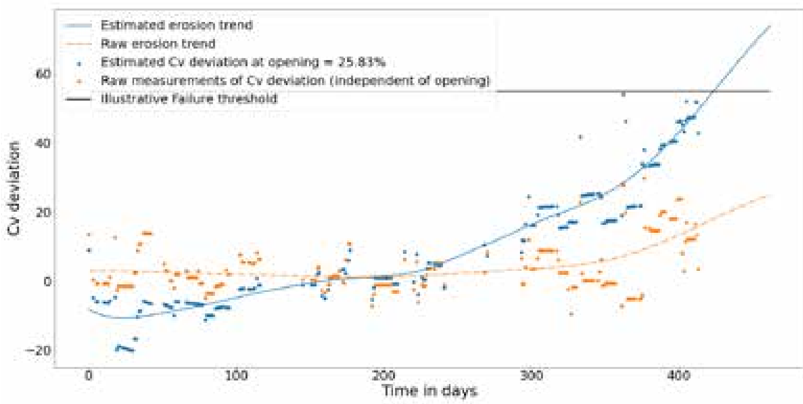


Figure 1: The raw Cv deviation measurements (in orange) and estimated hidden Cv deviation (in blue).
Data source: Equinor.

[1] Data source: Equinor; [2] X. Liu, J. Matias, J. Jäschke, J. Vatn, Gibbs sampler for noisy Transformed Gamma process: Inference and remaining useful life estimation. Reliability Engineering & System Safety, Volume 217, 2022; [3] X. Liu, J. Vatn, Filtering noisy Gamma degradation process: Genz transform versus Gibbs sampler. 31st European Safety and Reliability Conference; [4] X. Liu, A. Zhang, J. Vatn, Modeling subsea choke valve erosion with a production-driven shock-associated degradation process. The 11th International Conference on Quality, Reliability, Risk, Maintenance, and Safety Engineering.

Data-driven prognostics and health management in safety systems

Data-driven and machine learning modelling for condition assessment, diagnostics, and prognostics of safety systems.

An associated project to SUBPRO, financed by the Faculty of Engineering at NTNU, in connection with the DNV professoriate (Professor Shen Yin) at Department of Mechanical and Industrial Engineering.

Green shift impact: An accurate fault diagnosis and prognosis leads to better utilization of components, thus providing less energy and materials consumption.

PhD student:
Muhammad Gibran Alfarizi

Project manager and supervisor:
Professor Shen Yin

Co-supervisor:
Professor Jørn Vatn

1. BACKGROUND

Prognostics and health management (PHM) has emerged as an essential approach for preventing catastrophic failure and increasing system availability by reducing downtime, extending maintenance cycles, executing time repair actions, and lowering life-cycle costs. PHM helps companies reduce inspection and repair costs and thus achieve competitive advantages in the global market by improving system reliability, maintainability, safety, and affordability. In the era of Industry 4.0, a growing number of data is available for diagnosis and prognosis purposes.

Unlike model/signal-based diagnosis, which requires a priori known models or signal patterns, data-driven diagnosis starts with a large amount of available historical data. Enabled by advanced machine learning, data-driven diagnosis learns from data to determine correlations, establish patterns, and evaluate trends leading to failures. The intelligent learning from a massive amount of data distinguishes data-driven diagnosis from model and signal-based diagnosis. The latter methods only require a small amount of data for redundancy checking.

This project seeks to incorporate data-driven techniques, especially but not limited to machine learning for anomaly detection, diagnostics, and prognostics aspect of PHM.

2. RESEARCH ACTIVITIES AND DELIVERABLES

The research activities of this project include:

- Study the state-of-the-art machine learning for PHM and find the challenges of implementing machine learning for PHM in industrial cases.
- Develop machine learning-based approaches to be implemented in industrial cases (e.g. subsea systems, manufacturing systems).
- Apply the developed methods to a study case, which can be obtained from publicly available data and from a company, to demonstrate and validate the methods.

The expected deliverables from this project include:

- An analysis of the use of data-driven methods for improving the reliability of safety systems.
- Contribute to the development of data-driven workflow (e.g., digital twins) in the industry by utilizing the massive volume of data streaming from their systems and sensors.
- Perform study cases using data-driven methods in industrial cases to demonstrate and validate the developed methods.

So far, we have investigated the use of extreme gradient boosting for fault diagnosis of a manufacturing test bench. The research has shown the feasibility of using AI aided fault diagnosis for the safety of industrial systems. The study has been submitted to Journal IEEE Transactions on Artificial Intelligence.

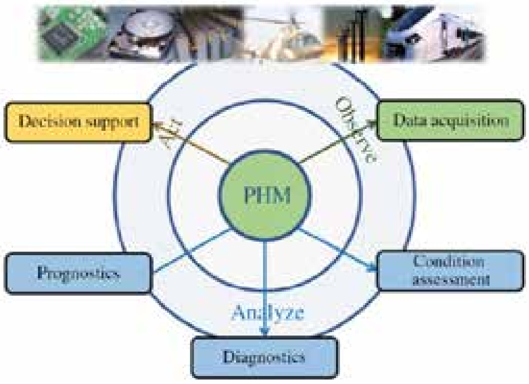


Figure 1. Framework for prognostics and health management.

3. INDUSTRY PARTICIPATION

A model to predict the remaining useful life of subsea choke valves using machine learning methods is in consideration and can be tested with data provided by the industrial partners, namely Equinor, DNV, and Lundin Energy Norway.

Results of this research can be used for decision support in the maintenance of subsea choke valves.

Results from the project have been presented at the bi-annual Reference group meetings for Field Architecture and RAMS in SUBPRO.

Ensuring functional safety of novel technologies

An alternative method to demonstrate safety of novel subsea technologies.

A spin-off project under Safety 4.0 – Demonstrating safety of novel subsea technologies. (http://www.dnv.com/research/oil-gas/safety40/)

PhD student:	**Nanda Anugrah Zikrullah**
Start date:	16.08.2018
Thesis defense date:	24.02.2022
Title of thesis:	Developing framework for novel subsea concepts and technologies
Title of trial lecture	"The role of digital twins in partial and complete integration of control and safety systems"
Thesis committee members:	Professor Faisal Kahn (Memorial University of Newfoundland, Canada) Professor Mitra Fouladirad (University of Marseille, France) Professor Shen Yin (NTNU, Norway) Professor Jørn Vatn (NTNU, Norway)
Supervisors:	Professor Mary Ann Lundteigen (NTNU, Norway) Functional Safety Researcher Meine J.P. van der Meulen (DNV, Norway) Associate Professor HyungJu Kim (USN, Norway)
Project manager:	Senior Principal Researcher Tore Myhrvold (DNV, Norway)

1. BACKGROUND FOR THE PROJECT

Cost savings, increased production efficiency, challenging environmental conditions (water depth pressure and temperature), and accessibility are some of the recurring subsea challenges when developing new or existing fields. Hence, they drive the emergence of novel subsea technologies that can tackle the challenge above more efficiently. The introduction of such novel concepts, however, also introduces uncertainty around the consequences of the activity (i.e., risk). The risk may affect either the financial aspects, environment or safety, as there is no or limited experience about the performance. This would be problematic for the industry, as several accidents have occurred in the past years, e.g., Philadelphia refinery explosion (2019), Deepwater horizon (2010), and Texas city refinery explosion (2005). Due to this, safety represents one of the critical properties of many novel systems. It is vital to demonstrate that the novel technology would behave as intended. Unfortunately, the current safety demonstration process is inefficient due to the lack of support from relevant standards and regulations.

2. WHAT I HAVE DONE

The objective of this project has been to develop and demonstrate the application of new safety assessment methods within the scope of functional safety, which can capture and manage the complex operational behavior of novel software-intensive systems. The methods should account for the characteristic of a novel subsea system 'integration of process control and safety' (see Figure 1), based on the safety assessment process identified in the functional safety standards. We have addressed five research topics, as follows:

- **Topic I -- Safe design principles.**

  This study clarifies several safe design principles that are derived from the design approaches in different industries. It is found that the governing functional safety standard, IEC 61508, is aligned with the safe design principles. These principles have been applied to the study case. The implication is that some processes need to be adapted for novel technology involving software-intensive systems with complex operational behaviors.

- **Topic II -- Solution-specific safety requirements.**

  Solution-specific refers to the actual technical solutions developed in a project. Two hazard analysis approaches that are often considered well suited for hazard analysis of novel technology, i.e., functional hazard analysis (FHA) and systems-theoretic process analysis (STPA) have been compared. The study investigates the characteristics of both methods in more detail by performing study cases on an equipment protection system in subsea processing applications. It is concluded that STPA is more suitable based on various factors, including the method's approach, modelling coverage, and analysis capability. The study also provides recommendations for the improvement of both methods.

- **Topic III -- Alternative integration concepts.**

  The study proposes a new classification method to distinguish different levels of integration within a subsea safety system, from complete independence to complete integration. STPA is then performed several

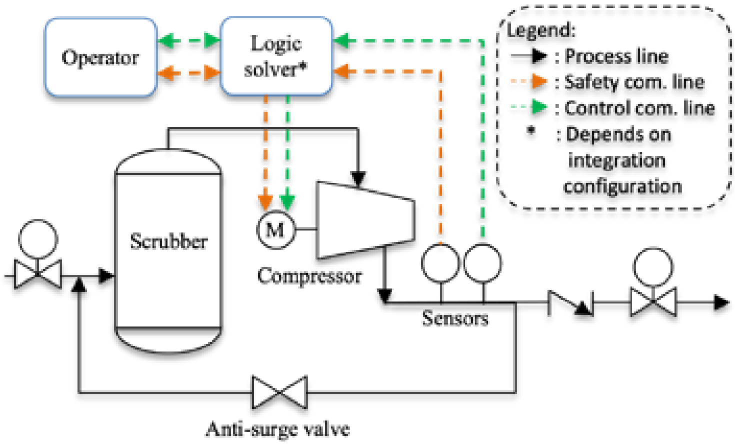


Figure 1: Study case - A subsea gas compression system with integration between process control and safety instrumented systems at the logic solvers.

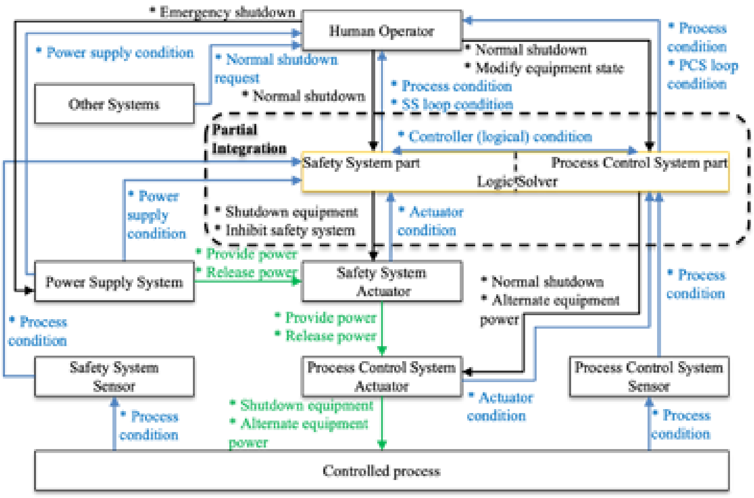


Figure 2: A hierarchical control structure model for a subsea gas compression system with complete integration at the logic solvers. (black color: control action; blue color: feedback; green color: power supply)

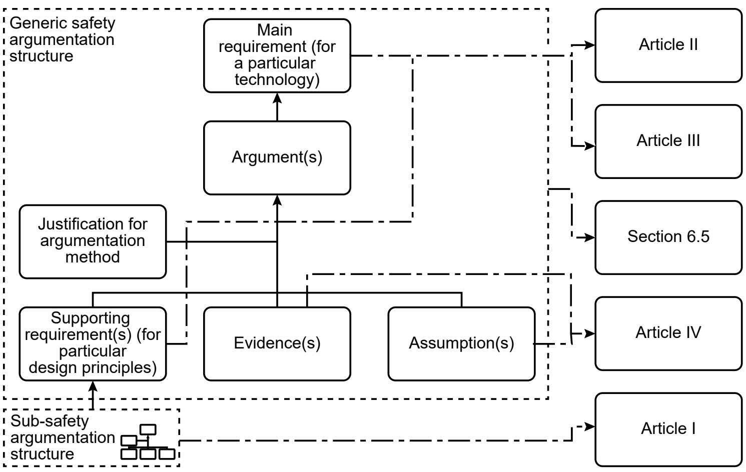


Figure 3: Overview of contribution on the safety argumentation concept.

times on systems with different levels of integration at the logic solver. The study also proposes a modelling technique in STPA to capture the different integration types (see Figure 2). The result found that integration does not necessarily change the system's functionality, but it may introduce new interactions leading to hazards. Nevertheless, the magnitude of risk for the hazard is unknown.

- **Topic IV -- Effect on risk.**

  The study proposes a modelling pattern to quantify the hazardous scenarios' frequency. A text-based finite-state automata modelling pattern implemented in Altarica 3.0 has been developed. The capability of this approach is demonstrated by performing a study case on the STPA results from the topic III study. It is found that the method is capable of capturing dependencies while also highlighting the inefficiency of STPA caused by unnecessary requirement productions. The study also discusses the method's limitation when compared with other quantification processes recommended in the standards.

- **Topic V -- Safety argumentation.**

  This topic summarizes all the preceding results to clarify the link between the developed methods and approaches with the safety argumentation concept for novel technology (Figure 3). The concept is based on an argument-induced evidence model. While the PhD work does not cover all aspects of the safety argumentation concept, this PhD highlights the current state of the research and the required further work to build a complete safety demonstration framework for novel technology.

3. MAIN RESULTS

The overall implications of the framework and methods developed in the PhD project are that the engineers or analysts now have more knowledge and an improved set of resources to carry out safety demonstrations of novel technology involving software-intensive systems. The overall development process for the framework has been explained in the thesis and scrutinized through a systematic peer review process. The work also serves as an input for the ongoing joint industry research project Safety 4.0, which aims to enable and accelerate the uptake of novel subsea solutions by developing a standardized safety demonstration framework.

4. INNOVATION PROJECT
I have performed a three-months Innovation Project, financed by SUBPRO, with title "Industrialization of novel functional safety assessment method". This Innovation Project intends to make the results from the PhD work more easily available to the industry participants in both SFI SUBPRO and Safety 4.0 by transferring knowledge developed in the PhD project into practical use. This has been done by developing a technical report for guidelines of novel Risk Analysis methods developed in the PhD project and by arranging a workshop for transfer of knowledge from the project to the industry partners. The technical report is accessible for SUBPRO and Safety 4.0 partners.

5. FURTHER WORK
The following future research directions have been proposed, based on the scope and limitation of the framework developed in this project:

- **Generic application of the framework**

  The framework for the safety demonstration process is developed with the use cases from the subsea oil and gas industry. Theoretically, the proposed framework could still work for other safe design principles. However, this has not been proven. Therefore, for future work, a pilot study on other systems with different characteristics would be useful to verify and validate the proposed framework.

- **Uncertainty management of the results**

  All hazard analysis methods, including STPA, are performed based on the current contextual assumption. Hence, there is a risk for unknown unknowns due to uncertainty in the assumptions and the system's modification. There is a need to investigate a method for managing uncertainty in the hazard analysis results, e.g., identifying the risk of deviations in the assumptions.

- **Management of software and systematic safety integrity**

  The software and systematic safety integrity aspects for the complex systems have not been covered during this PhD project due to limited technical details and the starting point of the research, which is from a high-level perspective. It would be necessary to have the actual technology, not just a concept, to propose a tailored method for verifying the safety of the complex system.

- **Testing of the safety argumentation concept**

  It is known that a safety argument typically ends in a large safety argumentation model with interdependencies in the evidence, assumptions, and sub-structures. When the systems become too large, the network in the structure becomes complex, leading to difficulty in checking the consistency of the structure. A pilot study is required to identify the new problems caused by this complex structure.

6. COMPLETE LIST OF PUBLICATIONS AND REPORTS
Articles (conference & journal):

a. N. A. Zikrullah, H. Kim, M. J. P. van der Meulen, M. A. Lundteigen, Clarifying implementation of safe design principles in IEC61508: Challenges of novel subsea technology development, in: Proceedings of the 29th European Safety and Reliability Conference (ESREL), Research Publishing, 2019, pp. 2928–2936.

b. N. A. Zikrullah, H. Kim, M. J. P. van der Meulen, G. Skofteland, M. A. Lundteigen, A comparison of hazard analysis methods capability for safety requirements generation, Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability. 2021, 1748006X211003463.

c. N. A. Zikrullah, M. J. P. van der Meulen, G. Skofteland, M. A. Lundteigen, A comparison of hazardous scenarios in architectures with different integration types, in: Proceedings of the 30th European Safety and Reliability Conference and the 15th Probabilistic Safety Assessment and Management Conference (ESREL 2020 PSAM15), Research Publishing Services, 2020, pp. 4001–4008.

d. N. A. Zikrullah, M. J. P. van der Meulen, M. A. Lundteigen, Finite-state automata modeling pattern of systems-theoretic process analysis results, Reliability Engineering \& System Safety. (n.d.), under review.

Datasets (analysis results and software codes):

e. N. A. Zikrullah, M. J. P. van der Meulen, G. Skofteland. M. A. Lundteigen, "Systems-Theoretic Process Analysis results for system with different integration types", Mendeley Data, V1, (2021), DOI: 10.17632/prwtzmt3kg.1

g. N. A. Zikrullah, M. J. P. van der Meulen, M. A. Lundteigen, Systems-theoretic process analysis - finite state automata (STPA-FSA) modeling approach source code, Mendeley Data V1, (2021), DOI: 10.17632/39g8ywjc7j.1.

Technical reports (internal):

h. N. A. Zikrullah, Risk analysis with Systems-Theoretic Process Analysis, Technical Report from the Innovation project, (2021).

7. MY NEW JOB
Company/institution: DNV
Position/area of work: Functional Safety Consultant

PROFESSOR
GISLE ØYE

RESEARCH AREA MANAGER

RESEARCH AREA

Separation – Fluid characterization

Enhancement of separation efficiency and flow assurance.

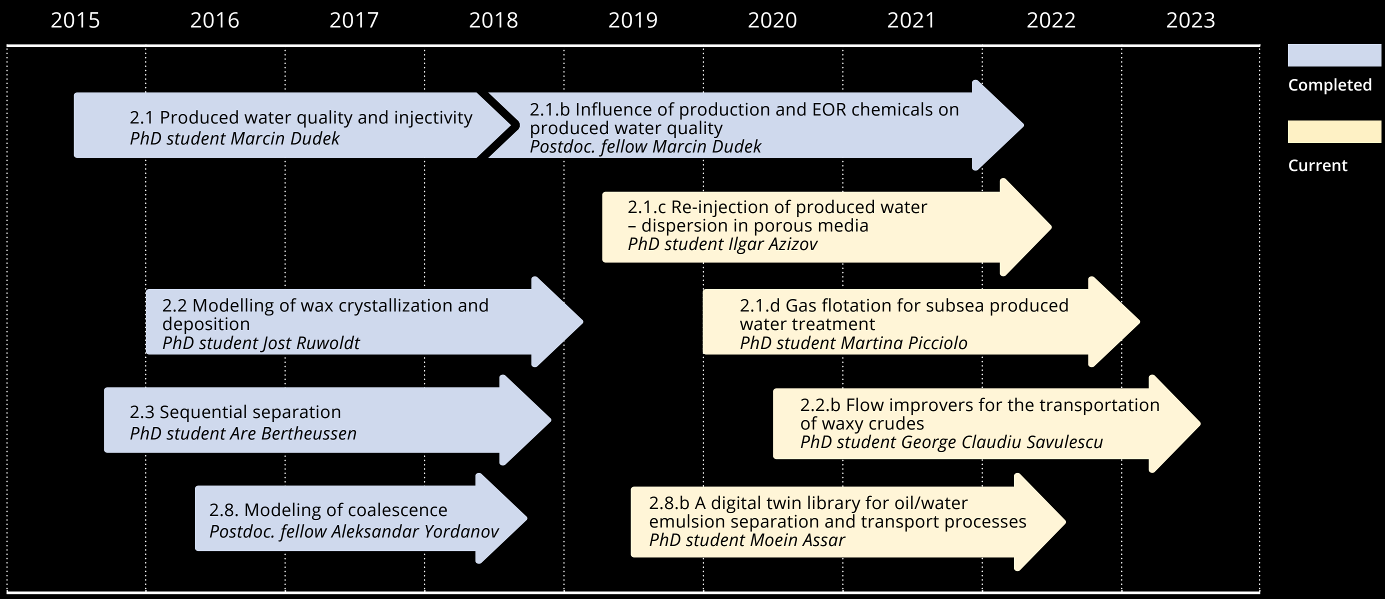
Successful subsea installations require high efficiency and minimal maintenance need of the processing equipment. This means that the behavior of the fluids must be well understood. Efficient separation of gas, oil and water and reliable transport of the hydrocarbons are central for optimization of subsea 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.

There were five ongoing projects within this area in 2021, see the overview of completed and current projects.

The project "Influence of production and EOR chemicals on produced water quality" was finished in the first quarter of 2022.

For description of individual projects: See input from Marcin Dudek, Ilgar Azizov, Martina Piccioli, George-Claudiu Savulescu and Moein Assar on the following pages.

Completed and current projects



The Separation - Fluid characterization team
From the left: PhD student Moein Assar, Dr. Sebastien Charles Simon, Professor Gisle Øye, PhD student George Claudiu Savulescu and PhD student Ilgar Azizov. Professor Magne Hillestad, Associate Professor Brian A. Grimes, Postdoctoral fellow Marcin Dudek and PhD student Martina Piccioli were not present when the picture was taken.

2.1.c Re-injection of produced water - dispersions in porous media

A new methodology for understanding of transport and retention phenomenon

Green shift impact: Cleaner oil and gas production by minimizing discharges of produced water.

PhD student:
Ilgar Azizov

Project manager and main supervisor:
Professor Gisle Øye

Co-supervisor:
Postdoctoral fellow
Marcin Dudek

1. BACKGROUND FOR THE PROJECT

Petroleum production yields large volumes of produced water (PW), which contains toxic components, e.g., crude oil, dissolved organics, etc. which might cause pollution if disposed to the sea. Produced water re-injection (PWRI) is an environmentally sound way of produced water management. PWRI is often considered to be the base case for new fields as regulations concerning the discharge of PW become stricter.

The limitation for PWRI is that the injectivity declines due to pore clogging in the reservoir by oil droplets and particles present in PW. To date, the retention phenomenon is not completely understood, although numerous studies are reported. The main reason is the inability of experimental techniques utilized (typically core-flooding) in the literature to visualize pore-scale events, leaving a number of gaps in the knowledge. Methods such as X-ray imaging would elucidate this matter; however, they are more expensive and complex to employ.

2. A MICROFLUIDICS METHOD DIMINISHING EXISTING GAPS

Microfluidics is a field of science that studies transport and manipulation phenomena of fluids in confined microchannels. In contrast to core-flooding, microfluidics allows visualization (imaging) of fluids at a pore-scale at a reasonable cost. The objectives of the project are the development of a microfluidic method and experimental investigation of the gaps found in the literature, to understand the factors influencing capture of droplets and particles in porous media.

3. ACTIVITIES, RESULTS AND INDUSTRY PARTICIPATION

Equinor showed interest in the project and contributed through several mentoring sessions helping to structure the project and identify the industry interests. To date, the project resulted in several peer-reviewed journal publications [1][2][3] and several conference/workshop presentations to share the results with the industry and academia. Firstly, a literature review was performed to identify and reflect on the gaps in the knowledge [1].

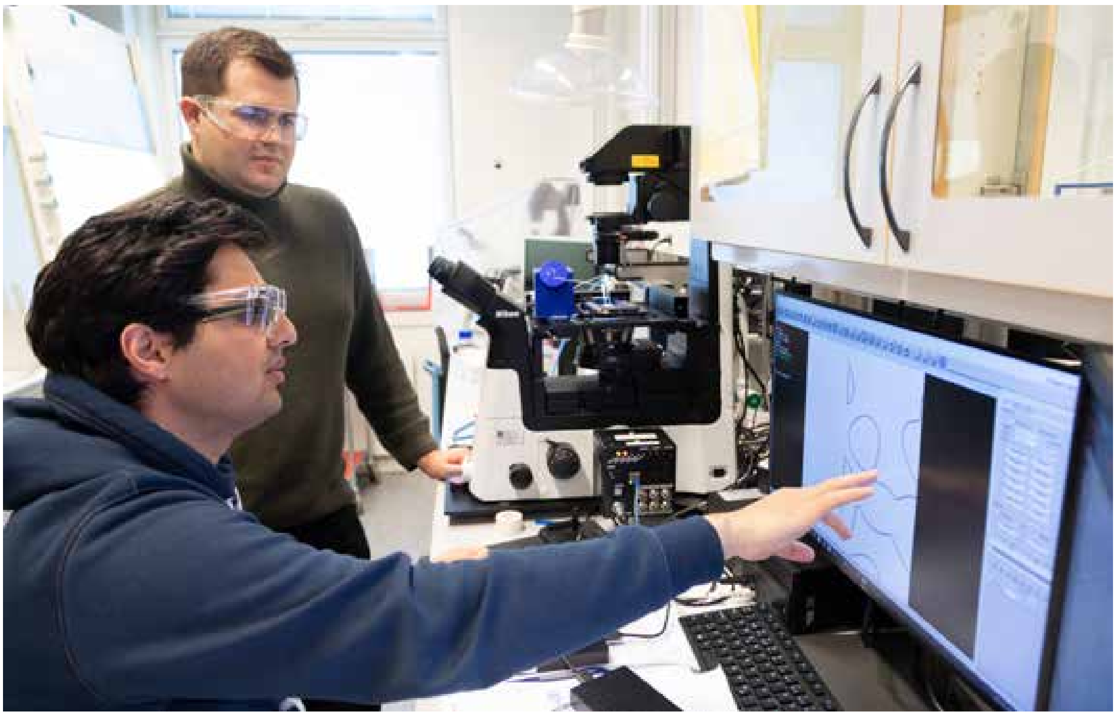


Figure 1: Microfluidic laboratory for studying capture of droplets and particles in porous media.
In the foreground; PhD student Ilgar Azizov. Behind, PhD student George Claudiu Savulescu

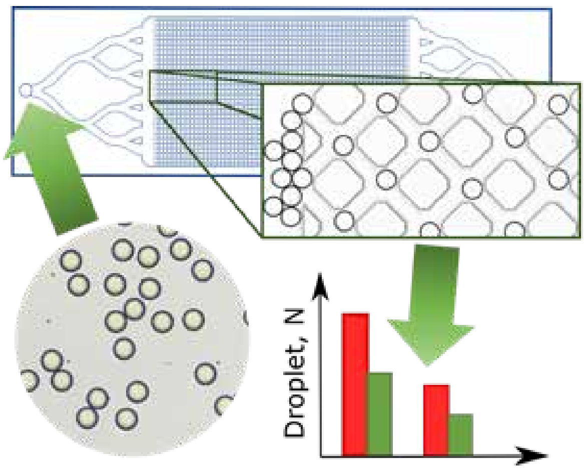
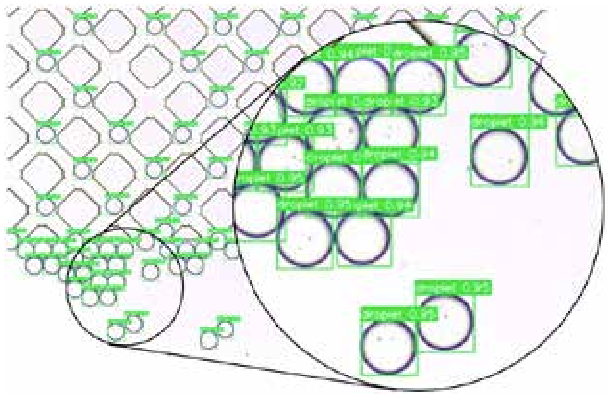


Figure 2. A graphical summary of the developed microfluidic method:

a) Mono- or polydisperse emulsion is injected into a microfluidic pore network, the flow and retention of droplets is imaged, and the images are processed to obtain quantitative data.



b) The images are processed utilizing a deep learning model for detection of objects, herein droplets, on images.

The review paper summarized physical and physicochemical parameters that can affect retention of droplets, examined the gaps, and provided an outlook on the future studies. Secondly, a microfluidics method that allows systematic studies of transport of mono- and tailored polydisperse emulsions was developed and utilized to investigate physical parameters influencing the capture [2].

The results from the experiments showed that the droplet size has a dramatic effect on the pore clogging. Droplets that are larger than pore throats underwent complete retention, while droplets that are smaller than pore throats showed little to no retention in the monodisperse emulsion experiments. Additionally, the experiments with polydisperse emulsions showed that the larger droplets are facilitators for the retention of the smaller droplets. The summary of the method is visualized in Figure 2a. The reader is referred to the paper [2] for more detailed information. Additionally, state of the art pipeline for image analysis was developed to analyze the data/images obtained using the microfluidic method (Figure 2b) [3]. The approach utilizes open-source computer vision libraries employing AI for image analysis.

4. POTENTIAL APPLICATION OF RESULTS

Understanding the parameters affecting the retention is essential to obtain models of injectivity decline and define injection water specifications. It is expected that addressing the gaps in the knowledge will 1) help to improve the existing models and increase their effectiveness; 2) help the industry to define more effective injection water specifications. The project is built on the microfluidics competence developed in SUBPRO project 2.1 – "Produced water quality and injectivity" (Marcin Dudek). New microfluidic methodology will extend our existing microfluidics toolbox and provide foundation for future studies.

5. PUBLICATIONS

[1] Azizov, Ilgar; Dudek, Marcin; Øye, Gisle. (2021). Journal of Petroleum Science and Engineering, vol. 206, 109057

[2] Azizov, Ilgar; Dudek, Marcin; Øye, Gisle. (2022). Chemical Engineering Science, vol. 248, Part A, 117152

[3] Rutkowski, Gregory Philip; Azizov, Ilgar; Unmann, Evan; Dudek, Marcin; Grimes, Brian Arthur. (2022). Machine Learning with Applications, vol. 7. 100222

2.1.d Gas flotation for subsea produced water treatment

The conditions at the seabed level can improve the oil removal efficiency.

Green shift impact: Seabed water treatment can reduce the environmental footprint and optimize the production.

PhD student:
Martina Piccioli

Project manager and main supervisor:
Professor Gisle Øye

Co-Supervisors:
Postdoctoral fellow
Marcin Dudek
Svein Viggo Aanesen
(Equinor)

1. BACKGROUND OF THE PROJECT

Gas flotation is a separation technique used in the upstream petroleum processing to reduce oil and solid particles concentration in produced water (PW). It relies on the dispersion or nucleation of gas bubbles in the water phase and their attachment to oil droplets or solid particles, which makes them rise faster. Nowadays significant attention is given to subsea produced water treatment, and gas flotation is considered a strong candidate. Moreover, due to the lower energy required to pump the produced water to the topside platform level, subsea produced water treatment can result in a substantial decrease of CO2 emissions.

At the seabed level, the process is performed at high ambient pressures and different temperatures, influencing the fluid behavior. The literature review revealed several gaps when it comes to: (i) performance of gas flotation at high pressure (ii) design of the subsea equipment for gas flotation (iii) understanding the microscopic phenomena involved in the process.

The aim of this project is to provide new experimental methods and data that the industry can benefit from and apply to develop subsea gas flotation technology.

2. EXPERIMENTAL METHODS

1. **High-pressure gas flotation set-up**
   Experiments regarding the oil removal efficiencies at the expected seabed conditions (e.g. high pressure and high temperature) are performed with a high-pressure rig at the Ugelstad lab. The flotation rig (Figure 1) has undergone some modifications that include: installation of pressure transducer (PT) and a temperature transmitter (TT) and a new design for the base of the cell. The rig can accommodate conditions up to 80 bar and 80°C.

2. **Microfluidics**
   Microfluidics is a newly developed method that enables the study of fundamental aspects of dispersions at capillary level. With this technique it is possible to follow the entire coalescence event, from when the oil droplet and the gas bubble encounter, to when the oil spreads over the gas bubble (Figure 2). Microfluidics methods to study attachment efficiency and drainage time have been developed at Ugelstad lab at NTNU, in order to combine microfluidic data and results from gas flotation experiments. This combination may allow to understand whether microfluidic data can give information about larger scale processes.

3. INDUSTRIAL PARTICIPATION

The project is performed in collaboration with Equinor, and one of the co-supervisors is employed in Equinor. Moreover, Aker Solutions has expressed interest in following the development of this project. The industry partners have committed to delivering crude oil samples for experiments.

4. COLLABORATION WITH OTHER SUBPRO PROJECTS

This project is closely related to two other SUBPRO projects:

- **2.1.b Influence of production chemicals and EOR chemicals on produced water quality** (Marcin Dudek). In this project a microfluidic methodology to study gas flotation was established and it will be used for several experiments in the current PhD project.

- **2.1.c Re-injection of produced water – dispersion in porous media** (Ilgar Azizov). This project and the current project are closely related to each other, since the efficiency of water treatment process is crucial for produced water re-injection as the success of the injection operations is dependent on the injected water quality.

5. PROJECT RESULTS

With the renovated set-up, gravity separation and gas flotation experiments could start. The focus is to understand the effect of pressure on the separation. Some initial results showed that increasing the pressure may increase the separation efficiency. In figure 3 it is possible to observe the effect of pressure on droplets coalescence when working at 2 and 20 bar. From the picture it is clear that at 20 bar there is much less oil left in the water.

A microfluidic method to study the drainage time has been established recently, and experiments just started.

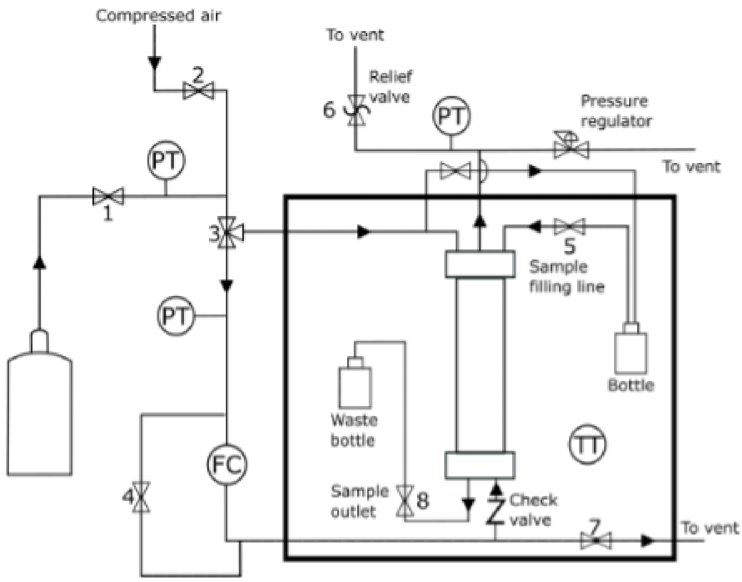


Figure 1: High-pressure rig in operation at Ugelstad lab at NTNU

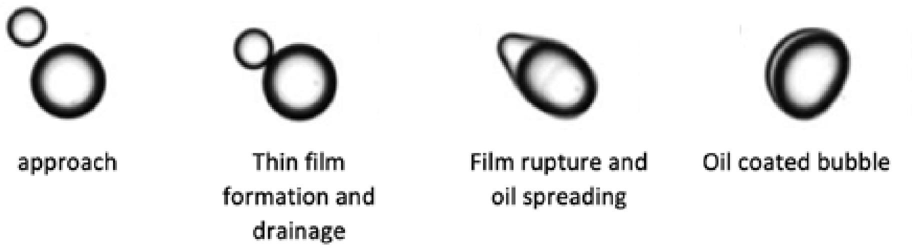


Figure 2: Drop-bubble interaction stages as observed in the microfluidic test rig.

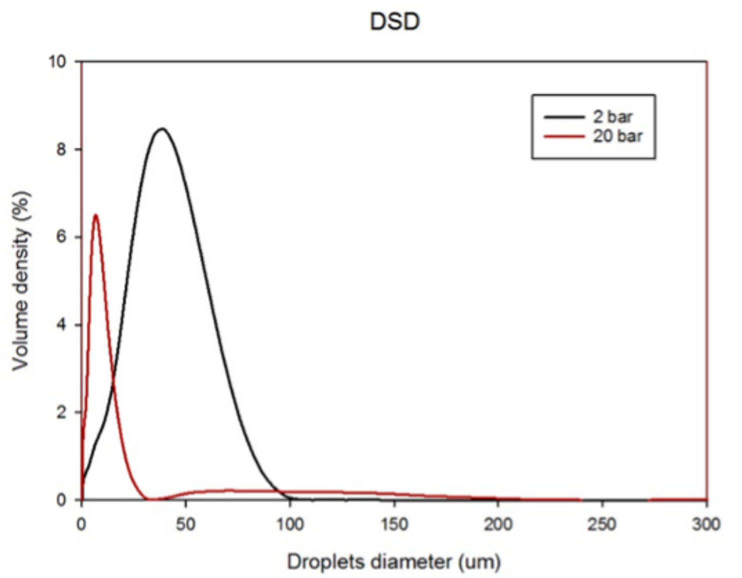


Figure 3: Oil droplets size distribution (DSD) of samples pressurized at 2 and 20 bar, from experiments with the test rig in Figure 1.

2.2.b Flow improvers for the transportation of waxy crudes

Understanding the interactions between wax inhibitor and waxes to improve the treatment of waxy oils

Phd student:
George-Claudiu Savulescu

Project manager and main supervisor:
Professor Gisle Øye

Co-supervisors:
Dr. Sébastien Simon
Professor Geir Humborstad Sørland

1. BACKGROUND FOR THE PROJECT
One of the current trends in oil industry is to extract oils in subsea conditions in harsher conditions such as very cold environments. This brings extra challenges for the transportation and processing of oil since waxes can crystallize and deposit at low temperatures leading to decreased productivity. The consequences of wax crystallization can be mitigated by the addition of pour point depressants (PPDs), which lower the temperature at which the waxy oil loses its ability to flow freely. However, there are still high uncertainties regarding their exact behavior and inhibitors must be tailored on a case-to-case basis. This project, which started in autumn 2020, is the continuation of the activities performed in the project "2.2 Modelling of wax crystallization and deposition" (Jost Ruwoldt). We are currently developing and implementing new techniques and procedures to characterize and quantify the interactions between waxes, crude oil components (asphaltenes), and wax inhibitors to understand the complex interactions in waxy crude oils and how PPDs work.

2. EXPERIMENTAL APPROACH
The activities are divided in 2 parts:

- The first part focuses on research using nuclear magnetic resonance (NMR) to study the effect of asphaltenes and PPDs on the interactions between the crystal network and the dissolved species, alongside with the wax precipitation evolution with temperature. The study starts from the analysis of model systems and gradually progresses towards real systems.
- The second part involves atomic force microscopy (AFM) investigations of the interactions between wax crystals and inhibitors in solvent or crude oil environment at nanoscale level.

Equinor is collaborating with the project by providing selected samples for the PhD project

3. MAIN RESULTS
The methods and conclusions drawn in the project are expected to allow design and choice of more efficient wax inhibitors as well as reducing the empirical aspect of the choice of an inhibitor for a specific oil. So far, improved low field nuclear magnetic resonance (NMR) methods have been developed to focus on the following determinations:

- Insights about the mobility of the wax molecules with the temperature. As a wax crystal network forms at low temperature due to wax precipitation, dissolved wax molecules display a reduction in mobility, as they become trapped in the pores and interact with the species of solids in the crystal network (Figure 1). The amount of wax crystals trapped in the wax crystal network was relatively quantified, and thus, the effect of PPDs and asphaltenes on such interactions has been investigated.
- Measurements of wax precipitation curves using 2 different NMR approaches and a comparison of the new methods with differential scanning calorimetry (DSC). The methods have started from model wax-solvent systems and progressed towards crude oil systems (Figure 2).

4. OUTLOOK
AFM is a technique that will be used intensively in the project. Contacts have been taken in 2021 and a 3-month research visit at TU Eindhoven in the Netherlands is expected in summer 2022, under the supervision of Professor Maja Rucker. During this visit, I will obtain the training to perform AFM on wax surfaces with asphaltene and PPD-coated AFM tips in a liquid environment, starting from a model solvent system and gradually moving towards a crude oil system. After this training is acquired, AFM research will be continued in the Nanolab at NTNU in the last 2 months of 2022 and in 2023.

5. POTENTIAL APPLICATIONS OF THE RESULTS, TRANSFER OF KNOWLEDGE TO INDUSTRY
This project aims to develop a standardized method with NMR to quantify wax precipitation evolution with temperature. Understanding the effect of PPD and asphaltenes on wax crystallization at the molecular level by investigating interactions could also facilitate the tailoring of a suitable inhibitor in specific industrial circumstances. Transfer to the industry will be performed both through scientific articles and presentations.

6. PUBLICATIONS
(1) Savulescu, G. C.; Simon, S.; Sørland, G.; Øye, G. New Nuclear Magnetic Resonance Approaches on the Evolution of Wax Mobility during Wax Crystallization. *Energy & Fuels* 2022, 36 (1), 350–360. https://doi.org/10.1021/acs.energyfuels.1c03613.

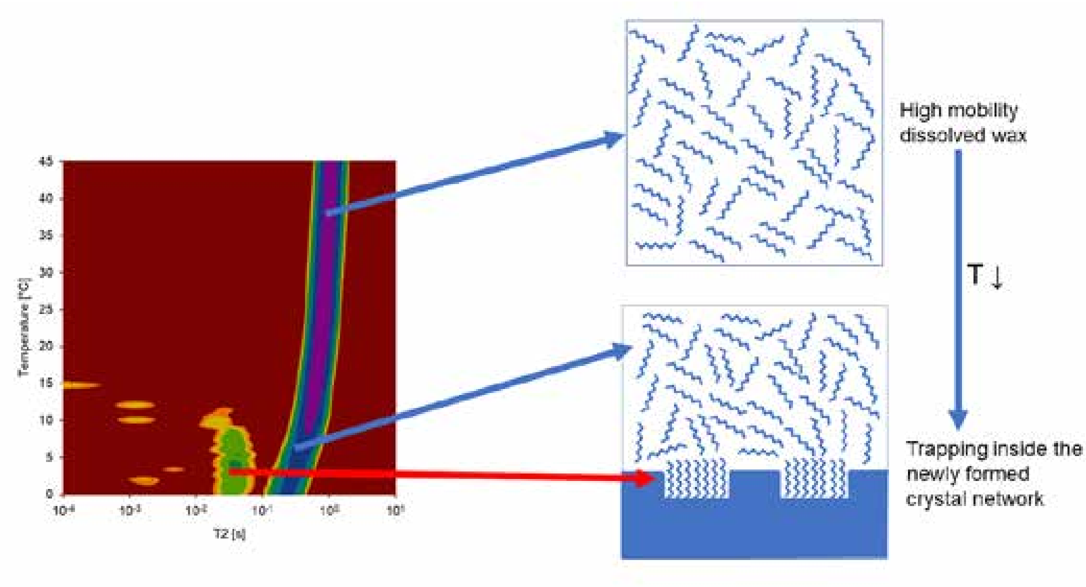


Figure 1 presents a low field NMR relaxation time T2 distribution for a sample containing 5% wax in deuterated toluene. T2 provides information about the mobility of liquid molecules in solution: the higher the T2 is, the higher the mobility is. Firstly, the right side peak at T2=0.1-1s shows the wax dissolved in liquid. It broadens and decreases in T2 as the wax starts to precipitate at temperatures below 20 degrees Celsius and thus has decreases in mobility. Therefore, by quantifying the intensity of the this right side peak, one can directly determine the wax precipitation evolution with temperature. Secondly, the low T2 side peak at T2=0.01s below 20 degrees Celsius reflects a low mobility area, corresponding to dissolved wax molecules trapped in the newly-formed wax crystal network. The new method created in this project allows to quantify this area and assess the impact of inhibitors on wax mobility during crystallization.

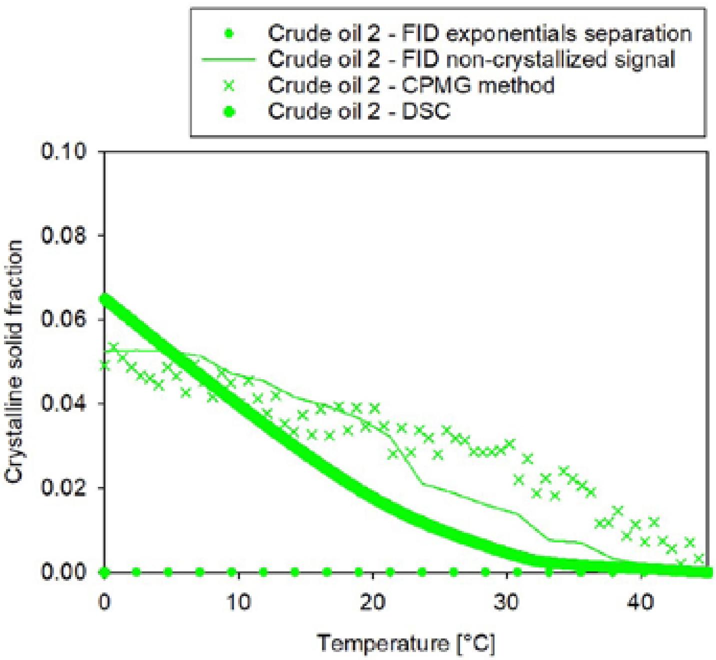


Figure 2 presents the evolution of the solid fraction of a selected crude oil, determined by 3 methods: Two NMR methods developed during this project (FID and CPMG) and one more established method (DSC-differential scanning calorimetry). The DSC method validates NMR results, as a similar crystallization pattern can be observed.

2.8.b A digital twin library for oil/water emulsion separation and transport processes

A portable and modular library based on population balance models for design, optimization, and control of crude oil / produced water processes.

Green shift impact: The model library can be utilized to optimize the produced water treatment processes, leading to cleaner disposal to the environment

Phd student:
Moein Assar

Project manager and main supervisor:
Associate Professor Brian Arthur Grimes

Co-supervisors:
Professor
Magne Hillestad
Adjunct Professor
Audun Faanes

(Equinor)

1. BACKGROUND

The separation and transport of multiphase fluids, in the form of crude oil and water emulsions, is an economically and environmentally crucial process in the petroleum industry. Consequently, the development of fundamentally advanced, yet simply implemented, models for separation and transport of multiphase fluids, on the one hand, would be a valuable tool for process and system engineers tasked with developing, controlling, and optimizing subsea transport and separation processes.

On the other hand, these models can allow researchers in industry and academia to utilize the results of particle coalescence and breakage studies for estimation of model parameters without having to construct advanced models themselves.

2. DEVELOPMENT OF THE MODEL LIBRARY

A major factor affecting multiphase separation and transportation is the size distribution of the droplets in the multiphase flow, since the settling time for particles is dependent on the particle size. Population balance models (PBE) provide a theoretical framework to model multiphase fluid by applying fundamental advances of particle coalescence and breakage modeling in form of droplet size distributions. According to the level of complexity in them as well as physics involved, these models are solved for dynamic droplet size evolution in 0, 1, and 2 spatial dimensions. Consequently, the library structure has been arranged according to these three types of models which can cover wide applications ranging from pipe multi-phase flow to batch settler/ skimmer and 3-phase separator. In this approach, these modules can be connected in different arrangements to model more complex processes providing a modular simulation capability for library users.

The computational core of the library is programmed in C++ facilitating a modular design and development using C++ powerful object-oriented features together with its memory handling and existing numerical libraries which ensure fast calculation speeds on modern computational platforms.

Another unique feature of this model library is the portability across computational platforms that has been envisaged. It will allow the PBE models to be readily incorporated in common general-purpose or specialized simulation software packages such as MATLAB, Python and HYSYS.

3. A NEW INSIGHT TO MODEL GRAVITATIONAL SEPARATION AND DENSE PACKED LAYER

Theoretically, gravitational separation processes are affected by binary coalescence of the droplets, hindered settling/rising of the droplets, and interfacial coalescence. Despite the simplicity of the related physical phenomena, there are still no generally accepted mathematical models in the literature. One of the main challenges in modeling efforts is the lack of a proper description for the interfacial coalescence phenomenon as well as a conservative model to follow the physical restriction posed at dense packed layer. In this project, the hinderance of the droplets by surrounding droplets is described as an axial dispersion phenomenon in the system. By considering the advection, dispersion and binary coalescence, a novel model is developed in the form of a population balance equation.

The other considered phenomenon in the model is the physical restriction due to dense packing where settling/ rising droplets cannot enter a region with a specific volume fraction (typically 0.85). Mathematically, this phenomenon can be described by infinite diffusion where all excess droplets will immediately diffuse back to the surrounding region with a lower volume fraction. The developed model shows immense promise to model industrial gravitational separation processes, as in contrary with other existing models, it always predicts the volume fraction between zero and that of dense packed layer.

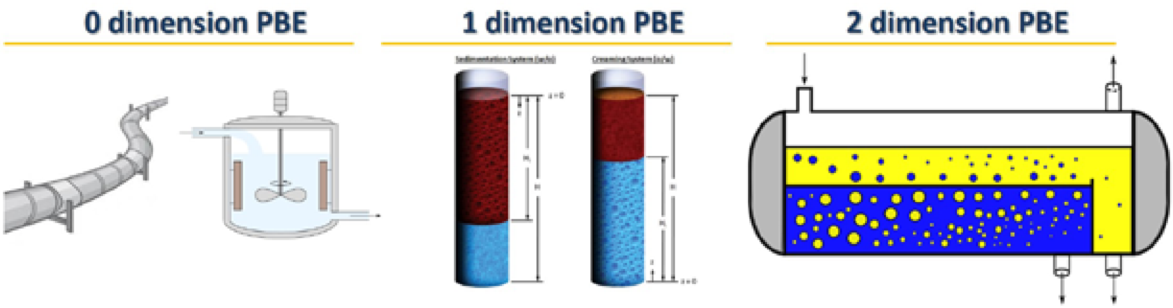


Figure 1. Population balanced model (PBE) library modules and their applications

- Pipe multi-phase flow (left)
- Batch settler/skimmer (middle)
- 3-phase separator (right)

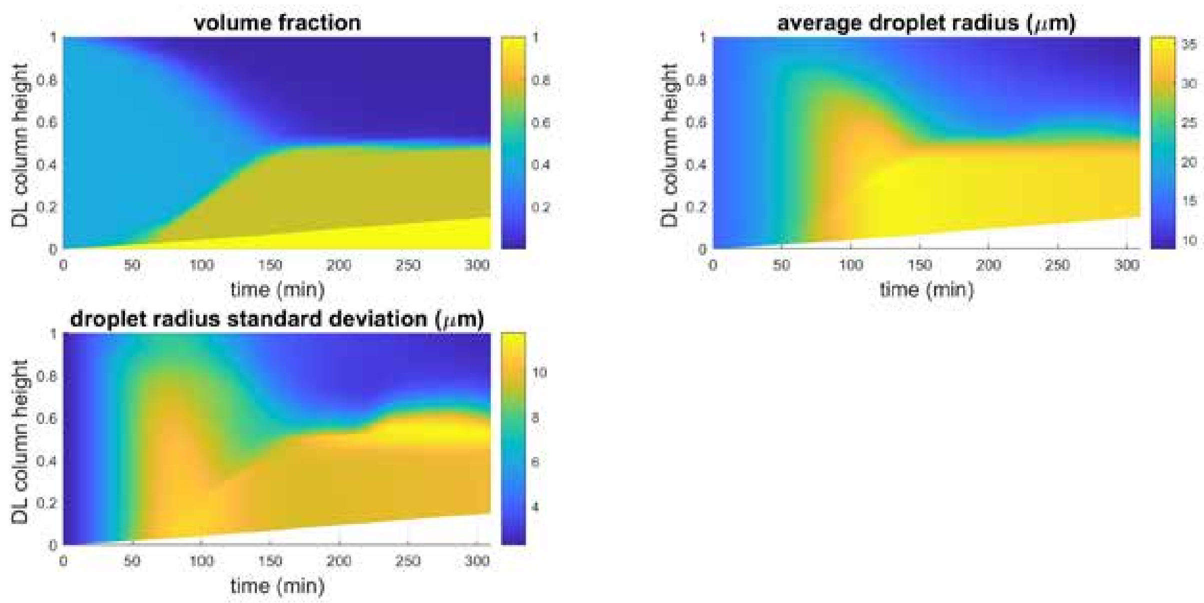


Figure 2. Time-space contours for moment features of a water in oil batch settler

X axis is the elapsed time in the process, y axis is the height of the column;
In the top-left graph, light yellow colour (volume fraction = 1) corresponds to the separated water phase, dark yellow colour (volume fraction = 0.75) corresponds to the dense packed layer; the model predicts a sharp interface between the dense packed layer and hindered settling region which is in perfect agreement with the experiments.

2.1.b Influence of production and EOR chemicals on produced water quality

Production chemicals can have unpredicted and unwanted effects on produced water treatment.

Green shift impact: Better fundamental understanding of fluids during produced water treatment could lead to lower harmful discharge to the environment

Postdoctoral fellow:	**Marcin Dudek**
Start date:	20.06.2018
Final date:	09.02.2022
Title of thesis:	Influence of chemicals on produced water quality
Project manager:	Professor Gisle Øye

1. BACKGROUND FOR THE PROJECT

Addition of production chemicals is an essential part of petroleum production and processing. Many different additives are used in order to avoid fouling of process units and pipelines, reducing corrosion, or enhancing oil recovery. Many of these chemicals are surface-active and could potentially impact the separation processes, including produced water treatment, by affecting particle coalescence and emulsion stability. With the increasing volumes of produced water through the life cycle of a field, the unknown effect of these chemicals on the separation processes is undesirable and therefore requires better fundamental understanding.

2. WHAT I HAVE DONE

The project was a continuation of a PhD project in SUBPRO and Ugelstad Laboratory at NTNU, focused on the produced water quality. In the present project, we used and improved the previously developed microfluidic methodologies for studying the effect of production chemicals on the fundamental phenomena occurring during produced water treatment, such as coalescence between crude oil droplets. Microfluidics is a technique that allows observation and manipulation of fluids in small, transparent channels. Emulsion droplets are generated in a controlled manner and their interactions are visualized by microscopy coupled with high-speed imaging.

While the previous PhD project was focused on building the experimental setup, creating methodologies and testing different ideas in a limited experimental matrix, the present project started with extending the testing conditions to even more water and oil chemistries, as well as different microfluidic chip designs. This allowed for, for example, testing the effect of oil-water interface aging on the emulsion stability or measuring the coalescence and contact times between droplets. Improved image and data processing tools streamlined the analysis and resulted in obtaining previously unavailable information, such as coalescence time between specific drop sizes or distribution of approach velocities. Additional improvements to the chip design focused on dynamic addition of a chemical during measurements (e.g., a flocculant), which would greatly speed up the screening process of various additives. These were successfully applied to tests with flocculants and partially with demulsifiers in oil-continuous systems. Some initial work was also done on characterizing oil-water partitioning with a microfluidic inline ultraviolet–visible spectroscopy (UV-Vis) system. Finally, a temperature-control holder was developed and supported the experimental campaign testing the effects of wax and wax inhibitors on the coalescence in water-continuous systems.

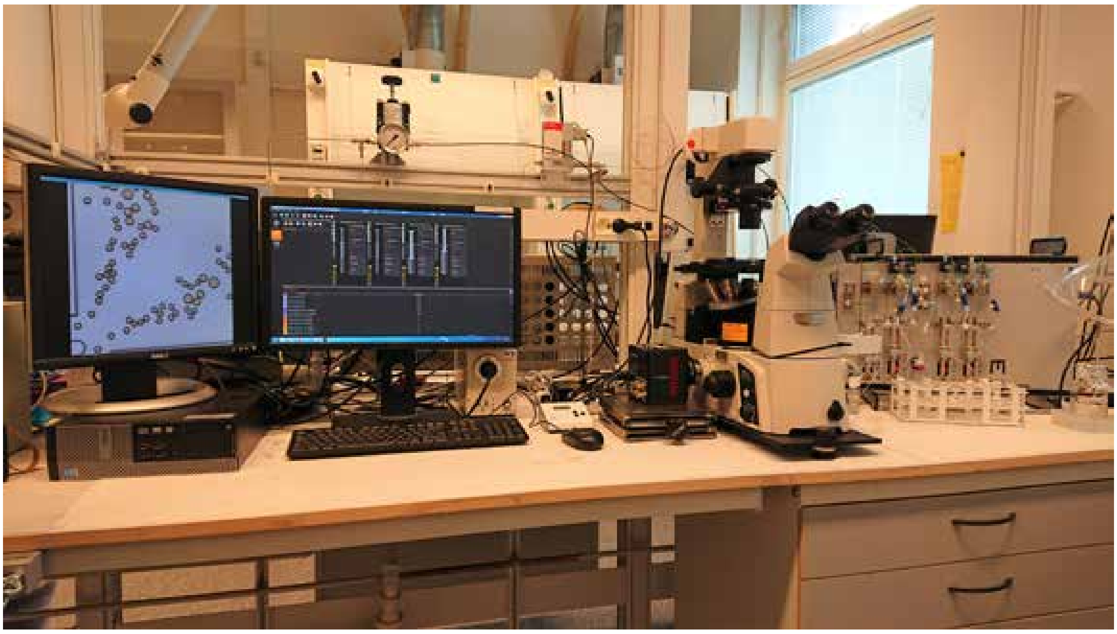


Figure 1: One of the microfluidic setups, developed during the PhD and Postdoc projects in SUBPRO.

This project was closely related to two other projects in the same Research Area of SUBPRO, namely "2.1.c Re-injection of produced water – dispersions in porous media" (Ilgar Azizov) and "2.1.d Gas flotation for subsea produced water treatment" (Martina Piccioli), and the Postdoctoral fellow was also co-supervising the PhD students involved in these projects. In addition, several collaborations with other SUBPRO projects were established, including: 2.2, 2.7, 2.9, 3.5b and 3.7[1], resulting in shared publications. Other collaborations, both internal and external, were also pursued, for example: 3-month research stay on scale precipitation (ETH, Switzerland), scale inhibitor study (Herriot-Watt University, Scotland), membrane treatment of produced water (IBM, NTNU), microfluidic oil recovery studies and image analysis with neural networks (both at Department of Chemical Engineering, NTNU).

The project had support from the industrial partners in SUBPRO, in the form of chemical samples and individual meetings to discuss the progress and plans.

3. MAIN RESULTS

The project has developed several novel microfluidic techniques, focused on stability measurements, including:

- Microfluidic technique for simultaneous measurements of hundreds of droplet coalescence and contact events (see Figure 2)
- Microfluidic measurements of emulsion stability and other experiment at increased temperatures
- Dynamic addition and mixing of additives on-chip, specifically related to separation improvers (see Figure 3)
- Inline UV-Vis measurements in microfluidic systems with real-time analysis

4. NEW INSIGHT AND KNOWLEDGE

Virtually all the developed methodologies were used in several experimental campaigns, aimed at testing emulsion stability in various conditions. Many different colloidal aspects of produced water treatment were investigated during the project, details of which can be found in the publications listed below. The main insights were related to:

- Colloidal perspective of produced water and review of tools for investigating it
- Identification of crude oil and water components responsible for improved stability of produced water emulsions
- Flocculant and wax inhibitor effects on coalescence between oil droplets

[1] 2.2 Modelling of wax crystallization and deposition; 2.7 Experiments on fluid particle breakage; 2.9 Compact separation; 3.5.b Automatic control of hydrocyclones for produced water treatment; 3.7 Estimation of unmeasured variables

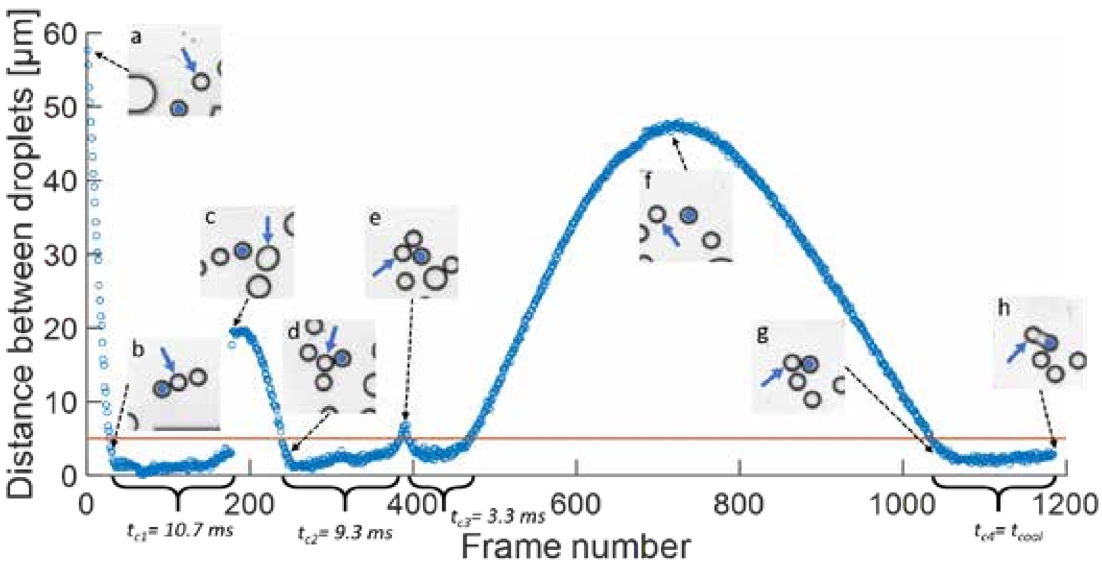


Figure 2 Graphical description of contact and coalescence time measurement.
Vertical axis depicts the distance between the blue-dotted droplet and another, closest droplet in the channel.
The horizontal axis shows the frame number (i.e., time of events during the recording).
Various insets visualize different events during flow, for example contact between droplets (which results in measured contact times t_{c1}, t_{c2} and t_{c3}), as well as final coalescence event (t_{coal}). Hundreds of events were detected per few second high-speed recording.

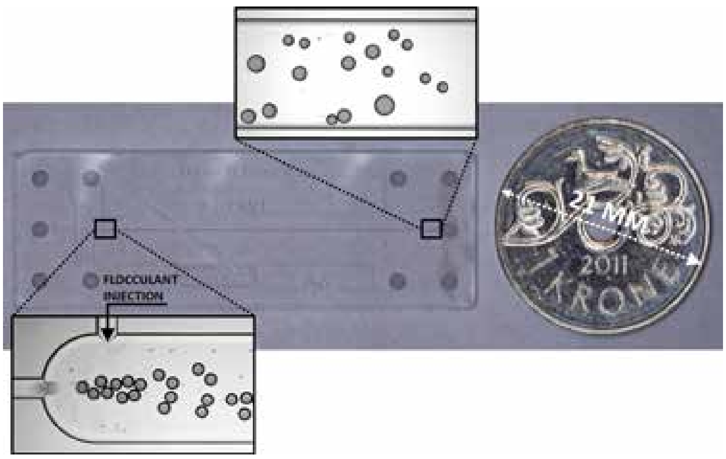


Figure 3 Design of a microfluidic chip with a channel for an additive injection. Initially monodisperse droplets are put in contact with the flocculant at the inlet of the coalescence chamber, and the effect of the additive can be seen at the outlet where larger droplets are detected, signifying improved coalescence.

5. INNOVATION

Microfluidic methods have large potential for testing chemicals or obtaining better understanding about separation or recovery processes. Unlike many other techniques, they are relatively easy to use under higher pressure or temperature conditions, as well as providing good visualization possibilities. Additionally, one of the biggest advantages of microfluidics is the minimal amounts of samples needed and waste generated.

Most methodologies were tested with real crude oils and production chemicals. Some were also compared to traditional techniques with satisfactory results and with possibilities for improvements in the future. Towards the end of the project, a great step was made in streamlining the image processing by using neural networks, which can also be adapted for other purposes and outside of microfluidic application. Overall, the response from the industry, both in and outside SUBPRO, was always (cautiously) positive, and we are satisfied that we were able to develop the microfluidic expertise at Ugelstad Laboratory and spread the knowledge about microfluidics to industrial circles.

6. FURTHER WORK

There were several aspects uncovered in this project that could potentially be worth exploring in the future. Firstly, the extension of the current microfluidic methodologies to oil-continuous systems could prove useful in replacing the sample- and time-consuming bottle tests. Furthermore, some work on oil-water partitioning with the inline UV-Vis microfluidic spectrophotometer was initiated and some promising results were obtained. This technique could be used, for example, for testing the partition coefficients of production chemicals. Other ideas could be related to automatization of the measurement process, together with online analysis of image data based on neural networks.

7. COMPLETE LIST OF PUBLICATIONS AND REPORTS

Journal Papers:

1. Das, T.; Heggheim, S. J.; Dudek, M.; Verheyleweghen, A.; Jäschke, J., Optimal Operation of a Subsea Separation System Including a Coalescence Based Gravity Separator Model and a Produced Water Treatment Section. Industrial & Engineering Chemistry Research 2019, 58 (10), 4168-4185.

2. Dudek, M.; Fernandes, D.; Helno Herø, E.; Øye, G., Microfluidic method for determining drop-drop coalescence and contact times in flow. Colloids Surf. Physicochem. Eng. Aspects 2020, 586, 124265.

3. Dudek, M.; Chicault, J.; Øye, G., Microfluidic Investigation of Crude Oil Droplet Coalescence: Effect of Oil/Water Composition and Droplet Aging. Energy Fuels 2020, 34 (5), 5110-5120.

4. Dudek, M.; Vik, E. A.; Aanesen, S. V.; Øye, G., Colloid chemistry and experimental techniques for understanding fundamental behaviour of produced water in oil and gas production. Adv. Colloid Interface Sci. 2020, 276, 102105.

5. Skjefstad, H. S.; Dudek, M.; Øye, G.; Stanko, M., The effect of upstream inlet choking and surfactant addition on the performance of a novel parallel pipe oil–water separator. Journal of Petroleum Science and Engineering 2020, 189, 106971.

6. Dudek, M.; Ullaland, H. S.; Wehrle, A.; Øye, G., Microfluidic testing of flocculants for produced water treatment: Comparison with other methodologies. Water Research X 2020, 9, 100073.

7. Piccioli, M.; Aanesen, S. V.; Zhao, H.; Dudek, M.; Øye, G., Gas Flotation of Petroleum Produced Water: A Review on Status, Fundamental Aspects, and Perspectives. Energy Fuels 2020, 34 (12), 15579-15592.

8. Azizov, I.; Dudek, M.; Øye, G., Studying droplet retention in porous media by novel microfluidic methods. Chem. Eng. Sci. 2022, 248, 117152.

9. Rutkowski, G. P.; Azizov, I.; Unmann, E.; Dudek, M.; Grimes, B. A., Microfluidic droplet detection via region-based and single-pass convolutional neural networks with comparison to conventional image analysis methodologies. Machine Learning with Applications 2022, 7, 100222.

10. Dudek, M.; Ruwoldt, J.; Øye, G., Characterization and assessment of wax and wax inhibitors systems in microfluidic oil-in-water coalescence experiments. Colloids Surf. Physicochem. Eng. Aspects 2022, 636, 128186.

11. Vallabhan K. G, M.; Dudek, M.; Holden, C., Experimental Test Setup for Deoiling Hydrocyclones Using Conventional Pressure Drop Ratio Control. SPE-107666-PA 2022, 1-13.

Conference presentations:

Bertheussen, Dudek, Simon, Øye, Sjöblom: Oral presentation at Produced Water Management 2019, Stavanger, Norway

Oral presentation at SSV, April 2019, Oslo, Norway: “Produced water under a microscope. Microfluidic applications”.

Dissolved Components in Produced Water and Their Influence on Gas Flotation Efficiency, Gisle Øye, Mona Eftekhardadkhah, Bartlomiej Gawel, Marcin Dudek, Produced Water Workshop 2019, Aberdeen, UK

Oil/Water Partitioning of Naphthenic Acids and Consequences for Produced Water, Are Bertheussen, Marcin Dudek, Sébastien Simon, Gisle Øye and Johan Sjöblom, Produced Water Workshop 2019, Aberdeen, UK

Oral presentation at PetroPhase, June 2019 Kanazawa, Japan: “Coalescence of crude oil drops in produced water using microfluidics”.

Poster presentation at MicroTAS, October 2019, Basel, Switzerland: “Microfluidic method for investigating kinetics of emulsion destabilization”.

Oral presentation at Microfluidics, November 2019, Paris, France: “Effect of flocculants on on-chip coalescence of crude oil droplets in produced water”

Oral presentation at Tekna Produced Water Management, January 2020, Stavanger, Norway: “Microfluidic approach for investigating flocculants for produced water treatment”

Oral presentation at Oil Field Chemistry Symposium, September 2020, Digital Edition: “Introducing Microfluidic Methods to evaluate the Performance of Oil Field Chemicals”

Oral presentation at Oil Field Chemistry Symposium, May 2021, Digital Edition: “Microfluidic Method to Investigate the Precipitation of Calcium/Magnesium Phosphonate Scale-Inhibitor Complexes”

Reports/Master theses:

- Project reports:
  - Hanne Skudal Ullaland
  - Karoline Øverlie Edøy
  - Okpala Chukwubuike
  - Diana Alexandra Ferreira Fernandes
  - Veslemøy Selvik
- Master theses:
  - Hanne Skudal Ullaland
  - Karoline Øverlie Edøy
  - Okpala Chukwubuike
  - Hege Landbø

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 equipment 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.

The PhD-student Eirik Helno Herø successfully defended his thesis in November 2021. The work presented in the thesis “Experimental Investigations of Single Oil Droplet Breakage in a Turbulent Water Flow” is also described in four peer-review papers covering the work.

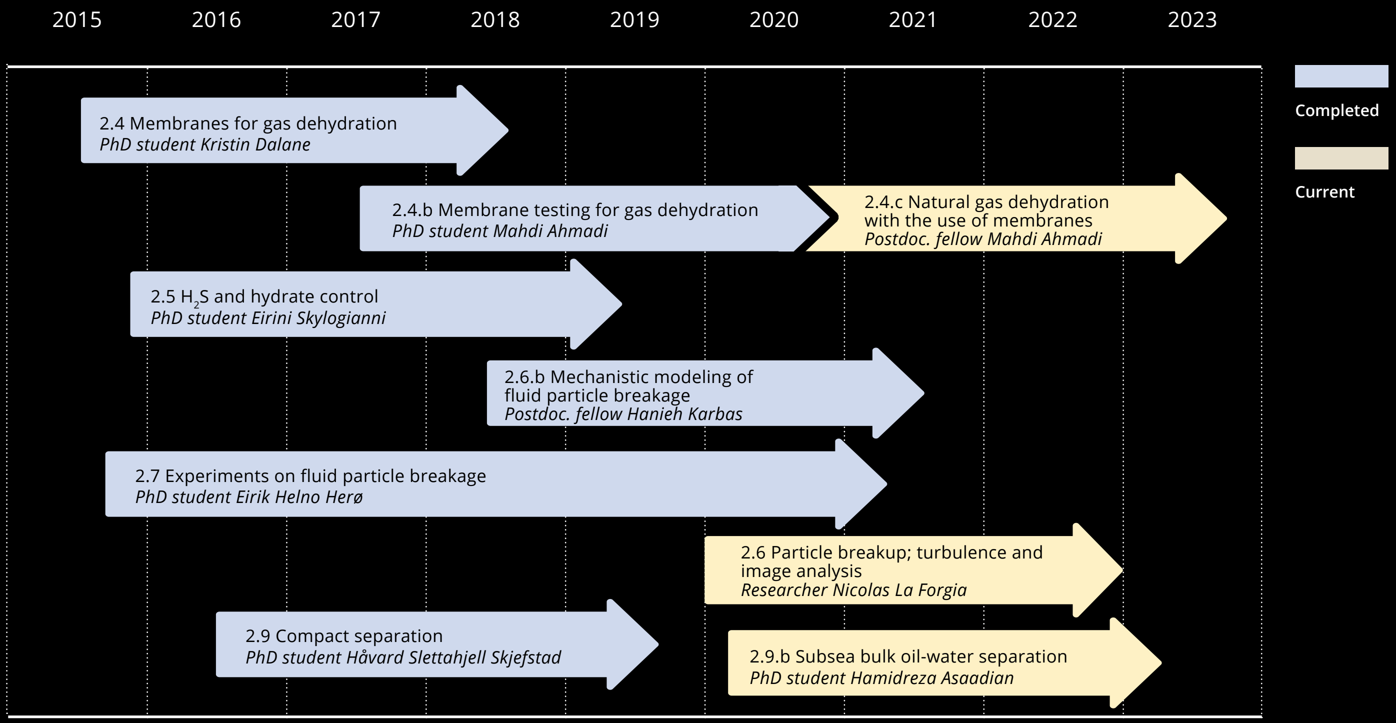
The project “2.7 Experiments on fluid particle breakage” which was finalized in 2021 has been followed up by a new project from 2020; “2.6 Particle breakup, turbulence and image analysis”. Nicolas La Forgia is now employed as a researcher in this project at the Department of Chemical Engineering.

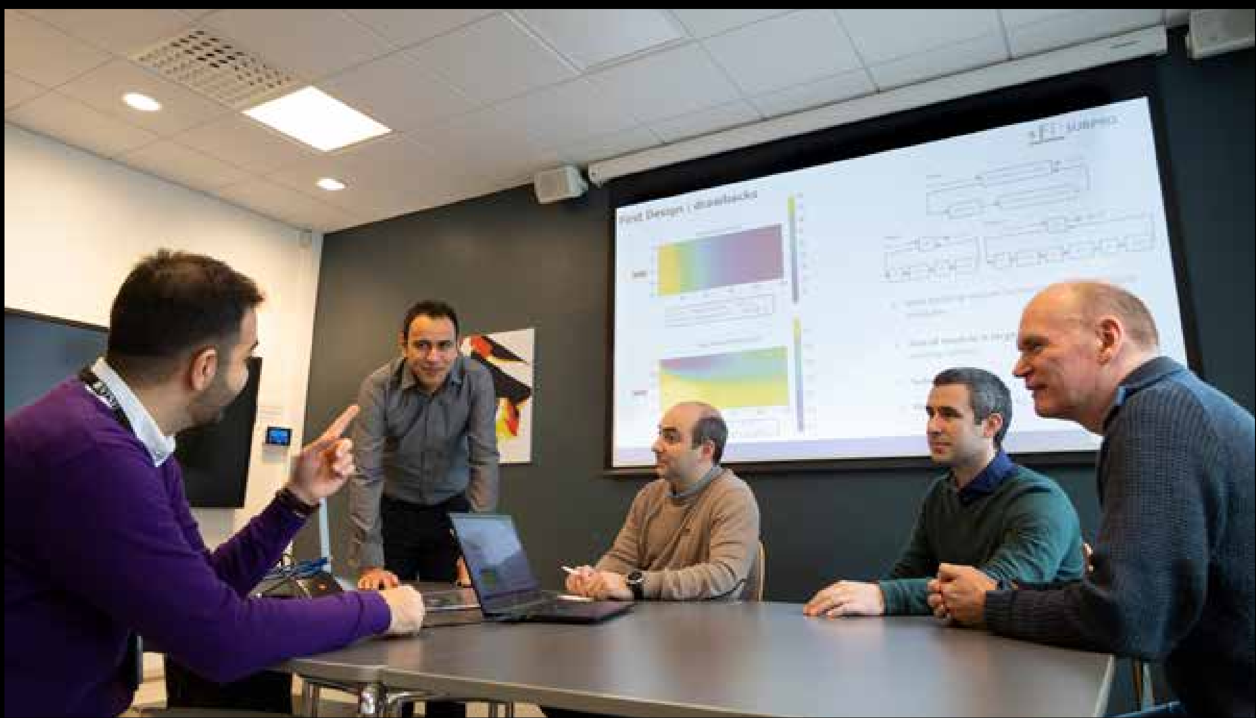
The project “2.4.b Membrane testing for gas dehydration” which was finalized by PhD student Mahdi Ahmadi in 2020 is followed up by Mahdi as a Postdoctoral fellow in the new project from 2021; “2.4.c Natural gas dehydration with the use of membranes”.

Postdoctoral fellow Hanieh Karbas Foroushan finalized the project “2.6.b Mechanistic modelling of fluid particle breakage” in 2021.

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

Completed and current projects





The Separation – Process concepts team. From the left: PhD student Hamidreza Asaadian, Postdoctoral fellow Mahdi Ahmadi, Researcher Nicolas La Forgia, Associate Professor Milan Stanko, Professor Hugo Jakobsen. Professor Magne Hillestad was not present when the picture was taken.

2.4.c Natural gas dehydration with the use of membranes

Subsea membrane gas dehydration technology enables feeding of dehydrated gas stream directly to pipelines.

Green shift impact: An environmentally friendly and energy-saving process that reduces methane loss.

Postdoctoral fellow:
Mahdi Ahmadi

Project manager and main supervisor:
Professor Magne Hillestad

Co-supervisors:
Professor Liyuan Deng
Dr. Eivind Johannessen
(Equinor)

1. SUBSEA DEHYDRATION PROCESS CONCEPT AND INDUSTRIAL OBJECTIVES

The main objective of this project is to design, optimize and introduce a reliable membrane-based separation process for subsea gas dehydration. The process includes individual membrane systems working at different operating conditions in a closed-loop, where *Triethylene glycol* (TEG) is the absorbent agent in the loop (Figure 1). A membrane contactor as absorber unit in hollow fiber configuration is connected to a pervaporation unit in plate-and-frame configuration assisted with dry methane as sweep gas. This work builds on the obtained experimental data from each membrane process to optimize the process according to the required specification provided by our industry partners (i.e., Equinor). The experimental data were collected for individual membrane processes in an earlier SUBPRO project "2.4.b Membrane testing for gas dehydration" (Mahdi Ahmadi). Durability of membrane material and TEG loss will be examined in the current project. The main criterion for the process is to meet the industrial specification by lowering the water content (dew point < -18 °C at 70 bara) and TEG content in the gas pipelines (TEG emission < 0.8 liter/MSm^3 gas). In our prior projects ("2.4 Membrane for gas dehydration", Kristin Dalane and "2.4.b Membrane testing for gas dehydration"), driving force for regeneration of TEG in the thermopervaporation unit was supplied by temperature gradient (maximum 70°C), thanks to low subsea water temperature. However, using cold water for generating driving force led to a temperature drop of TEG/water mixture along the membrane, which adversely affected the membrane performance and process design. Moreover, methane loss is a common issue in membrane processes for natural gas dehydration. Therefore, a novel subsea dehydration process was designed to reduce heat loss with zero methane loss. In the new design, the air gap and cooling system in thermopervaporation unit were removed and replaced with a dry methane stream at 1-3 bar. The outlet sweep gas is then cooled down, compressed, and recycled to the membrane contactor; therefore, low methane loss is expected.

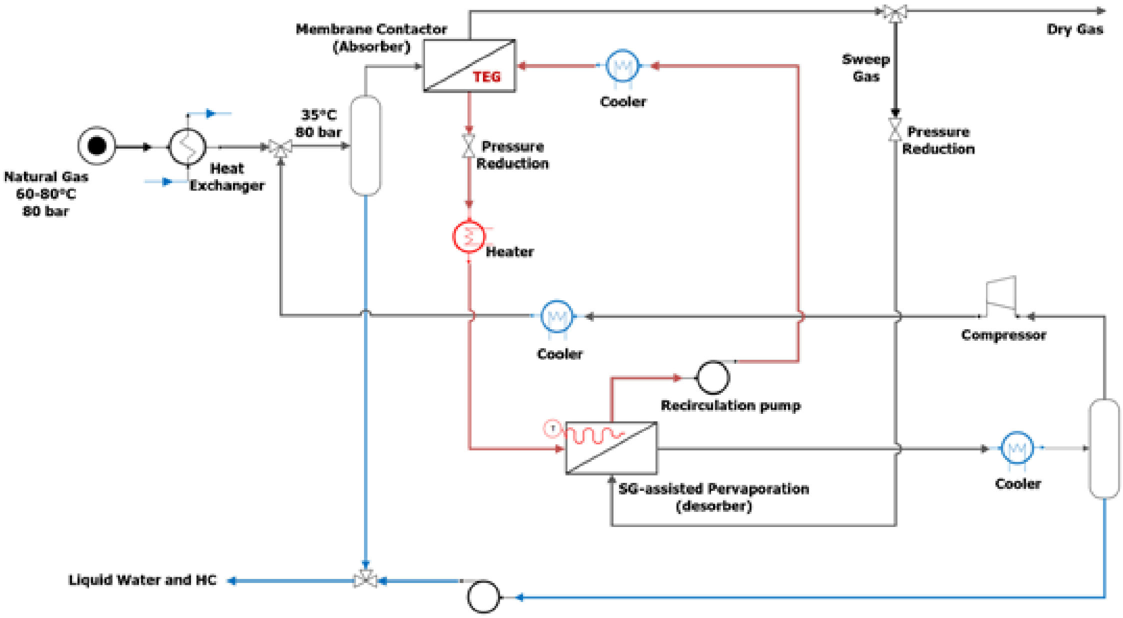


Figure 1: Process flow diagram of subsea membrane-based natural gas dehydration process.

2. MEMBRANE PERFORMANCE TESTING AND EXPERIMENTS

Durability of membranes and the TEG flux through the membrane will be evaluated experimentally to ensure longer lifetime of membrane materials. Membranes will be tested at different transmembrane pressure difference to optimize the safest pressure difference across the membrane. Membranes with longer lifetime such as hydrophobic polymeric membranes and inorganic membranes will be produced and tested in the membrane contactor and membrane thermopervaporation unit for higher flux and separation performance.

3. MODEL DEVELOPMENT AND VALIDATION, PROCESS DESIGN, AND OPTIMIZATION

Mathematical models describing thermodynamics and transport properties of components in the membrane contactor and membrane thermopervaporation units were developed and solved in Python (Figure 2-3). To reduce methane loss and heat loss, a novel configuration in the thermopervaporation unit using sweep gas was designed (Figure 1) and the new models were solved in Python (Figure 3). To implement the models in HYSYS, a fast and reliable numerical solver is required. Therefore, an iterative collocation-based numerical solver was developed based on linear algebra for nonlinear coupled differential equations. A C# platform (.NET) was used to create an interface in HYSYS, and novel unit operations (membrane contactor and thermopervaporation) were added as new extensions in Aspen HYSYS.

Design of specifications and process optimization will be carried out according to the outlet specification given by our industry partners. The process, then, will be evaluated for its technical and economic feasibility to ensure low TEG emission, low methane loss, and optimized membrane area and energy for the entire process. Using dry methane as sweep gas together with internal electrical heating in pervaporation unit guarantees very low temperature drop along the membrane, with improved separation efficiency (Figure 3).

All models are validated against experimentally measured data in the membrane laboratory at NTNU, using membrane testing rigs designed specifically for the subsea natural gas dehydration process.

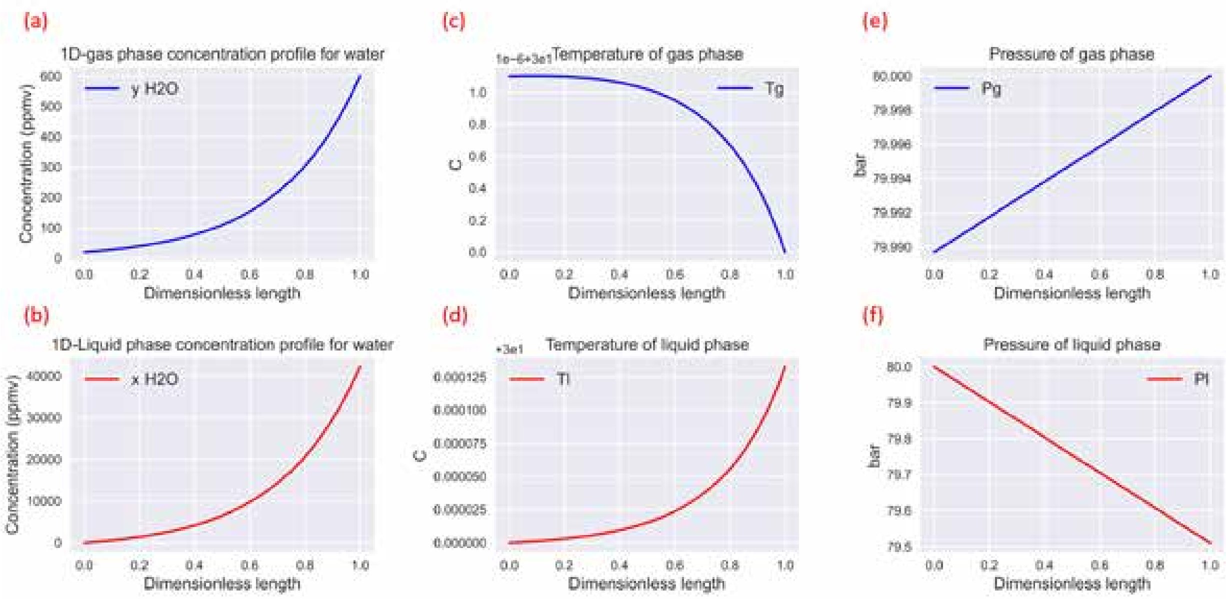


Figure 2: Concentration (a,b), temperature(c,d), and pressure (e,f) profiles in membrane contactor (absorber) for gas (1D) and liquid phases (1D). The process is a counter-current process and water content in inlet gas (~600ppmv) is captured by pure TEG and reduced to below 50 ppmv (pipeline specification). Heat of absorption has very low influence on temperature profile and a pressure drop is expected only in liquid phase (in lumen side of tubes) in membrane contactor.

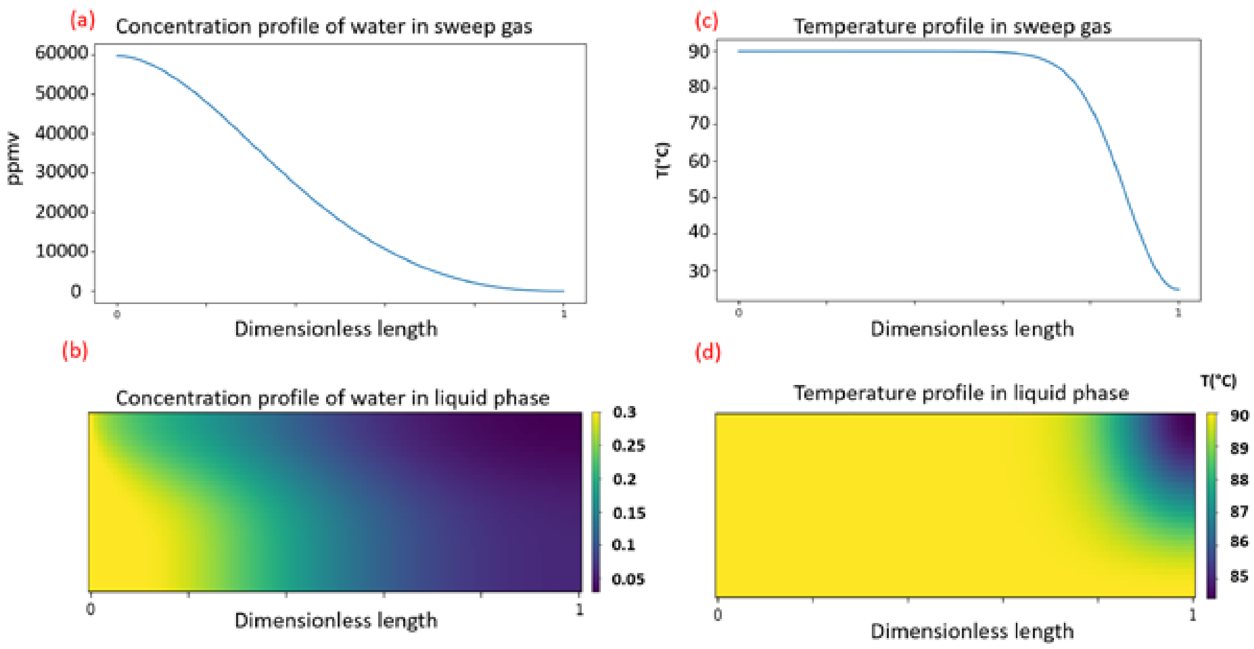


Figure 3: Concentration (a,b) and temperature profiles (c,d) in sweep gas (1D) and liquid side (2D) in membrane pervaporation unit with sweep gas flowing counter-current towards liquid phase. Inlet liquid temperature and water mole fraction of 90°C and 30% were used for simulation. An internal electrical heating plate is used in liquid phase channel to avoid temperature drop along the membrane (average outlet temperature drop of liquid phase is below 2°C)

4. POTENTIAL FOR INDUSTRIAL APPLICATION OF RESULTS

Application of conventional technologies such as absorber columns in natural gas dehydration is limited to onshore facilities, where glycols are frequently used in stationary equipment. However, offshore and subsea systems require more compact design, less environmental impact, and less moving parts with reliable performance for long-term operation. Our subsea membrane dehydration technology would benefit industries for longer unmanned operation in offshore, onshore, and subsea systems. Moreover, no methane loss is expected in our design that is crucially important in conventional membrane processes.

In addition, most commercial process design software such as Aspen HYSYS are limited to conventional technologies due to lack of proper and reliable models in membranes. Therefore, integration of membranes in Aspen HYSYS require a robust model and fast solver tuned with experimentally obtained data. Implementation of thermodynamics and transport models in open-source Python connected to Aspen HYSYS will significantly alter the future of membrane process design in static and dynamic process design for industries. We offer membrane unit operation interface in Aspen HYSYS with model and solver implementation in Python.

This project has been of interest to our industry partners, specifically to Equinor and TechnipFMC, which actively assisted with the design. The knowledge of membrane preparation methods and research on modeling is also shared with the partners.

5. LIST OF PUBLICATIONS

1. Ahmadi, Mahdi; Ansaloni, Luca; Hillestad, Magne; Deng, Liyuan. (2021) Solvent Regeneration by Thermopervaporation in Subsea Natural Gas Dehydration: An Experimental and Simulation Study. Industrial & Engineering Chemistry Research. vol. 60 (17).

2. Mahdi Ahmadi, Arne Lindbråthen, Liyuan Deng, Magne Hillestad (2022). Submitted to the 28th Underwater Technology Conference, Bergen, Norway, 14-16 June2022.

2.6 Particle breakup; turbulence and image analysis

High speed image processing of single oil droplet breakage helps to improve models for phase distribution in oil-water separation.

Researcher:
Nicolas La Forgia

Project manager and supervisor:
Professor
Hugo Atle Jakobsen

1. BACKGROUND

Phase separation is one of the most important challenges for the design of many industrial processes in the oil and gas industry. Processes such as oil and water separation are critical not only for the oil production but also for the treatment of produced water and for oil and water transportation. In these processes, the size distribution of the oil droplets in water is critical for the separation efficiency, and as such is a key aspect that needs to be properly modelled to design optimized separators. Consequently, investigation of models that could potentially predict particle size distribution in such systems have gained an increasing attention. However, due to the complexity of the interaction of the different fluid particles with turbulent fluid flow, the development of such models requires the extensive support of experimental observation of breakage and coalescence phenomena. Several experimental studies have been conducted. However, more experimental data is required to fully understand the breakage phenomena.

The main goals of this project are:

- To develop tools for the accurate interpretation of measurements from experiments on particle breakage, through image processing.
- To perform statistical analysis and uncertainty evaluation of the measurements.
- To produce a database of experimental data from breakage of oil droplets under different flow conditions and fluid properties.
- To gain a deeper understanding of and describe the physical mechanism of the breakage phenomena, that could lead to better modelling tools for the prediction of phase distribution evolution.

2. RESEARCH ACTIVITIES AND RESULTS

In this project, the focus is on the experimental investigation of the breakage of oil droplets in water. To avoid the coupling of breakage and coalescence phenomena, the experimental facility tracks the individual injected oil droplet in the turbulent flow and studies the following breakage event. In this regard, the use of high-speed imaging techniques allowed the direct visualization of the breakage phenomena. The project has developed a software for tracking the evolution of the position and deformation of the oil droplets, the breakage event, and the subsequent production of daughter droplets and their size distribution.

In the figure 3, an example of a droplet travelling in the test section is shown. As it travels through the section (from left to right in the image, corresponding to vertical travel in the test coloumn), the droplets get deformed as a result of the turbulent flow conditions, and at some point, the deformation leads to the breakage into multiple daughter droplets.

Figure 1: Particle breakage test rig.

Researcher Nicolas La Forgia in front of the vertical flow column where the oil droplets break up, caused by turbulent flow conditions.

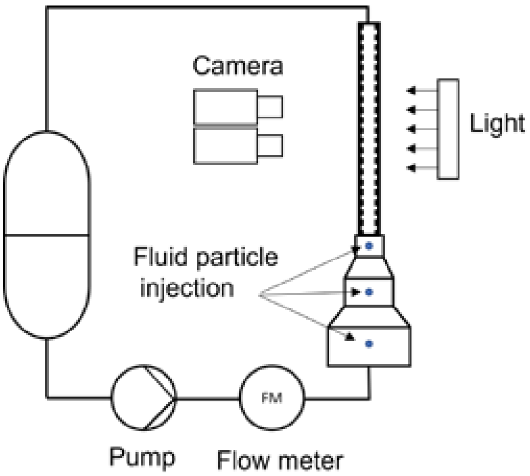


Figure 2: Experimental facility, consisting of a closed loop of water, a pump and a flow meter for controlling the flow conditions, a test section with high-speed cameras and backlight illumination and injection ports for the oil droplet incorporation. Profiles mounted on the tube walls of the test section were used to generate turbulent flow conditions, causing the particle breakage. The blue points represent the location of the ports for injection of oil droplets into the water flow.

Figure 3: Example sequence of images of a single oil droplet travelling through the test section, deforming, and breaking into several daughter droplets.

During the project, a stretch collaboration has been conducted with the SUBPRO project "2.7 Experiments on fluid particle breakage" (Eirik Helno Herø), and several milestones have been accomplished in co-operation:

- The turbulent condition was mapped for the entire test section using a laser doppler velocimetry (LDV), which allows us to correlate the breakage position with a statistical measure of the turbulent condition for said position. This resulted in a publication in Chemical Engineering Science (La Forgia et. al. [1]).
- A novel and more accurate image processing method for the characterization of droplet size has been developed. This resulted in a publication in the Chemical Engineering Science: X Journal (La Forgia et. al. [2]).
- Breakage probability, breakage time and breakage frequency of octanol oil droplet has been characterized under different conditions. The statistical study of this measurement resulted in two publications in the Chemical Engineering Science: X Journal (Herø et. al. [3-4]), and one publication on Chemical Engineering & Technology (Herø et. al. [5]).

The project is currently at its final stage, and we are expecting to complete with the statistical analysis and measurements of different oils to study the influence of the properties on the breakage characteristics.

2. INDUSTRIAL PARTICIPATION AND USE OF THE RESULTS

During the year 2021, this project received contribution from an industrial partner (Aker Solutions), through meetings related to the discussion of different image processing techniques.

References:

[1] La Forgia, N., Herø, E. H., Solsvik, J., Jakobsen, H. A., "Dissipation rate estimation in a rectangular shaped test section with periodic structure at the walls". Chemical Engineering Science. 195. p. 159-178 (2018)

[2] La Forgia, N., Herø, E. H., Jakobsen H. A. "High-speed image processing of fluid particle breakage in turbulent flow". Chemical Engineering Science: X. 12. (2021).

[3] Herø, E. H., La Forgia, N., Solsvik J., Jakobsen H. A., "Single drop breakage in turbulent flow: Statistical data analysis", Chemical Engineering Science: X. (2020). 8.

[4] Herø, E. H., La Forgia, N., Solsvik J., Jakobsen H. A., "Single oil drop breakage in water: Impact of turbulence level in channel flow", Chemical Engineering Science: X. (2021). 12.

[5] Herø, E. H., La Forgia, N., Solsvik J., Jakobsen H. A., "Determination of breakage parameters in turbulent fluid-fluid breakage", Chemical Engineering & Technology. (2019). 42, No. 4, 903-909.

2.9 Subsea bulk oil-water separation

More efficient subsea bulk oil-water separation by improved separator design, use of multiphase flow fundamentals and developing predictive methods to size and design pipe type separators.

Green shift impact: Subsea separation of produced water increases the recovery rates for brown field installations, increases production rates, removes topside produced water bottlenecks and enables better utilization of existing topside facilities. Additionally, it reduces energy losses due to transport of water.

PhD student:
Hamidreza Asaadian

Project manager and main supervisor:
Associate Professor Milan Stanko

Co-supervisor:
Professor Gisle Øye

1. BACKGROUND

Management of produced water is one of the most important issues in production from mature oil fields. Subsea separation can be used to address this problem and brings additional benefits. It is therefore important to develop cost-effective subsea separator technologies, making the business case for subsea separation more attractive. This project is a continuation of previous SUBPRO project "2.9 Compact Separation" conducted by Håvard Skjefstad. This project developed a concept for bulk oil-water separation in pipe, tested it for several operational conditions and studied fundamental phenomena in oil-water separation in pipe. (Fig. 1)

2. RESEARCH ACTIVITIES AND DELIVERABLES

The main goal of this research is to further develop the separation concept developed by the previous project, by studying its performance under more realistic conditions, and to improve the general knowledge on oil-water separation in pipes. This project has the following tasks:

- Experimental study of the effect of crude oil spiking (see explanation below) on the separation efficiency and on the dispersion characteristics with or without inlet choking
- Experimental study of the effect of small amounts of gas (air) on separation efficiency

Experimental study of the effect of crude oil spiking on the separation efficiency and on the dispersion characteristics with or without inlet choking

In the experiments, we used both Exxsol D60-water mixtures and the same mixtures blended with real crude oil. A disadvantage of using Exxsol D60-water mixtures is that often the separation characteristics do not match those of real crude-water mixtures. To mimic the separation characteristics of real crude oil mixtures, we added small quantities of real crude to the Exxsol D60, a process called "crude oil spiking". During the last year we have worked on determining separation characteristics of the resulting fluid mixture. We performed separation bottle tests for different spiking amounts and compared the results against bottle tests with the original crude. Rheology properties, emulsion characteristics and inversion point were studied under flowing conditions by using a mini-loop (pipe rheometer). The results of this study suggest that the Pal & Rhodes rheology model with adjusted equation constants is the most suitable to predict the emulsion viscosity in pipe (Fig. 4).

Our first test campaign was focused on determining drainage potential curves for a single tapping point (drainage point) in the pipe separator with spiked and un-spiked Exxsol D60 and comparison against a simple numerical model. The drainage potential gives a relationship between the water cut of a stream tapped from the bottom of the pipe versus the flow of tapped water (Fig.2). This work showed that the main factor affecting the shape of the drainage potential curves is the flow pattern of the oil-water mixture approaching the tapping point (Fig. 3). Crude spiking reduces considerably the drainage potential for oil continuous regimes (low water cuts).

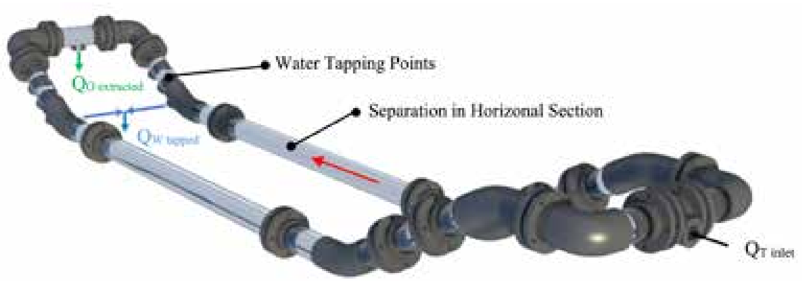


Figure 1: Test rig

Figure 2: Drainage Potential

The next experimental campaign was focused on measuring the efficiency and water cut ratio of the separator operating with spiked oil for various total flowrates and inlet water-cuts. Two different concentrations of crude oil (e.g., 185 and 400 ppm) were used to observe the effect of crude concentration on the separation characteristics. Flow pattern of liquid-liquid mixture in pipe were determined before the inlet and along the separator. Crude oil spiking significantly reduces the efficiency of the pipe separator for oil continuous regimes (low water cuts). (Fig. 5)

A numerical model based on Population balance has been developed to predict separation performance and to predict the distribution of each phase along the separator. The model has been tuned to experimental data gathered in the experimental campaigns. This task is performed in cooperation with and led by PhD student Moein Assar in the SUBPRO project “2.8.b. A digital twin library for oil/water emulsion separation and transport”. This numerical model could be used to perform separator design, i.e. determining pipe diameters, number of parallel branches and serial steps.

Results from this task will be published as three journal articles and one conference paper. Two manuscripts have already been prepared and submitted about the drainage potential curves and the population balance model.

Experimental study of the effect of small amounts of gas (air) on separation efficiency

The experimental rig is ready to run experiments with air in 2022. Small amounts of gas will be introduced to inlet flow as dispersed bubble or layer flow pattern and effect of gas presence on separation efficiency will be investigated.

The first task of the project is almost finished and some of the activities from second task that are planned for 2022 are:

- Experimental quantification of effect of small amounts of air on the separation efficiency
- Further development of separation design methods using numerical methods
- Experimental quantification of the evolution of the droplet size distribution along the separator using particle imaging
- Experimental study of fluid maldistribution in parallel pipes

3. POTENTIAL FOR INDUSTRIAL APPLICATION, FURTHER WORK

We have had several technical meetings with experts from Equinor and SINTEF to get advice to design our experimental procedures, and to present our results and get feedback.

Results of this research can be readily used by the industry to design and manufacture an oil-water separator with expected improved performance compared to existing oil-water separators in the market. Ultimately, we hope to contribute to improve and facilitate the management of produced water and optimize oil and gas production.

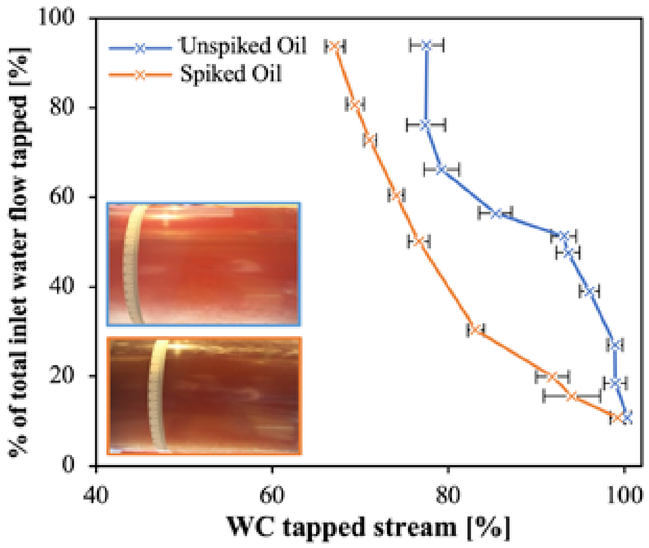


Figure 3: Emulsion Rheology Model

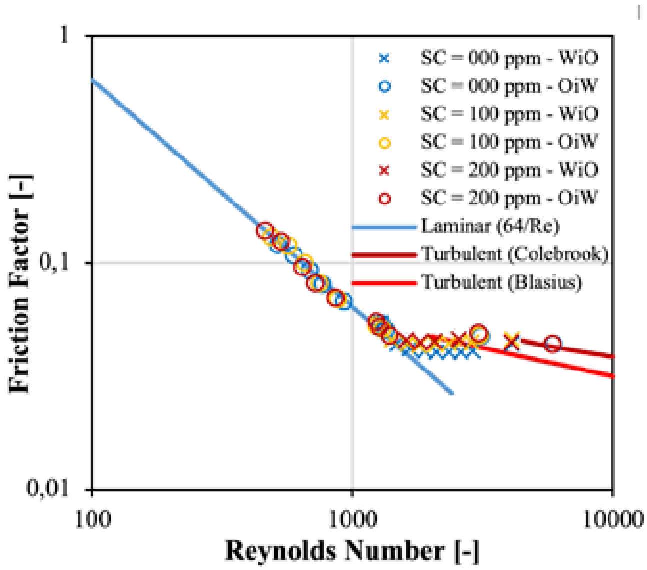


Figure 4: Drainage Potential Curves

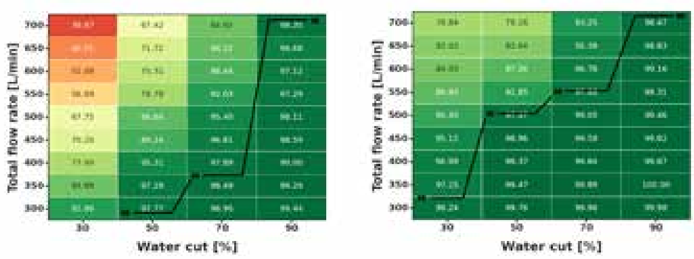


Figure 5: Seperation Efficiency with 400 ppm crude spiking (left) and without crude spiking (right)

2.6.b Mechanistic modelling of fluid particle breakage

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

Postdoctoral fellow:	**Hanieh Karbas Foroushan**
Start date:	14.09.2018
Thesis defense data:	01.05.2021
Title of thesis:	Mechanistic modeling of droplet breakage
Project manager and supervisor:	Hugo Atle Jakobsen

1. UNDERSTANDING PARTICLE BREAKAGE MECHANISMS IS ESSENTIAL FOR DESIGNING EFFICIENT SEPARATORS

Having subsea processing as one of the most effective ways for enhancement of oil and gas production, multiphase separators are recognized as the primary aid to separate the fluid components of wellbore multiphase flows for further processing and transportation. There is a wide range of methods used to design multiphase separators. The design of separators, however, does not appear to be trivial, as it essentially requires careful considerations of underlying physical phenomena, one being accurate quantification of fluid particle breakage and coalescence mechanisms. Separation efficiency is therefore 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.

2. ANALYSIS OF FLUID-PARTICLE INTERFACE INSTABILITY AND ITS SHAPE OSCILLATIONS

Acquiring knowledge on the dynamics of dispersed phase fluid particles and continuous fluid interaction and interface instability enables better understanding of fluid particle breakage and helps to identify the possible factors affecting the instability of the interface, leading to a breakage. Considering the random nature of the turbulent flow, a fluid particle in a turbulent field can be subjected to various-size deformations over a certain period of time.

The aim of this work is to evaluate the possibility of instability analysis implementation in fluid particle breakage modelling to possibly redefine or improve the determination of major parameters required for breakage predictions. Moreover, to gain a better understanding of bubble breakage in the turbulent field, experiments have been performed, which can eventually assist in re-evaluating the accuracy of the currently available breakage models.

3. RESEARCH ACTIVITIES AND DELIVERABLES

The study comprised several stages:

- A model has been developed to study the forced oscillations of a fluid particle interface, providing qualitative judgements on the deformation/instability of a fluid particle subjected to a pre-defined force. The analysis was done through a weakly-nonlinear perturbation approach, where the effect of higher-order nonlinearities on the shape oscillations and shape-mode interactions was investigated. Figure 1. shows the dimensionless oscillations of a droplet with density of 750 Kg/m3, 0.0015 Pa-s, and interfacial tension of 0.0085 N/m in water, for two different cases: in the upper Figure (a) the droplet experiences oscillations due to combination of excitations at frequencies equal to its natural frequencies at modes 2 and 3, whereas in the lower Figure (b) the droplet is subjected to oscillations at half of the natural frequencies at modes 2 and 3. In the second case, the deformation surpasses the diameter of the droplet, implying the possibility of a breakage. Moreover, looking at the oscillation trends, it can be concluded that the deformations that a fluid particle in reality undergoes might be by a combination of different excitations at different frequencies resulted from successive or simultaneous interactions of the fluid particle with turbulent structures.

- Experiments of air bubble breakage in a turbulent flow of a mixture of Iso-propanol, 2-propanol, and water at three different turbulence levels were performed. According to the experiments, various patterns of breakage are recognized for bubbles, as presented in Figure 2.

- New breakage models were proposed for better prediction of breakage time and daughter size distribution based on the cascade breakage concept.

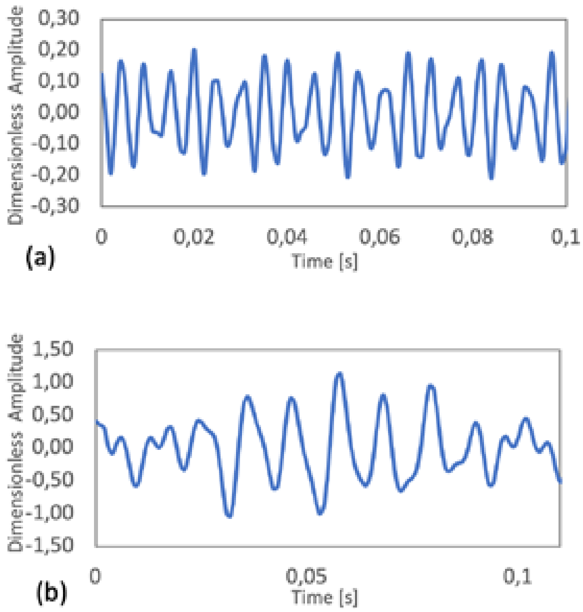


Figure 1: Oscillations of a droplet, excited at multiple modes and combined excitations at Left: f_2 and f_3 , Right: $f_2/2$ and $f_3/2$

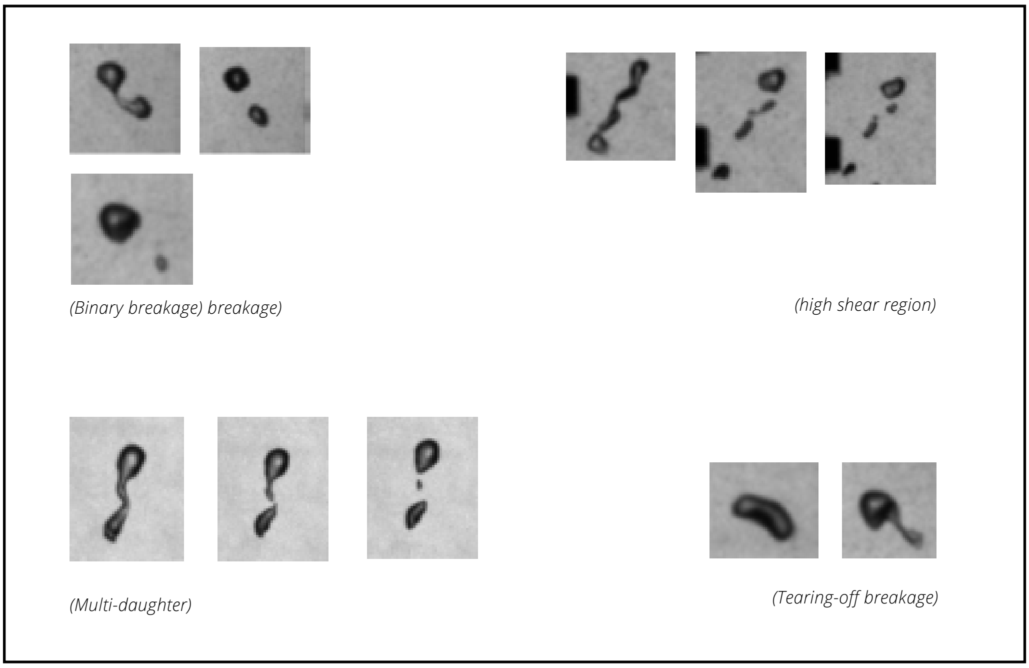


Figure 2: Bubble breakage patterns

Figure 3 (a) shows the cascade breakage frequency calculated by four old models and compared against the new proposed model, which offers great improvements in the prediction of breakage frequency.

Figure 3(b) presents an example of the daughter size distribution obtained for the breakage of bubbles with mean diameter of 3.2 mm in a turbulent field with a mean turbulent dissipation rate of 0.93 m2/s3. As for the breakage time predictions, the new model is constructed to introduce the effect of kinematic viscosity of the continuous phase, interfacial tension, and more importantly, average number of daughters into the breakage time calculation, as it is an influential factor to be considered in the calculation of cascade breakage time. For the prediction of daughter size distribution, different from the old models that were mainly suitable for initial breakage, the model proposed provides an asymmetric (L-shape) distribution taking into account all the daughters produced in the consequent breakages after the initial breakage. More discussions are provided in [3]. Compared to the old models and approaches, both models developed in this work offer improvements in prediction of breakage time/ frequency and daughter size distribution, hence, a more accurate overall prediction of fluid particle breakage.

4. PROPOSED FUTURE WORK

- Extend the model to the case of fluid particle deformation in turbulent field, investigating forced oscillations of a fluid particle due to its random interactions with turbulent structures.
- Implement the instability analysis into conventional particle breakage models and evaluate its influence on predictions

5. PUBLICATIONS

[1] Foroushan, H.K. and Jakobsen, H.A., 2020. On the Dynamics of Fluid Particle Breakage Induced by Hydrodynamic Instabilities: A Review of Modelling Approaches. Chemical Engineering Science, p.115575. https://doi.org/10.1016/j.ces.2020.115575

[2] Foroushan, H.K. and Jakobsen, H.A., 2021. On the Instability of Fluid Particle Interface and Shape Oscillations. International Journal of Multiphase Flow, 136, p.103520. https://doi.org/10.1016/j.ijmultiphaseflow.2020.103520

[3] Foroushan, H.K. and Jakobsen H.A, 2021. Experimental Study of Single Bubble Breakage in Turbulent Fluid Flow Field: Evaluation of Breakage Models, Journal of Chemical Engineering Science (under review).

6. MY NEW JOB

Hanieh is currently a senior consultant for risk management and consequence modelling at Vysus Group (formerly Lloyd's Register Energy).

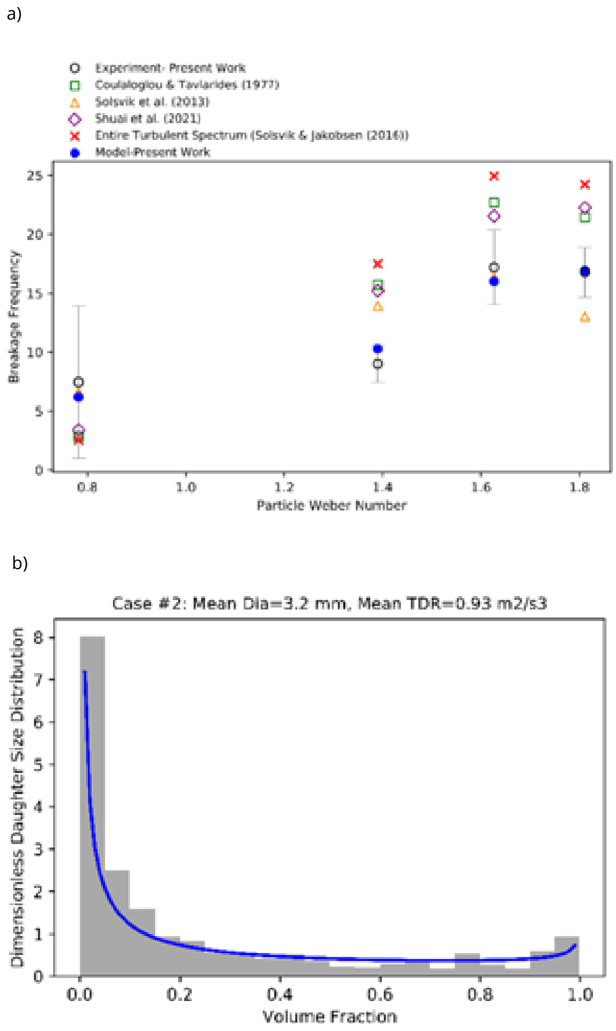


Figure 3: Proposed breakage models

2.7 Experiments on fluid particle breakage

Experimental data from single oil-droplet breakage investigations may assist developing design models for complex phase separation equipment.

PhD student:	**Eirik Helno Herø**
Start date:	18.08.2015
Thesis defense data:	05.11.2021
Title of thesis:	Experimental Investigations of Single Oil Droplet Breakage in a Turbulent Water Flow
Thesis committee members:	Professor Ronnie Andersson, Chalmers University of Technology, Gothenburg, Sweden Director of research PhD Nida Sheibat-Othman, CNRS/Université Claude Bernard Lyon-I, Lyon, France Associate Professor Milan Stanko, Department of Geoscience and Petroleum, NTNU
Supervisor:	Professor Hugo A. Jakobsen

1. BACKGROUND

Understanding the mechanisms of phase separation is key for many industrial processes, especially for subsea processing. In particular, the separation of oil and water plays a major role in the design of separators, where a big challenge is accurate and predictive modelling of the droplet size distribution of the dispersed phase. Understanding the particle breakage phenomena and designing and operating the separator such as to minimize breakage allows for larger droplets, which are easier to separate. The breakup process is determined by the properties of the phases, the system properties such as surface tension, and continuous phase flow characteristics. In particular, the turbulence level is critical for the breakup process. Many models have been proposed for turbulent breakup, but the models are currently not universal and thus not accurate for a wide range of operating conditions. To describe the breakup process, we must determine the breakage time, breakage probability, *number of daughters and the daughter size distribution functions.*

2. WHAT I HAVE DONE

In this project, the breakage phenomena were investigated experimentally by high-speed imaging of single octanol droplets in a turbulent water flow. A new experimental facility was designed and produced based on four criteria:

1. A single droplet should be considered in each experiment.

2. The entire breakup process should be captured by camera and interpreted by a clearly defined procedure.

3. Repeatable and reproducible experiments should allow for sufficient statistical accuracy of the data.

4. The flow conditions in the region of breakage should be well known.

To fulfill the determined criteria, a facility utilizing channel flow was constructed (Figure 1).

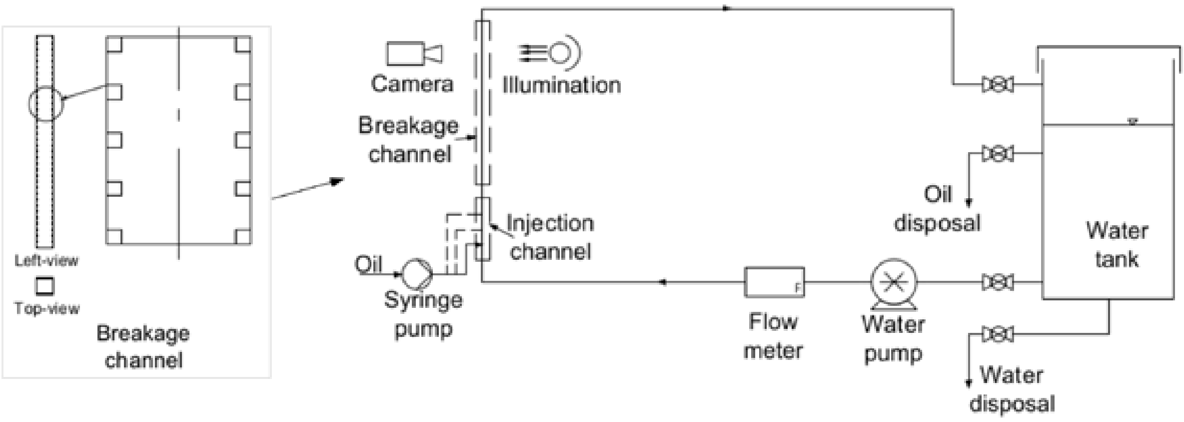


Figure 1: Schematic diagram of the experimental setup.

To study the continuous flow turbulence characteristics a Liquid-Doppler Velocimeter investigation was performed. The continuous phase flow conditions such as turbulence level can be determined from these instantaneous velocity measurements. To extract information on breakages from high-speed images, a well-defined image analysis was employed. The resulting data was combined to data points using a clearly defined statistical analysis procedure. Finally, the data points were investigated and compared to known model concepts.

The project was carried out in close collaboration with the SUBPRO project " 2.6 Particle breakup; turbulence and image analysis" (Nicolas La Forgia), and several of the publications were prepared in co-operation.

3. MAIN RESULTS
The impact of both the mother drop size and the turbulence characteristics on the particle breakage was investigated. Known correlations and model concepts could be fitted to the experimental data for the breakage time and the breakage probability with reasonable accuracy. However, the model parameter values were different from previous investigations, thus the models cannot be considered universal. The average number of daughters and the daughter size distribution function exhibits behaviors which are not in agreement with available model concepts.

4. INNOVATION
The experimental data from this work provides, for the first time, a complete set of data required to describe the breakup process. Hence, there is no longer a need to rely on experimental data gathered from different campaigns and incomplete data sets for model validation.

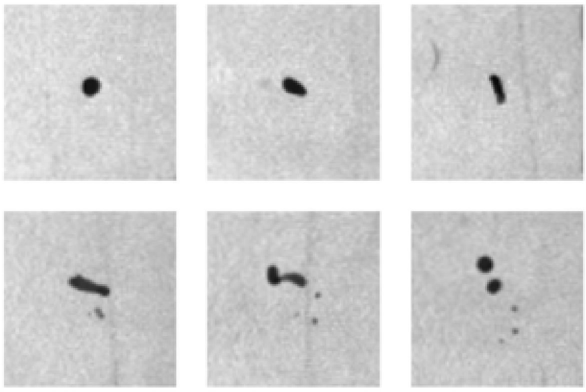


Figure 2: Image series of a breakup event, as captured by the camera

5. FURTHER WORK
Additional work could be performed on different dispersed oil phases, as well as increasing the range of droplet sizes and the range of turbulence intensity considered. This additional data would help to develop universal models.

6. COMPLETE LIST OF PUBLICATIONS AND REPORTS
Journal papers

La Forgia, N., Herø, E. H., Solsvik, J. and Jakobsen, H. A. Dissipation rate estimation in a rectangular shaped test section with periodic structure at the walls. Chemical Engineering Science 195, 159–178 (2018).

Herø, E. H., La Forgia, N., Solsvik, J. and Jakobsen, H. A. Determination of Breakage Parameters in Turbulent Fluid-Fluid Breakage. Chem. Eng. Technol. 42, 903–909 (2019).

Herø, E. H., La Forgia, N., Solsvik, J. and Jakobsen, H. A. Single Drop Breakage in Turbulent Flow: Statistical Data Analysis. Chemical Engineering Science X 100082 (2020).

Herø, E. H., La Forgia, N., Solsvik, J. and Jakobsen, H. A. Single Oil Drop Breakage in Water: Impact of Turbulence Level in Channel Flow. Chemical Engineering Science X 100111 (2021)

Conference papers

Shi, J., Herø*, E. H., Solsvik, J. and Jakobsen, H. A. Experimental and numerical study on single droplet breakage in turbulent flow. 12th International Conference on Computational Fluid Dynamics in the Oil and Gas, Metallurgical and Process Industries. Trondheim, Norway, May 30 - June 1, 2017.

Herø, E. H., La Forgia, N., Shi, J., Solsvik, J. and Jakobsen, H. A. On the turbulent dissipation rate in experimental investigation of single droplet breakage in fluid-fluid system. 6th International Conference on Population Balance Modelling, Ghent, Belgium, 7 - 9 May, 2018.

Herø, E. H., La Forgia, N., Solsvik, J. and Jakobsen, H. A., Investigation of the impact of turbulence on oil droplet breakage. Tekna Separation Technology 2018, Stavanger, Norway, October 16 - 17, 2018.

Poster: Herø, E. H., Shi, J., Solsvik, J. and Jakobsen, H. A., Experimental investigation of single fluid particle breakage due to turbulence. 22nd International Congress of Chemical and Process Engineering CHISA 2016, Prague, Czechia, 27 - 31 August, 2016.

7. MY NEW JOB
Company/institution: Sparebank1 SMN

Position/area of work: Data warehouse consultant

ASSOCIATE PROFESSOR
JOHANNES JÄSCHKE

RESEARCH AREA
MANAGER

RESEARCH AREA

System Control

Our goal is to design control systems and digital twins to realize intelligent autonomous production systems that ensure safe and optimal operation of subsea production and processing systems. This enables us to reduce emissions to air and water.

Subsea production and processing installations can improve the field economics by increasing recovery and reducing operation costs. However, they are not easily accessible and depend on being operated remotely.

Our vision is that subsea processes are operated autonomously, or with minimal human intervention and supervision. This means that the process should be able to regulate and monitor itself and make optimal operation decisions automatically.

In System control we study the development of new methods, models and tools related to autonomous, safe and optimal operation of such complex subsea processes.

Our current research focuses on:

- Short and medium-term production optimization of large-scale installations
- Production optimization taking equipment degradation into account
- Control algorithms and digital twins for energy-efficient production and processing
- Estimating unmeasured process variables, such as flow rates (Virtual Flow Metering) and sensor drift, (the latter applying digital twin models)
- Methods for determining the quality of the used digital twin models

Our overall aim is to develop tools and methods that are simple and robust enough for use in industrial subsea applications. The developed models are based on first-principles physics as well as data and machine learning. Controller, estimation, and optimization algorithms are developed using state-of-the-art methods and tested on industrially relevant case studies. We consider applications in subsea separation, boosting (multiphase pumping and compression) and gas-lifted wells.

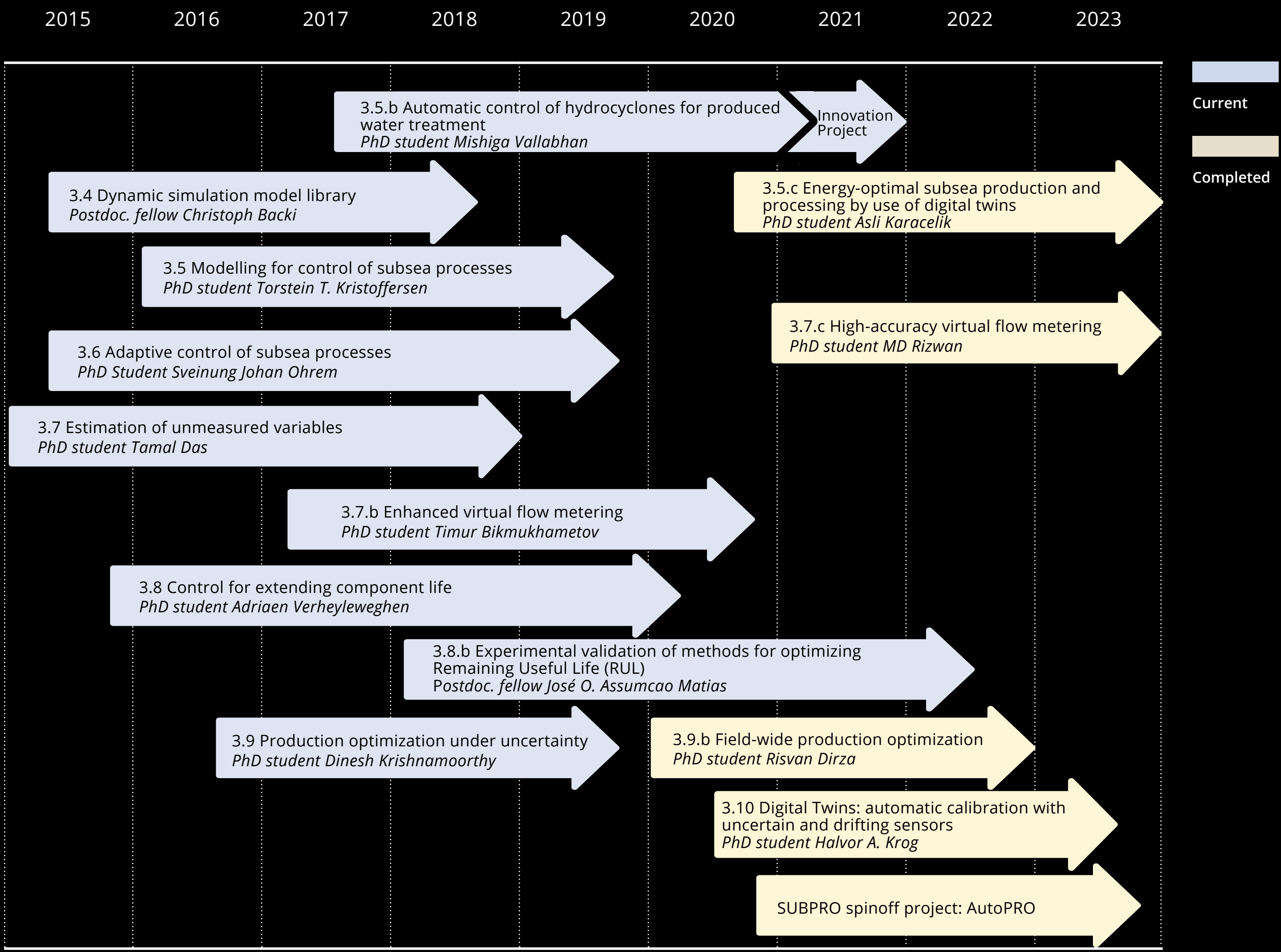
In the last year, we completed two projects:

- “3.5.b Automatic control of hydrocyclones for produced water treatment”
- (PhD student Mishiga Vallabhan)
- “3.8.b Experimental validation of methods for optimizing Remaining Useful Life (RUL)” (Postdoctoral fellow José Octavio Assumpcao Matias).

No new project started in the Systems Control area.

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

Completed and current projects



The System Control team at the compact subsea separator test rig.
From the left: Associate Professor Christian Holden, PhD student Md Rizwan, PhD student Halvor Aarnes Krog, Associate Professor Johannes Jäschke Professor Sigurd Skogestad, PhD student Risvan Dirza, PhD student Asli Karacelik

3.5.c Energy-optimal subsea production and processing by use of digital twins

Digital solution to reduce environmental footprint.

Green shift impact: Energy consumed per unit of production will be decreased.

PhD student:
Asli Karacelik

Project manager and main supervisor: Associate Professor Christian Holden

Co-supervisors: Adjunct Professor Gunleiv Skofteland (Equinor) Professor Sigurd Skogestad

1. BACKGROUND

Energy-efficient strategies are highly demanded in oil and gas fields to reduce production costs and carbon dioxide emissions. One way to increase efficiency is to improve the effectiveness of the process control. This project will develop and test advanced models for process control and optimization, based on model predictive control (MPC) and nonlinear model predictive control (NMPC), using machine learning and the so-called Bayesian Neural Network.

We will study a complete production system including gas-lift, three-phase gravity separator, hydrocyclone, injection pump, and a booster pump. These sub-systems mutually interact in complex ways, and an optimal point for a single sub-system alone might result in high costs for another.

Model predictive control (MPC) and nonlinear model predictive control (NMPC) with different optimization strategies are the themes of this study. MPC uses linear system models, whereas NMPC uses nonlinear system models. We want to understand how nonlinear dynamics affect subsea production and how NMPC can improve the control system.

2. RESEARCH DONE SO FAR

First, we studied the gas-lift system, which is highly nonlinear due to gas injection into the system. In this system, the liquid outflow rate depends on the well pressure. Gas injection increases this rate to some extent. However, giving more gas may result in a pressure increase, and this causes a new equilibrium in the system. When we increase pressure in the system, gas pressure resists the well pressure, which results in a lower liquid outflow rate. Therefore, there should be an optimum value for the gas accumulation in this highly nonlinear system.

We compared model predictive control (MPC) and nonlinear model predictive control (NMPC) for a gas-lift system using quadratic programming algorithm (QP) and sequential quadratic programming algorithm (SQP) in MATLAB, respectively. Gas injection rate is the manipulated variable in this system. We defined two different cases for the control variable. In the first case, gas accumulation (pressure) is the control variable, and in the second case, liquid outflow rate is the control variable. In this system, we cannot control the liquid outflow rate because well pressure mainly determines the liquid outflow rate. We wanted to understand the physical behavior of the system as a whole by investigating feasible and infeasible areas.

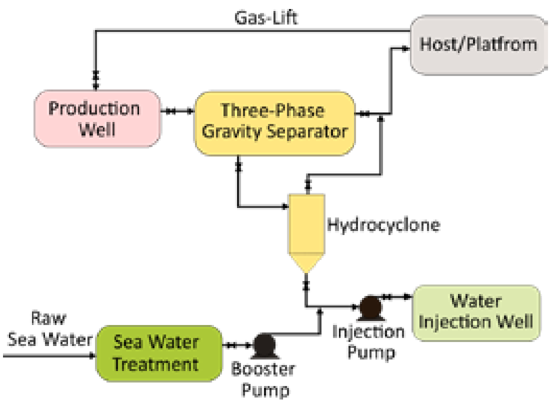


Figure 1: Flow diagram of subsea production and processing system

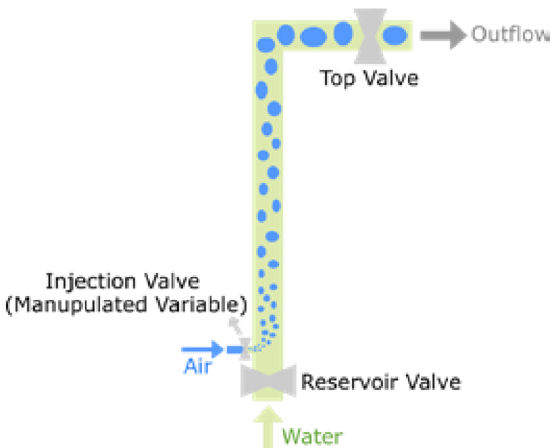


Figure 2: Gas-lift test system

3. RESULTS

We are testing different control schemes to improve the operational control of hydrocyclones when subjected to disturbances such as changes in inlet oil concentration and oil droplet distribution. The experimental results could be useful for industry to improve the operational efficiency of produced water treatment systems. The test facility can be used for testing different use cases from industry. The tests have so far given the following results:

1. Offset (deviation from the setpoint) in NMPC is lower than in MPC for both gas accumulation (pressure) and liquid outflow rate (ref. Figure 3 and 4). The offset of gas accumulation is higher than the offset of liquid outflow rate because nonlinearity in gas accumulation is higher.

2. NMPC gives a faster response than MPC when the system state is high above the operating region for gas accumulation (ref. Figure 5).

3. MPC doesn't respond efficiently to the nonlinear dynamics of the system. It gives a good response for an unachievable setpoint (ref. Figure 6).

4. We wanted to understand the effect of initial conditions on the global optimum as optimization methods don't guarantee a global optimum. We found steady-state conditions by changing the gas inflow rate (ref. Figure 7).

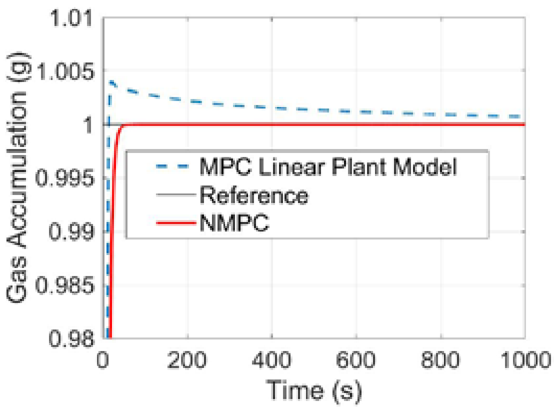


Figure 3: Gas accumulation offset

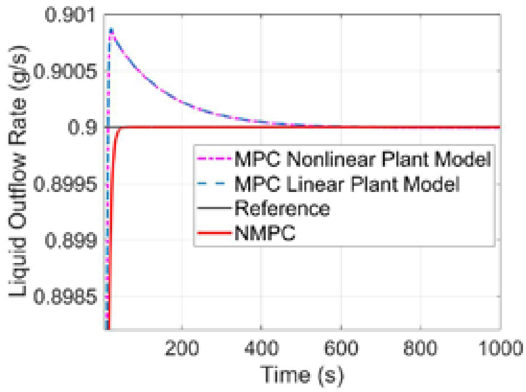


Figure 4: Liquid accumulation offset

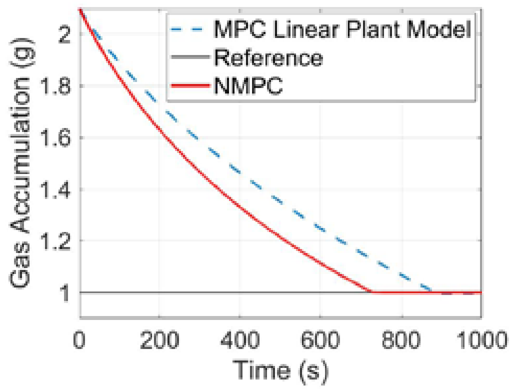


Figure 5: Gas accumulation offset high above operating point

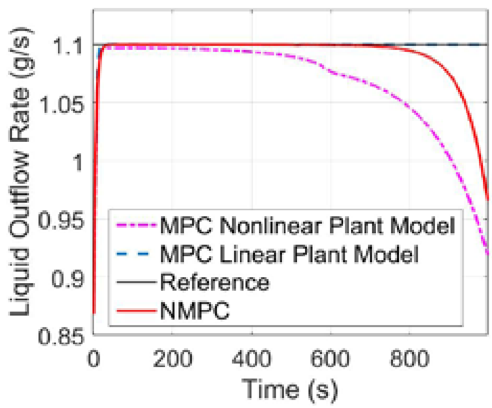


Figure 6: Unachievable setpoint for liquid outflow rate

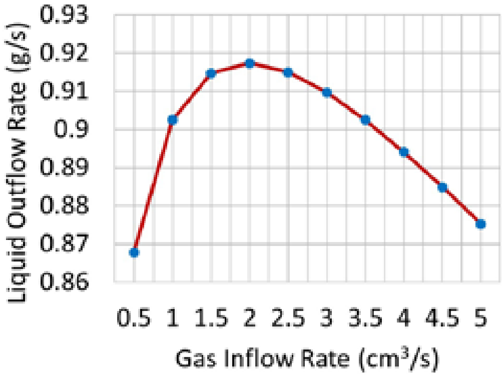
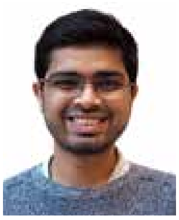


Figure 7: Liquid outflow rate at steady state

3.7.c High- accuracy virtual flow metering with machine learning and first principles models

A new method for accurate and inexpensive virtual multiphase flowrate metering, based on machine learning and first principles models

Green shift impact: Cheap and accurate virtual flow metering has a great potential, as it enables oil and gas industry to develop enhanced process control and optimization systems, leading to improved efficiency and reduced environmental footprint.



PhD student:
Md Rizwan

Project manager and main supervisor:
Associate Professor Christian Holden

Co-supervisors:
Associate Professor Johannes Jäschke
Associate Professor Milan Stanko

1. BACKGROUND

Multiphase flow metering provides an essential input to control and optimization systems for oil and gas production. Traditionally, flowrates have been measured by well tests which are associated with production losses, as they involve re-routing of the produced multiphase fluid streams to a test separator for estimation of single-phase flowrates. Alternatively, in-line multiphase flow meters have been applied. However, these sensors are costly to purchase and maintain in subsea operation. Another possible way to estimate multiphase flowrates is so called **Virtual Flow Metering (VFM)**, where the physical flow meters are replaced by cheaper, more accurate sensors (such as pressure or temperature) giving input to a mathematical model of the process, that allows the flow rate to be calculated rather than measured. These new possibilities to model complex systems are also facilitated by the recent availability of computing power and advances in machine learning algorithms. The plan is to bring virtual flow metering to its full potential; that is, building more powerful process control and optimization systems with accurate and inexpensive flow measurements based on reliable sensors instead of using inaccurate and expensive physical flow meters.

Most of the models for VFM developed in the past can be broadly classified into two categories, i.e., first principles models and machine learning models. These two approaches have associated advantages and limitations. The first principles models require a detailed understanding of the underlying physical phenomena of the complex process system which may be difficult and time-consuming to develop, but offers higher trust in the model predictions. On the other hand, machine learning models do not require deep process understanding, but require larger amounts of input data and have poor generalizability, meaning their performance is limited to the characteristics of the specific set of training data used in their development.

The goal of this project is to develop tools that combine machine learning methods with knowledge-based first principles models to develop hybrid models. These hybrid models will have higher predictive performance and can further be used to control and optimize overall production systems.

2. RESEARCH ACTIVITIES

The hybrid models will be developed for whole production systems, including several wells, subsea processing systems and topside facilities. A special focus will be put on finding methods that allow development of hybrid models with limited input data. Here, we believe that simplified first principles models can play an important role as they make partial prior information available to these hybrid models.

The ongoing case study involves a steady-state pipe flow simulation. The first principles pipe model is developed in Python and the synthetic training data is generated using OLGA simulation. The plan is to develop a hybrid model that enables the first-principles VFM model to utilize the information in the training data.

This hybrid VFM model is a probabilistic model, and we utilize Bayesian inference to estimate the unknown model parameters. Hence, we get a probability distribution rather than a point estimate of the unknown model parameters. This is useful as the probability distribution of estimated value helps quantifying the confidence that we can put in the developed hybrid model. In this case study, we estimate the unknown model parameter i.e., pipe roughness, $\in$ which is then used in Colebrook equation to calculate the friction factor ξ_{mix}. The calculated friction factor is then combined with the first principles model equations to estimate the multiphase flowrates (see Figure 1).

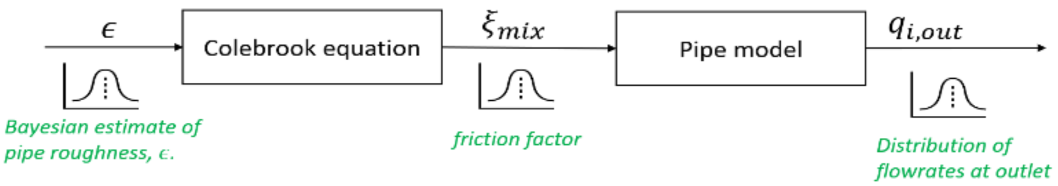


Figure 1: Illustration of a hybrid model developed for the VFM. The unknown model parameter is estimated using Bayesian inference and combined with the first principles based pipe model to get a distribution of the estimated flowrates.

Furthermore, we plan to combine static local models with dynamic models that capture the behavior of the system on a larger scale. In this approach the local machine learning model is trained using the limited input data to model certain parts of the system, for example, a choke. The output of this step is a trained local machine learning model of a part of the process system, which is then combined with overall first principles mass balance, that describes the system on a slower scale. This hybrid model is then used for the estimation of unmeasured variables, enabling decision making for process control and production optimization. This is visualized in Figure 2. We will investigate other promising approaches, too.

3. INNOVATION POTENTIAL AND INDUSTRIAL COLLABORATION

The project is motivated by the industry's need to operate existing assets economically and has received attention from industry partners (TechnipFMC) developing hybrid models for the VFM. Hence, we are planning to establish close collaborations with TechnipFMC to develop and apply the methods to industrial field data.

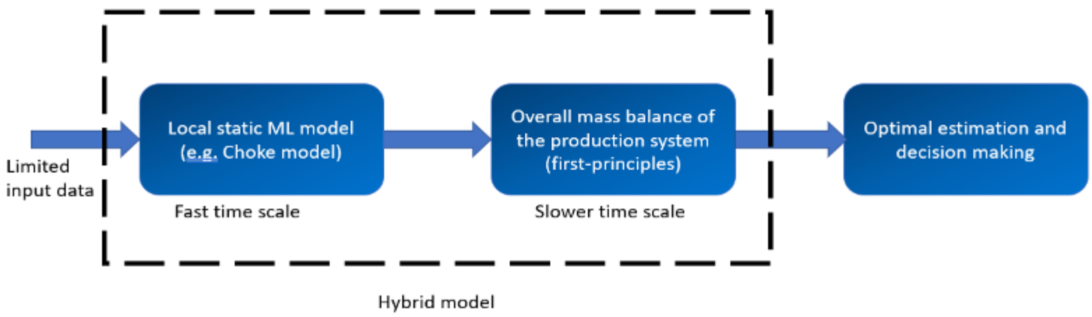


Figure 2: A possible way of combining first-principles models with data-driven machine learning (ML) models.

3.9.b Field-wide Production Optimization

Digital solutions to assist end-to-end oil and gas production optimization.

Green shift impact: Automated field-wide production optimization can contribute to reducing the carbon footprint of the daily operations by ensuring efficient resources utilization.

PhD student:
Risvan Dirza

Project manager and main supervisor:
Professor
Sigurd Skogestad

Co-supervisor:
Postdoctoral fellow
Dinesh Krishnamoorthy

1. WHY DO WE NEED A FIELD-WIDE PRODUCTION OPTIMIZATION?

With increasing energy demands, stringent emission regulations, and the volatile oil price, the complexity of oil and gas production is increasing. Consequently, daily production optimization is becoming a challenging task, where the objective is to maximize the operational profits as well as to minimize emissions and optimize resource allocation (e.g., lift-gas, fuel-gas, power, instrument gas) on a day-to-day basis. The production optimization requires a detailed model of the system to determine the optimal operation of the entire field. This is also known as field-wide production optimization. However, as the complexity and the scale of the systems increases, the models used may not be accurate enough to capture the real production system. This may lead to a sub-optimal operation.

Several discussions have been conducted with the industry partners Kongsberg Digital and Aker BP to determine possible case studies to demonstrate a field-wide production optimization. Kongsberg Digital has provided access to use a K-Spice simulator completed with data from a real case production system. Aker BP has granted access to analyze operation data in one of their production fields. These resources are essential to construct case studies that demonstrate important aspects of the project.

2. USING MODEL AND REAL-TIME PRODUCTION DATA TO SUPPORT OPTIMAL DECISION MAKING

The project has developed different methods to optimize production, given a large and/or complex oil and gas production system. One way to deal with the modeling task is to construct a simple/proxy model in parts (subsystem models). By doing so, it is practically easier to construct a sufficiently good model. Consequently, the subsystem models may have coupled variables such as shared resources to deal with, to obtain optimal operation for the entire production system. Each subsystem has typically a local numerical solver, that may have a numerical robustness issue. To avoid that solver, which is an initial goal of this project, we have developed a method, called DFRTO/Primal-dual, that can optimize the operation automatically using a trusted and proven tool such as simple feedback-based PID controllers [1][2][3], and we have validated the method in an experimental lab rig [4]. However, this method has a slow timescale constraint controller that may lead to significant back-off. To minimize the back-off, we have modified the method by introducing direct constraint control [5]. The next research question of introducing direct constraint control is how to select the right input to directly control the constraint. We address this issue in [6]. Introducing direct constraint control in fact is not enough to reduce the back-off if we have saturated input. Therefore, we introduce multi-input direct constraint control [7]. Alternatively, one can reformulate the problem into a primal decomposition framework [8]. This framework can also be formulated in graph-based theory [9]. Instead of using a simple/proxy model, one can construct a surrogate model or optimizer, that requires data, where machine learning tools can be useful. It is also possible to improve a less accurate model using data. In summary, this project focuses on developing and implementing (as far as possible) simple tools where real-time data can be utilized to make optimal decisions, given a large and/or complex production system.

3. WHAT WE HAVE DONE SO FAR

Several results have been obtained in the second year of this project to address open problems which we discussed in the previous section.

Deliverables

The following deliverables have been submitted, and some of the works have been published and presented:

[1] "Optimal Resource Allocation using Distributed Feedback-based Real-time Optimization." International Federation of Automatic Control Symposium on Advanced Control of Chemical Processes 2021 (Keynote Paper-Published).

[2] "Optimal Resource Allocation in a Subsea Oil Production Network Using Distributed Feedback-Based RTO. "
American Institute of Chemical Engineers Annual Meeting 2021 (Presentation).

[3] "Real-time Feedback-based Optimization Applied to an Energy-aware Gas-lift Optimization Problem"

[4] "Validation of Distributed Feedback-optimizing Control on an Experimental Gas-lifted Oil Well Rig" (Collaboration with SUBPRO Project 3.8.b Experimental validation of methods-Remaining Useful Life (RUL), José Matias)

[5] "Primal-dual Feedback-optimizing Control with Direct Constraint Control for Oil Production." The 14th International Symposium on Process System Engineering (Accepted).

[6] "Systematic Pairing Selection for Economic-oriented Constraint Control." The 32nd European Symposium on Computer-Aided Process Engineering (Accepted)

[7] "Online Feedback-based Optimization with Multi-input Direct Constraint Control."

[8] "Real-time Optimal Resource Allocation using Online Primal Decomposition" (Collaboration with SUBPRO Project 3.7.c High-accuracy virtual flow metering with machine learning and first principles models).

[9] Real-Time Optimal Resource Allocation and Constraint Negotiation Applied to A Subsea Oil Production Network". Society of Petroleum Engineers Annual Technical Conference and Exhibition 2021 (Published).

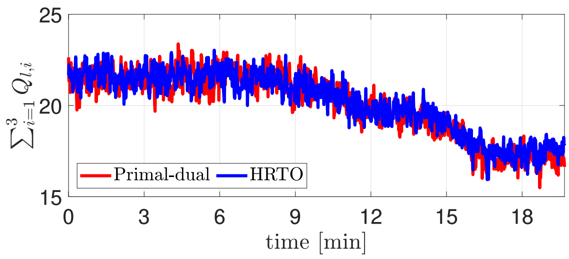


Figure 1: Results of experimental validation (ref. deliverable [4]): Our proposed approach applied and extended in [1][2] and [3] (indicated by the solid red line) has comparable performance, i.e., the same oil production rate, as the previous method Hybrid Real-time Optimization (HRTO) that still requires numerical solver (indicated by the solid blue line).

4. POTENTIAL INDUSTRIAL APPLICATIONS

As an ultimate goal, it is expected that the results from this project can be used for automated field-wide production optimization (or part of it) to increase daily operating income and to reduce operator workload. This will result in safer, more environmental-friendly, and better-optimized production.

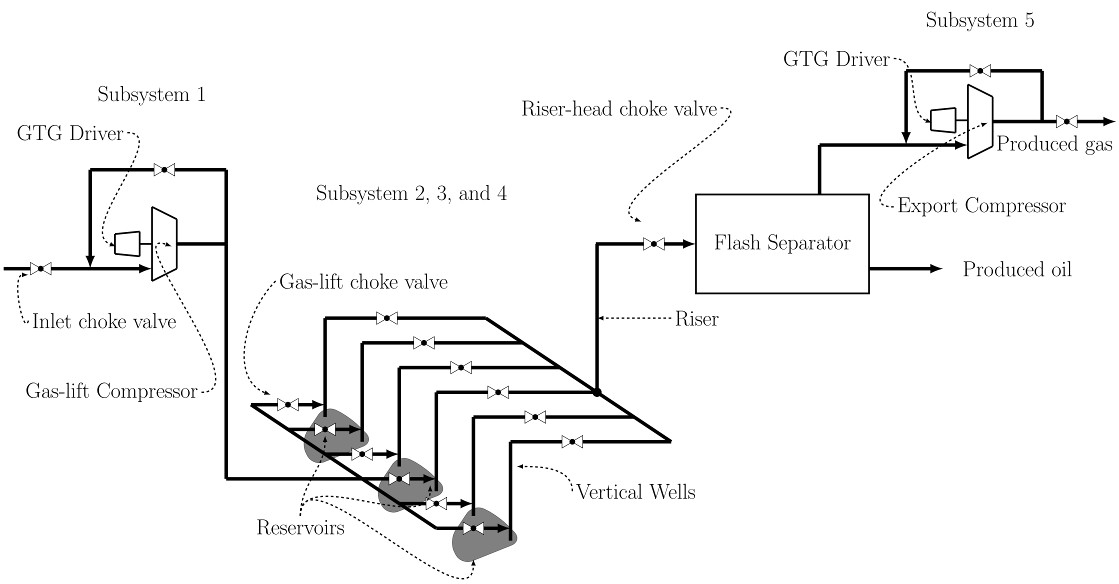


Figure 2: Selected "synthetic" case system for the project, comprising production and processing system for an oil and gas field with gas lift, control valves, separator, and gas lift compressor and export compressor [3].

3.10 Digital Twins: automatic calibration and decision making with uncertain and drifting sensors

How to trust your model when the measurements are drifting from the true value.

Green shift impact: The optimal operation of an asset, including minimizing the environmental impact, relies on matching the model with the physical asset to the greatest possible extent.

PhD Student:
Halvor Aarnes Krog

Project manager and supervisor: Associated Professor Johannes Jäschke

1. HOW CAN YOU TRUST YOUR PROCESS MODEL WHEN YOU KNOW YOUR SENSORS ARE DRIFTING?

All sensors drift over time. For example, assume that a temperature sensor was calibrated within 0.1 % accuracy when installed. The sensor could report that the temperature of the fluid was 100,1°C while the real value was 100,0°C. After some years of operation, all though the true value might be unchanged at 100,0°C, the sensor would have drifted and consequently could report a value of 103,0°C instead. As these measurements are often used to calibrate (or as input to) a process model, it would result into a mismatch between the model and the true plant. Any optimization based on the model may therefore result in sub-optimal plant performance. For top side facilities, the solution to the drift problem is simply to recalibrate the sensor at regular service intervals. This is not possible when the sensor is installed on the seabed. The drift must instead be estimated from the process data and process model.

Incorporating information about the sensor drift into the modelling phase is one of the aims of this project. Furthermore, automatic model calibration and model selection routines which take sensor drift into account will also be investigated. The overall project goals are therefore to

i. Minimize the real plant-model mismatch, resulting in operation closer to the truly optimal point.

ii. Inform whether your model is trustworthy or not, by quantifying the uncertainty. This is important information if the model is to be used as a tool for decision making, e.g. related to condition based maintenance.

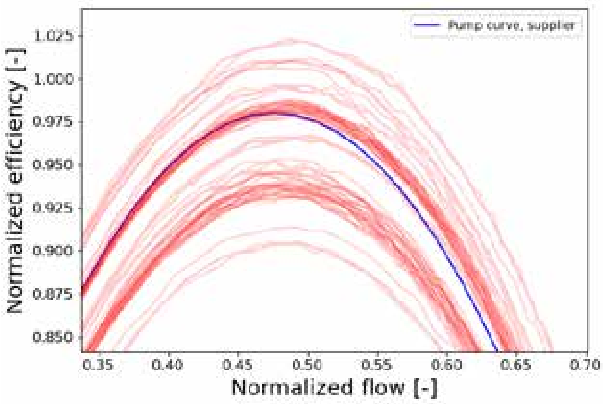
2. RESULTS THIS YEAR

State estimation is all about estimating quantities which are not directly measured, or refining low quality measurements to reliable estimates. This is done by combining information from a process model and available (uncertain) measurements. A model is never equal to the reality, and the state estimator needs to have user-supplied information about the uncertainty of the model. The uncertainty is called process noise, and a new method for quantifying the process noise has been developed and submitted to the DYCPOS conference.

A case study to estimate sensor drift on a subsea booster pump together with Aker Solutions and Equinor is one of the final goals of this project. To find out which state estimation method is most applicable to the booster pump, a simulator of the pump has been developed. State estimators with different pros and cons are currently tested on this simulator. The state estimator which is most suitable in the simulator will then be deployed on real data from our industry partners.

3. POTENTIAL INDUSTRIAL APPLICATIONS

Knowing when you can, or cannot, trust your model and measurements as decision making tools is important. If a decision is based on a model which is not reflecting reality, it may have significant adverse impacts on the economical operation of the plant. A modelling framework which incorporates uncertainty also in its input from the sensors has the potential for a broad usage area within the industry.



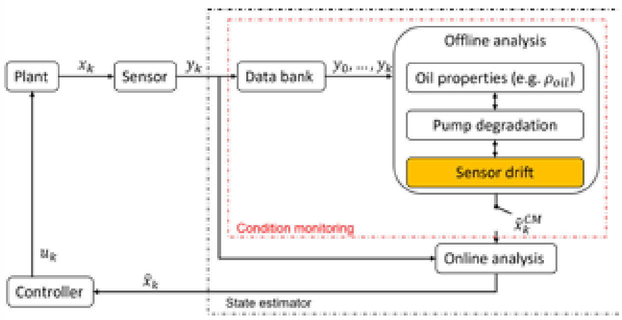


Figure 1: Efficiency vs flowrate for a pump in normalized values. Normalized efficiency means that the best operating point (BOP = max(actual efficiency)) is numerically adjusted close to 1. Hence, a value of 1 in normalized efficiency does not mean that the actual efficiency is 100%.

The blue line is the efficiency curve when the pump and sensors are brand new. If the pump is running on a fixed rpm, but the flow is increased by opening a choke valve, the process trajectory based on available measurements can be plotted.

A red line in the plot is one such process trajectory based on sensors which were calibrated 10 years ago. Every sensor in the plant can drift with a maximum rate. By taking 50 random realizations from the range of possible drift values, we can get an idea about a «band» for the process which can be caused by sensor drift.

The red band is quite wide, and the older the sensor the wider the band. This means that if a process trajectory for a 10 year old pump is plotted and i) it deviates from the supplier´s specification but ii) it is placed inside the red band, the deviation may be caused solely by sensor drift. However, we can deduce more from this plot. If the actual process trajectory is below the blue line, the reason can be e.g. sensor drift or pump degradation. If the process trajectory is above the blue line, we can infer that the cause is non-physical (efficiency of the pump does not improve with time) and the reason for such a trajectory must be related to sensor drift.
It is likely that utilizing process knowledge such as this can improve the quality of our estimates of the sensor drift

Figure 2: Simplified flowsheet of a process control system based on a Digital twin (State estimator). The state estimator provides reliable state estimates, $\hat{x}_k$, to the controller. Sensor drift and other properties which vary slowly over time (e.g. thermodynamic oil properties, degradation of equipment) is estimated in the condition monitoring function. The findings from this project should be implemented as a part of the condition monitoring of the plant. The sensor drift box is colored red as it is the primary focus area of this thesis. The switch between «offline analysis» and «online analysis» means that the offline analysis can be conducted whenever the user wants (e.g. twice per year).

AutoPRO:
Digitalization for Autonomous Prognosis and Production Optimization in Offshore Production Systems

A SUBPRO spin-off project.

Johannes Jäschke
(Associate Professor, NTNU Systems Control, Project leader and PhD supervisor)

Yiliu Liu
(RAMS Systems Control NTNU, PhD supervisor)

Edmary Altamiranda
(Aker BP, Industrial PhD supervisor)

The collaboration between SUBPRO and the industry partners resulted in the spin-off project AutoPRO, funded by the Norwegian Research Council. The project involves the Department of Chemical Engineering and the RAMS group from Department of Mechanical and Industrial Engineering, and is a collaboration project between NTNU SUBPRO, Aker BP and 3 Chinese Universities: China Univ. of Petroleum (E. China), Ocean University of China, and Beihang University. On the Chinese side, the industrial partners are Yantai Jereh and the Chinese National Offshore Oil Cooperation (CNOOC)

The primary research question addressed in AutoPRO is:

How can digitalization help to synchronize and provide optimal production and maintenance decisions in subsea oil and gas production systems?

The project builds on and advances novel technologies to realize the digital transformation of the oil and gas industry. More specifically, we use and develop methods from big data, artificial intelligence and machine learning, combined with in-depth domain knowledge, for decision-making for operation, control and maintenance.

In AutoPRO, there are two ongoing PhD projects at NTNU, and one postdoc project to start up in 2022. The projects are associated to the Systems Control Group and the RAMS group in SUBPRO:

1. Big-data digital twin modelling and diagnosis
(Evren M. Turan – Systems Control)

2. Condition-based maintenance decision-making with digital twins for subsea systems
(Malik Mohsin Abbas – RAMS)

3. Autonomous production optimization with degrading equipment
(Postdoc project TBA – Systems Control)

In memory of Sandeep Prakash

Sandeep Prakash worked as a PhD student in the project "Autonomous production optimization with degrading equipment" up to 2021, when he passed away unexpectedly.

The collaboration between Norway and China currently takes place in form of common online seminars. Student and lecturer exchange between Norway and China is planned, as soon as the circumstances allow for it.

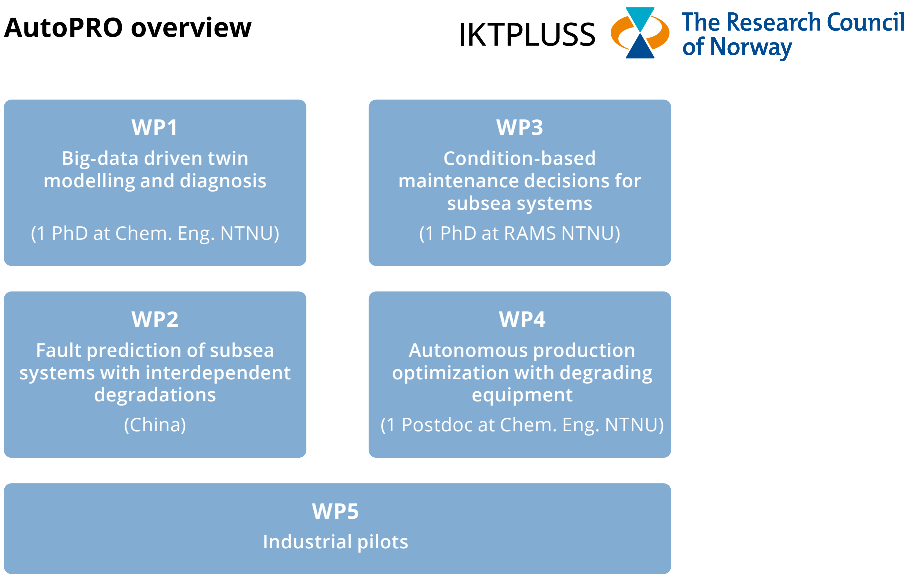


Figure 1: AutoPRO Project organization

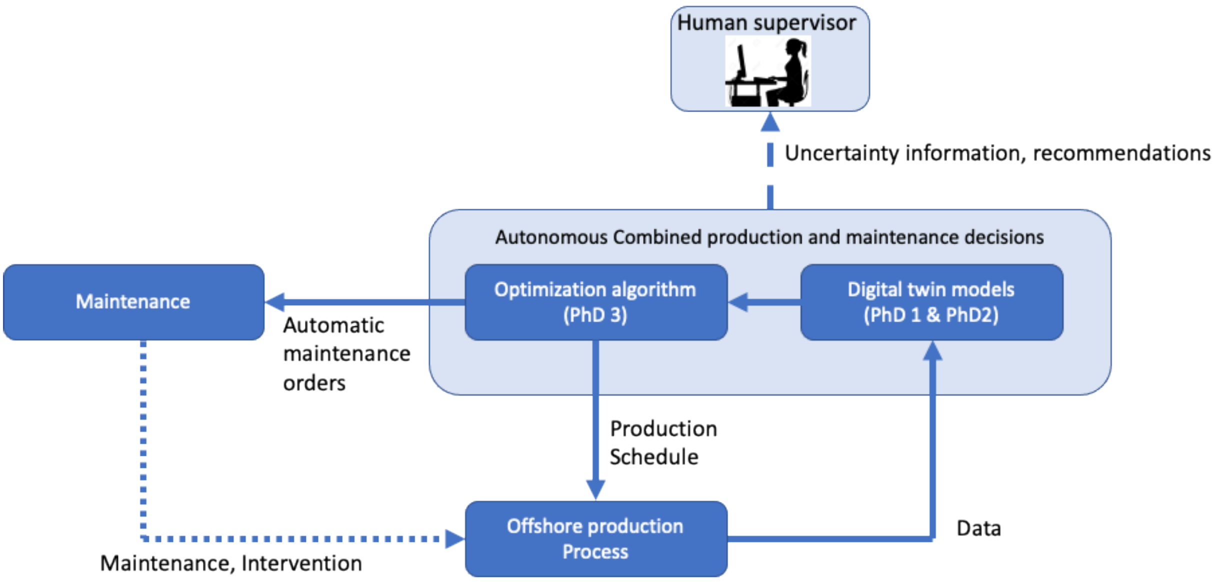


Figure 2: AutoPRO concept for realizing autonomous Production, including automatic matinenance ordering. Only high-level information is passed to the human supervisor.

FINAL PROJECT REPORT

3.5.b Automatic control of hydrocyclones for produced water treatment

A theoretical and experimental study of novel control schemes

Green shift impact: New control schemes can improve the efficiency of hydrocyclones and improve the quality of the produced water discharged to the sea.

PhD graduate:	**Mishiga Vallabhan K. G**
Start date:	01.11.2017
Defense date:	Pending
Title of the thesis:	Produced water treatment using hydrocyclones: Theoretical and experimental studies of novel control schemes.
Thesis committee members:	Zhenyu Yang, Associate Professor, Aalborg University Denmark Rune Husveg, Researcher, Thyphonix AS, Norway
Supervisor:	Associate Professor Christian Holden
Co-supervisors:	Professor Sigurd Skogestad Professor Olav Egeland

1. BACKGROUND

Produced water (PW) is a non-lucrative by-product of oil and gas production, and the quantity increases as the field ages. Produced water is either discharged into the sea or re-injected in the reservoir to enhance pressure. As per the Norwegian Environment Agency, 126.4 million m3 of produced water was discharged into the Norwegian sea in the year 2020. The discharge of produced water has to meet the European organization OSPAR's criteria, where the amount of dispersed oil is limited to 30 mg per litre of discharged water, on a monthly average. In addition, an efficient produced-water treatment system must meet environmental regulations before discharging the PW to the sea. De-oiling hydrocyclones, compact floatation units (CFUs), or their combination are commonly used for produced water treatment. Maintaining the efficiency of this compact equipment at varying process conditions is always a challenge.

This project focuses on de-oiling hydrocyclones, which are commonly used as produced-water treatment equipment on the Norwegian Continental Shelf. The compact and light nature of these hydrocyclones, which do not require any additional chemicals or gases to be injected for the operation, makes them attractive for subsea processing.

The main problem with hydrocyclones is the low residence time, which makes them more susceptible to upstream variations such as the changes in inlet oil concentration, changes in inflow rate and changes in droplet distribution. Typically, the ratio of pressure drop at inlet and the two outlets of the hydrocyclone is maintained using a pressure drop ratio (PDR) controller. This is an indirect way of maintaining the separation of hydrocyclones in the presence of disturbances. Also, this method is not effective in the presence of disturbance such as change in inlet oil concentration and change in inlet droplet distribution.

In this project we focused on designing and analyzing new controllers for hydrocyclones using direct oil concentration measurements. The main performance criteria for new controllers were to maintain water reject oil concentration at 30 ppm. The study in this project is relevant for both topside and subsea separation.

1. WHAT I HAVE DONE

- **Mathematical modelling:**
  A control-oriented mathematical model of the hydrocyclones was developed. This model has a static pressure-to-flow relationship which can estimate the flowrates and the pressures at the outlet of the hydrocyclones when the inlet conditions are known. The separation inside the hydrocyclone is approximated using a polynomial derived from droplet trajectory analysis. A simple mass-balance model is formulated to capture the dynamics and is used for the control. This model was used for developing new control schemes for de-oiling hydrocyclones.

- **Design and simulation study of new controllers:**
  New controllers for de-oiling hydrocyclones to improve separation which regulates the oil concentration of the underflow (water reject) at 30 ppm were designed and analyzed in simulation. Here, three model-based controllers; a model predictive, a

feedback linearization and a sliding mode controller were developed. We used the hydrocyclone model developed in this project for designing these controllers. Two model free controllers: a cascade and a feed-forward were also tested in simulation. In cascade control, the pressure drop ratio (PDR) and the oil concentration at the water reject are the secondary and primary process variables, respectively. Here, the primary controller is the oil concentration controller, and this controller gives the setpoint to the traditional PDR controller. In the feed forward controller we are using predictive static map as the feed-forward algorithm. The predictive model acts as a supervisory layer and gives the setpoint to the traditional PDR controller.

- **Test rig construction and testing of control schemes:** As part of this project a test rig was constructed, with industrial scale hydrocyclone liners and other auxiliary systems, to support the testing of the controllers. The test rig can emulate the first stage gravity separator and generate different disturbances at the inlet of the hydrocyclones installed in the rig. We implemented three new control schemes: a cascade, a feed-forward, and a direct control scheme on this test rig.

- SUBPPRO project collaboration:
    - "2.1.b Influence of chemicals on produced water quality" (Marcin Dudek, Postdoctoral fellow)
    - "3.8.b Experimental validation of methods - Remaining Useful Life (RUL)" (José Matias, Postdoctoral fellow)

- **Industrial cooperation:** We have received input from Equinor during the design phase of the rig. During the reference group meeting, Equinor showed interest in the results of the new control schemes that we proposed, especially cascade control scheme. Recently Kongsberg Digital has indicated some further research objectives and they may be interested to use the test rig and the sensor readings from the rig for updating the models.

3. MAIN RESULTS

- A mathematical model for hydrocyclones was developed, which can be used for studying different control schemes. It can also be used for estimation of oil concentration in produced water.

- Different control schemes were proposed for hydrocyclones to mitigate the problems of PDR controllers. All these controllers were studied in simulation, and results shows that new control schemes were able to handle the disturbances such as change in oil concentration and droplet distribution at the inlet of the hydrocyclones. Also, the controllers were able to maintain the oil concentration at the water reject at 30 ppm.

- Three of the newly proposed control schemes were tested at the experimental test rig and all of them showed better performance than traditional PDR control with disturbance such as change in inlet oil concentration and droplet distribution. The performance criteria for all the three control schemes was to keep the water-reject concentration below 30 ppm. Different disturbances such as change in inflow rate, change in inlet oil concentration and change in inlet droplet distribution were created at the test rig and all the three control schemes were able to keep the oil concentration at a given setpoint (30 ppm).

- A pump and tank system module capable of emulating the first stage gravity separator, was constructed and commissioned during this project. This test setup can generate changes in inflow rate, oil concentration and droplet distribution which can be used as an input system to any produced water treatment equipment, and this can be used for testing related to industrial use cases.

4. INNOVATION, INDUSTRIAL APPLICATION OF PROJECT RESULTS

- The three new control schemes- cascade, feed forward and direct schemes - were proven to mitigate the problems of traditional PDR control scheme. The results indicate that cascade control scheme would be an easy choice to be implemented in the industry and can be added as a supervisory layer to existing PDR control scheme.

- The experimental test rig developed in this project can be utilized for testing industrial use cases for produced water treatment. The laboratory is equipped with two online oil-in-water analyzers placed at the inlet and the water reject of the hydrocyclones. These sensors can measure oil concentration, droplet size (Dv50) and can give droplet distribution.

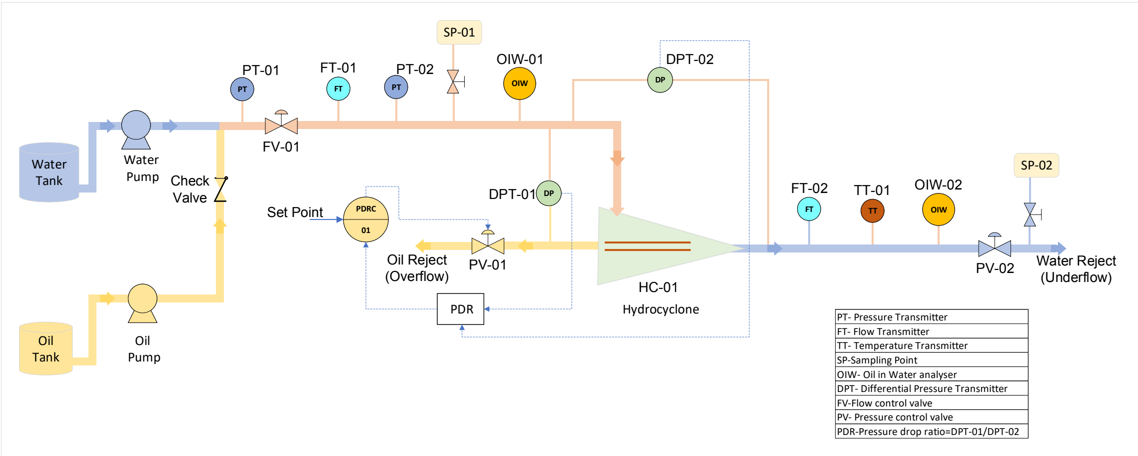


Figure 1: Simplified P&ID of the new experimental test rig at NTNU

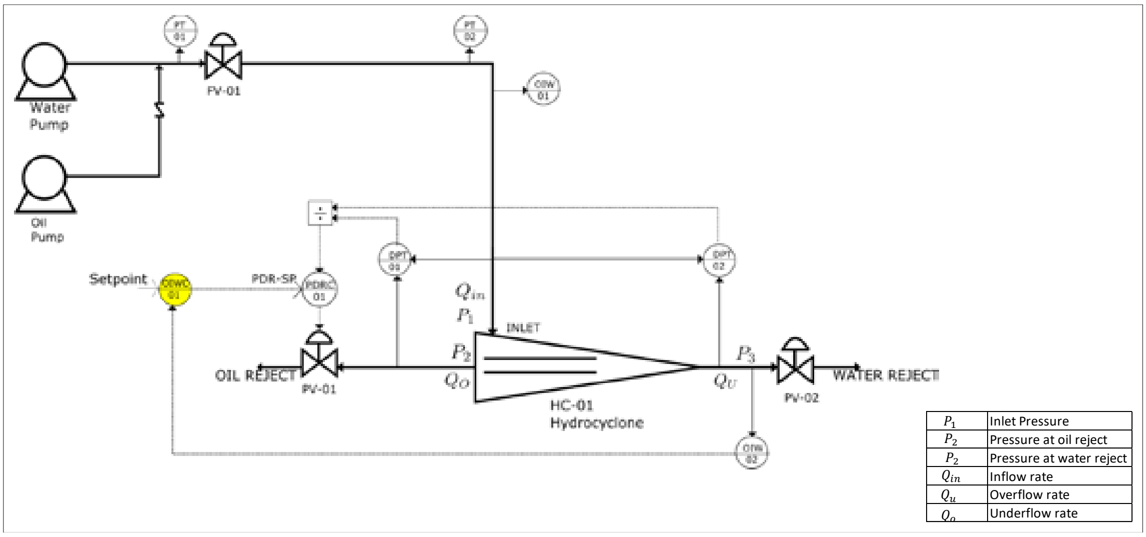


Figure 2: New cascade control scheme for hydrocyclones implemented on the test rig

5. FURTHER WORK

- To make use of the hydrocyclone model as part of a complete separation system, the model needs to be validated and model parameters need to updated using real-time or experimental data. Relationships between the percentage of separated oil and the overflow rate is an important factor that needs to be validated based on the experimental data.

- An optimized control strategy to maximize the water removal capacity of the hydrocyclone while keeping the oil-in-water concentration at the limit prescribed by the environmental agencies is another possibility of future work. For this, the interaction of hydrocyclones with upstream separators such as a gravity separator or a pipe separator needs to be considered.

- The test-setup at NTNU is equipped with two series hydrocyclones and corresponding control valves and instrumentation at the oil reject and water reject outlets. As a future work, new control schemes proposed in this project can be tested for two series hydrocyclones at the test rig.

6. COMPLETE LIST OF PUBLICATIONS AND REPORTS

1. Vallabhan KG, M. V., Holden, C., and Skogestad, S. (2020). A First-Principles Approach for Control-Oriented Modeling of De-oiling Hydrocyclones. Industrial \& Engineering Chemistry Research, 59(42), 18937-18950.

2. M. Vallabhan, J. Matias and C. Holden. Feedforward, cascade and model predictive control algorithms for de-oiling hydrocyclones. Journal of Modeling, Identification and Control (MIC 2022).

3. M. Vallabhan and C. Holden, Non-linear control algorithms for de-oiling hydrocyclones, 2020 28th Mediterranean Conference on Control and Automation (MED), 2020, pp. 85-90, doi: 10.1109/MED48518.2020.9183115.

4. Vallabhan K. G., Mishiga, Dudek, Marcin, and Christian Holden. Experimental Test Setup for De-oiling Hydrocyclones Using Conventional Pressure Drop Ratio Control. SPE Prod & Oper (2022;): doi: https://doi.org/10.2118/208608-PA

5. Vallabhan K. G., Mishiga, Holden, Christian, and Skogestad Sigurd. De-oiling hydrocyclones: An experimental study of new control schemes. SPE Prod & Oper (2022;): Accepted for publication.

7. MY NEW JOB

Company/institution: ABB AS, Trondheim, Norway
Position/area of work: Senior Project Engineer Automation

Figure 3: Hydrocyclone test rig with pump and tank system.
PhD student Mishiga Vallabhan and her project manager and main supervisor Associate Professor Christian Holden.

FINAL PROJECT REPORT

3.8.b Validation of methods for optimizing remaining useful life (RUL) and experimental studies in gas-lift optimization

Experimental validation of cutting-edge automation methods that support decision-making on economic optimization and maintenance.

Postdoctoral fellow:	**José Otavio Assumpcao Matias**
Start date:	15.11.2018
Final date:	14.01.2022
Title of the thesis:	Experimental validation of methods - Remaining Useful Life (RUL)
Supervisor:	Associate Professor Johannes Jäschke

1. HEALTH-AWARE CONTROLLER (HAC): COMBINING PRODUCTION OPTIMIZATION AND EQUIPMENT HEALTH MONITORING

There is an intuitive trade-off between optimizing production and minimizing equipment degradation. In oil wells, for example, we want to extract as much oil as possible; however, the equipment tends to degrade faster if we increase the throughput.

To address this trade-off, we applied a Health-aware controller (HAC) proposed by Escobert et al. (2012)[1]. This tool combines production optimization techniques with equipment health monitoring. Consequently, the controller can maximize the system's economic performance, while preventing unexpected breakdowns. A block diagram illustrating this controller is shown below.

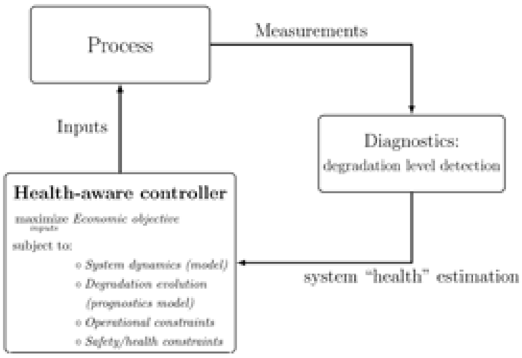


Figure 1: Health-aware controller block diagram

The health-aware controller has been previously studied in an earlier SUBPRO project, "3.8 *Control for extended project life*" (Adriaen Verheylewegen). Despite the encouraging results, the project outcomes were based on simulations only. To test the applicability of this type of controller, and to move it towards a higher Technical Readiness Level (TRL) and closer to implementation in industry, we designed and set up a lab rig on which accelerated life testing of critical components in oil production systems could be carried out.

The rig emulates a 3-well network where a mixture of water and air flows through a probe, which is placed inside an "erosion box". The probe and erosion box could for instance emulate a choke valve connected to a well. The probe was designed to erode fast, in less than 1 hour. Since its degradation is not only a function of time but also the flowrates of liquid and gas, we used our health-aware controller to define an operation policy that maximizes the liquid throughput and at the same time avoids that the probe erosion reaches a given threshold, corresponding to a breakdown, before the next planned maintenance.

[1] Escobet, T., Puig, V., & Nejjari, F. (2012, July). Health aware control and model-based prognosis. In 2012 20th Mediterranean Conference on Control & Automation (MED) (pp. 691-696). IEEE.

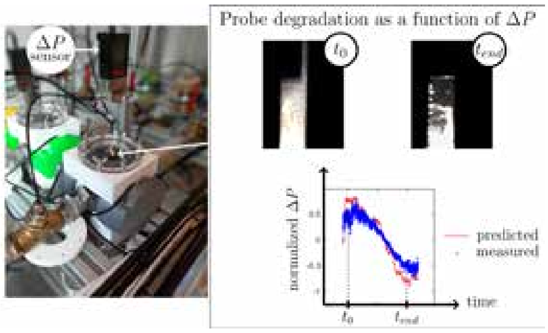


Figure 2: The left figure shows the "erosion box" of one of the wells, which consists of a chamber to place the probe as well as a set of cameras used for monitoring (the controller does not use the images). The initial (t0) and the final probe (tend) probe images are also shown. The white part of the image is the probe surface that is impeding the fluid flow. As the probe degrades, the cross-section area increases and the delta pressure (ΔP) along the "erosion box" decreases. Thus, we can use the delta pressure (ΔP) measurement as an indicator of the system health.

The main experimental results are shown below. We compared HAC with two different operation strategies. The first focuses only on maximizing liquid production (Max. Production). The second one (Min. Production) aims at guaranteeing that the system will not break until the next planned maintenance stop (arbitrarily chosen at t = 50 min) by adopting a worst-case scenario strategy with minimum liquid production. The use of the HAC focuses on optimal production combined with prevention of breakdown before scheduled maintenance, as mentioned above. The conclusion is that even with a very simplified predictive model of the system degradation, the HAC can avoid unexpected breakdowns and improve the economic performance.

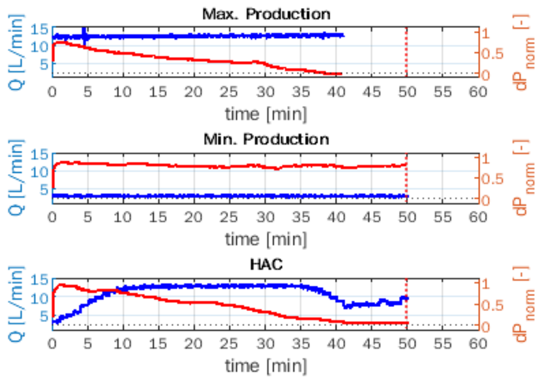


Figure 3: Experimental results of the three operation policies applied to the lab rig. In blue, we show the liquid production of the well and in red the normalized pressure drop over the probe. We also plot a line indicating the normalized pressure drop of 0. When the measured dPnorm along the "erosion box" reaches this value, we assume that the system is broken. We indicate the planned maintenance stop at t = 50 min.

2. INNOVATION PROJECT: EXPERIMENTAL STUDIES IN GAS-LIFT OPTIMIZATION

While the primary objective of the lab rig was to test the health-aware controller, the rig was designed in such a way that it also lends itself to testing gas lift optimization approaches. Since in previous and ongoing SUBPRO work (e.g. "3.9 Production optimization under uncertainty", Dinesh Krishnamoorthy, "3.9.b Field wide production optimization", Risvan Dirza), there has been a significant focus on production optimization using gas-lift methods, we also carried out an Innovation Project, in which we experimentally verified and tested control approaches for gas-lift optimization using the control infrastructure of the lab rig.

The experimental results complemented the previous findings obtained in simulations. We showed that the production optimization methods proposed in other SUBPRO projects (such as "Hybrid Real-time Optimization" and "Distributed Feedback-based Real-time Optimization") are feasible and have the potential to improve the system performance, which is a prerequisite for further research that may then lead to industrial validation.

For example, in the figure below (that is part of Matias et al. (2022)[2]), we compared the economic performance of Hybrid Real-time Optimization (HRTO) to the Steady-state Real-time Optimization (SSRTO) and Dynamic Real-time Optimization RTO (DRTO), which are state-of-the-art techniques for production optimization. The experimental results confirmed the in silico findings of Krishnamoorty et al. (2018)[3]: in gas-lift oil well networks, HRTO's economic performance is similar to DRTO's performance with a much lower computational cost.

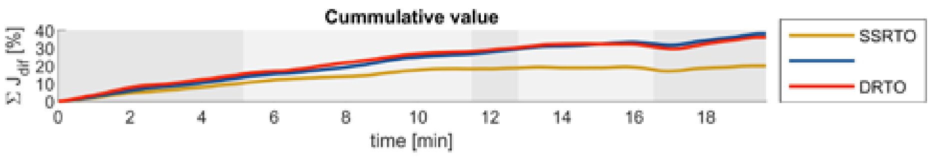


Figure 4: Comparing the economic performance of Hybrid Real-time Optimization, Steady-state Real-time Optimization, and Dynamic Real-time Optimization. Here, we normalized the profit J using the operation policy without any production optimization methods. More information in Matias et al. (2022)[2])

[2] MATIAS, JOSÉ; OLIVEIRA, JÚLIO P.C.; LE ROUX, GALO A.C.; JÄSCHKE, JOHANNES, Steady-state real-time optimization using transient measurements on an experimental rig, Journal of Process Control (under review), 2022.

[3] Krishnamoorthy, D., Foss, B., & Skogestad, S. (2018). Steady-state real-time optimization using transient measurements. Computers & Chemical Engineering, 115, 34-45.

3. MAIN OUTCOMES AND FUTURE WORK

This project led to several publications in international scientific journals and conferences with a strong focus on process systems engineering and process control. Additionally, I was able to co-supervise and collaborate with several Master's and Ph.D. students within SUBPRO, from the process control and RAMS groups. The rig was important to offer Master's and Ph.D. students at NTNU hands-on training experience, leading to graduates with a set of skills and expertise more tailored to the industry's needs. Moreover, I also had the opportunity to collaborate with exchange students from Brazil and Tanzania in projects based on the rig.

In addition to the lab rig, which can be used by other SUBPRO students to validate their approaches in the future, we also developed a "digital twin" of the rig. There, the students can run preliminary tests and check the potential challenges when using the lab. Also, the rig has a detailed manual that can be helpful for further revamping the system.

4. COMPLETE LIST OF PUBLICATIONS

Journal papers

MATIAS, JOSÉ; OLIVEIRA, JÚLIO P.C.; LE ROUX, GALO A.C.; JÄSCHKE, JOHANNES, Steady-state real-time optimization using transient measurements on an experimental rig, Journal of Process Control (under review), 2022.

VALLABHAN, MISHIGA; MATIAS, JOSÉ; HOLDEN, CHRISTIAN, Feedforward, cascade and model predictive control algorithms for de-oiling hydrocyclones, Modeling, Identification and Control (submitted), 2022.

MATIAS, JOSÉ; KUNGURTSEV, VYACHESLAV; EGAN, MALCOLM, Simultaneous online model identification and production optimization using modifier adaptation, Journal of Process Control, 2021.

LIU, XINGHENG; MATIAS, JOSÉ; JÄSCHKE, JOHANNES; VATN, JØRN, Gibbs sampler for noisy transformed gamma process: Inference and remaining useful life estimation, Reliability Engineering and System Safety, 2021.

MATIAS, JOSÉ; JÄSCHKE, JOHANNES, Online model maintenance in real-time optimization methods, Computers and Chemical Engineering, 2020.

MATIAS, JOSÉ; JÄSCHKE, JOHANNES , Online model maintenance via output modifier adaptation. Industrial and Engineering Chemistry Research, 2019.

Conference papers

NGUYEN, VINH P. B.; MATIAS, JOSÉ; JÄSCHKE, JOHANNES, Convolutional neural network as a steady-state detector for real-time optimization, European Control Conference (ECC) (submitted), 2022.

MATIAS, JOSÉ; GHEBREDNGL, SALMON Y.; JÄSCHKE, JOHANNES, Health-aware control using hybrid models applied to a gas-lifted oil well network, European Symposium on Computer Aided Process Engineering (ESCAPE) (submitted), 2022.

MATIAS, JOSÉ; MYRVANG, FRIDA B.; JÄSCHKE, JOHANNES, Implementation of extremum seeking control in an experimental lab-rig, Dynamics and Control of Process Systems, including Biosystems (DYCOPS) (submitted), 2022.

DIAS, ANA C.S.R.; MATIAS, JOSÉ; SOUZA Jr., MAURICIO B.; PINTO, JOSÉ C.; JÄSCHKE,

JOHANNES, Virtual flow metering: implementation on experimental rig, Brazilian Congress of Chemical Engineering, 2021.

MATIAS, JOSÉ; OLIVEIRA, JÚLIO P.C.; LE ROUX, GALO A.C.; JÄSCHKE, JOHANNES, Real-time optimization with persistent parameter adaptation applied to experimental rig, Advanced Control of Chemical Processes (ADCHEM), 2021.

JAHREN, JAN H.; MATIAS, JOSÉ; JÄSCHKE, JOHANNES, Data-driven modelling of choke valve erosion using data simulated from a first principles model, European Symposium on Computer Aided Process Engineering (ESCAPE), 2021

MATIAS, JOSÉ; ÅGOTNES JOACHIM; JÄSCHKE, JOHANNES, Health-aware advanced control applied to a gas-lifted oil well network, Advanced Maintenance Engineering, Services and Technologies (AMEST), 2020

MATIAS, JOSÉ; JÄSCHKE, JOHANNES, Using a neural network for estimating plant gradients in real-time optimization with modifier adaptation, Dynamics and Control of Process Systems, including Biosystems (DYCOPS), 2019

5. MY NEW JOB

Company/institution: McMaster University, Canada
Position/area of work: Postdoc

References

1 Escobet, T., V. Puig, and F. Nejjari. "Health aware control and model-based prognosis." 2012 20th Mediterranean Conference on Control & Automation (MED). IEEE, 2012.

2 Matias, José, et al. "Steady-state Real-time Optimization Using Transient Measurements on an Experimental Rig." arXiv preprint arXiv:2109.00795 (2021).

3 Krishnamoorthy, D., Foss, B., & Skogestad, S. (2018). Steady-state real-time optimization using transient measurements. Computers & Chemical Engineering, 115, 34-45.

Figure 5: From left to right: associate PhD student Allyne dos Santos (Faculty of Natural Sciences NTNU) and Postdoctoral fellow Jose Otavio Assumpcao Matias working on the lab rig developed in this project for testing the health-aware controller and control approaches for gas-lift optimization.

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 participation 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 are running case projects based on field data from the industry partners.

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

The PhD students present their work at industrial conferences like ESREL, Subsea Valley and Underwater Technology Conference. Due to covid-19 restrictions these activities were scaled down in 2021 but will be picked up again in 2022.

CROSS DISCIPLINE WORK
SUBPRO is a cross disciplinary project, involving four departments and three faculties at NTNU. The industry urges the researchers to stick their heads together and create synergies between the projects. This has become

PhD student Leonardo Sales presenting his project in a Reference group meeting February 2022

the working culture of SUBPRO. The PhD students arrange technical seminars (tech-lunches) at regular intervals, and many of the projects collaborate on common research tasks, leading to co-authoring of publications.

INTERNATIONAL COLLABORATION
The PhD students have the opportunity to arrange visits and work exchange periods at other universities and research institutions around the world.

The system control team together with the Norwegian delegation at the DYCOPS conference in Florianopolis in Brazil - 2019

Master students projects and summer internships at SUBPRO

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

NTNU is the major supplier of Master candidates to the oil and gas industry in Norway. SUBPRO has motivated the master students to studying petroleum related subjects, pointing at future field developments, technological and environmental challenges and the prospected job market. In 2021, about 20 master students delivered Master theses connected to SUBPRO. Some of these students were also hired by SUBPRO or their industry partners for summer internships.

The SUBPRO industry partners meet the master students at 4th grade usually at an annual spring term meeting at NTNU, where the industry presents subsea technology projects and opportunities for industrial Master projects . This industry - student meeting was arranged in early 2022, while in 2021, it was cancelled due to the Covid-19 restrictions. Still some students collaborated with industry partners during summer 2021.

Did you know that there are approximately five openings every year, to get a summer internship at SUBPRO research centre?

In 2021, SUBPRO offered five summer internships for fourth-grade students from NTNU.

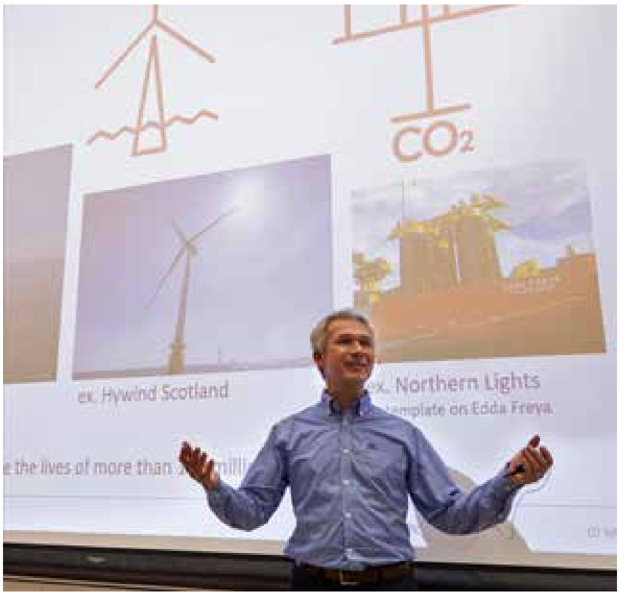
Further, the option to continue with the industry-oriented specialization project during the fall of 2021 and the Master thesis during the spring of 2022, was offered to the students.

The topics of the internships covered various research areas from SUBPRO and were as follows:

- Microfluidic testing of foam stability
- Fluid particle breakage experiments by high speed imaging
- Real-time Optimization using simplified models applied to a lab rig
- Online spectroscopy in microfluidic systems using Design of Experiments approach
- Virtual flow metering

SUBPRO encourages its summer students to extend their assignments after the Master degree, by applying for a PhD education at NTNU and SUBPRO.

Student-industry partner information meeting at NTNU in March 2022



Audun Faanes from Equinor presenting projects for sustainable energy production to the Master students at NTNU

Group session in the cross-disciplinary project Experts in Teamwork, which is mandatory for all Master students at NTNU. This group has chosen "Sustainable solutions for process industry" as their topic.

Social and collaborative experience

Through social events, colloquia and excursions, the PhD students and NTNU staff get to know each other and get insights in each other's projects.

The students are encouraged to collaborate across projects through sharing of technical advice, cooperation on research work and co-writing of publications.

Traditionally SUBPRO has arranged a social event and an excursion to an industrial site every year, and since 2019 these exursions have been combined with meeting fellows from the BRU21 project. Unfortunately, it was not possible to uphold our tradition in 2021, due to the Covid-19 restrictions, but we are restarting in 2022, with an excursion to SINTEF Multiphase Flow Laboratory in Trondheim and a social trip to Oppdal ski resort.

BRU21 is a parallel NTNU Research and Innovation Program that kicked off in 2018, with focus on Digital and Automation Solutions for the Oil and Gas Industry.

The combined BRU21/SUBPRO technical and social event took place for the first time through a social trip to Oppdal during 2019 where PhD students and postdocs from SUBPRO were able to initiate contact and social interaction together with their fellows from BRU21. One year later, from the 6th-7th March 2020, the two projects arranged a second common trip to Røros. The trip contained a program that combined both technical content and a lot of fun!

SUBPRO TECH-LUNCH

Due to Covid-19 restrictions, most of the Tech-lunch sessions at SUBPRO during 2021 took place on a digital platform, or at least with a digital option. Despite the physical distancing, PHD students and postdocs at SUBPRO were able to meet on regular intervals; in an informal context combining social interaction and multi- discipline collaboration possibilities through knowledge sharing.

PhD students Haoge Liu and Mehman Ahmadli discussing common aspects of their projects.

A technical presentation was included in each event – where topics and presenters were selected based on recommendations from the students themselves.

SUBPRO CHRISTMAS PARTY

At the end of every year all members of the SUBPRO team; management, project managers, PhD, postdocs and master students celebrate the achievement of a full year while enjoying a Christmas party, and announcing plans for the upcoming year.

In December 2021 we arranged a very nice and cosy Christmas party (julebord) for our staff, at Gløshaugen Campus.

Photo taken during a combined excursion for SUBPRO and BRU21 PhD students to the FMC Spoolbase at Orkanger facilities in March 2019, followed by a weekend stay at Oppdal downhill centre.

International Collaboration

Despite Covid travel restrictions, international collaborations at SUBPRO continued in 2021, but there has been less direct contact than in 2019 and earlier. Almost all conferences etc. have been digital.

Nevertheless, there have been some international collaboration activities:

- IAESTE exchange student: Jan Vyslouzil (Czech Republic)

- PhD student (Ludvig Björklund) is on a research stay in University of Aalen, Germany since September 2021.

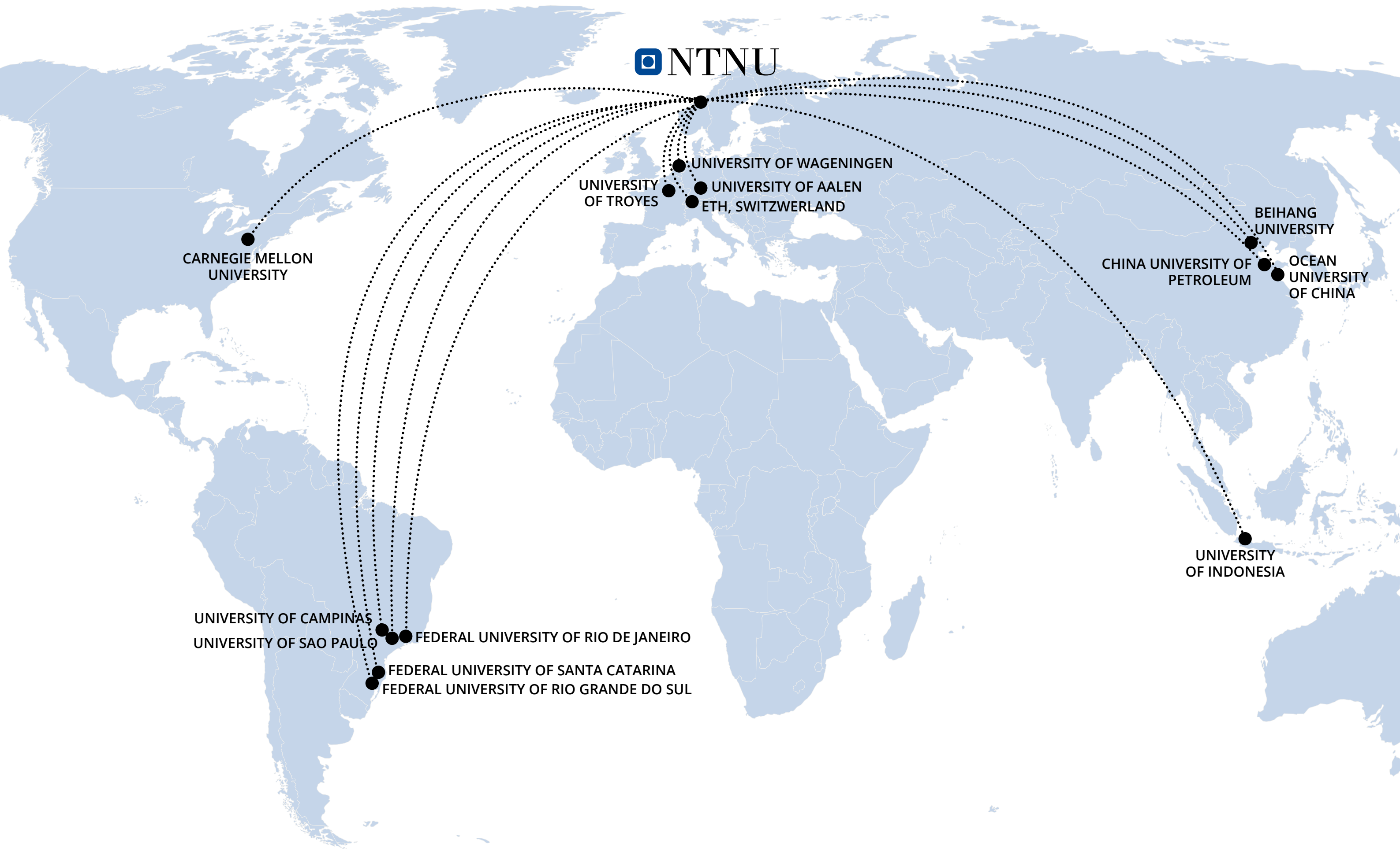
- Cooperation with Chinese universities through AutoPRO (ref. page 72).
    - China University of Petroleum (E. China)
    - Ocean University of China
    - Beihang University

- Cooperation and exchange with several universities in Brazil through the project INTPART: Visits / exchange stays between Norway and Brazil for PhD students within several research areas in SUBPRO.

  Collaboration with the following universities in Brazil:
    - Federal University of Rio de Janeiro/COPPE Federal
    - University of Santa Catarina
    - University of Sao Paulo
    - University of Campinas

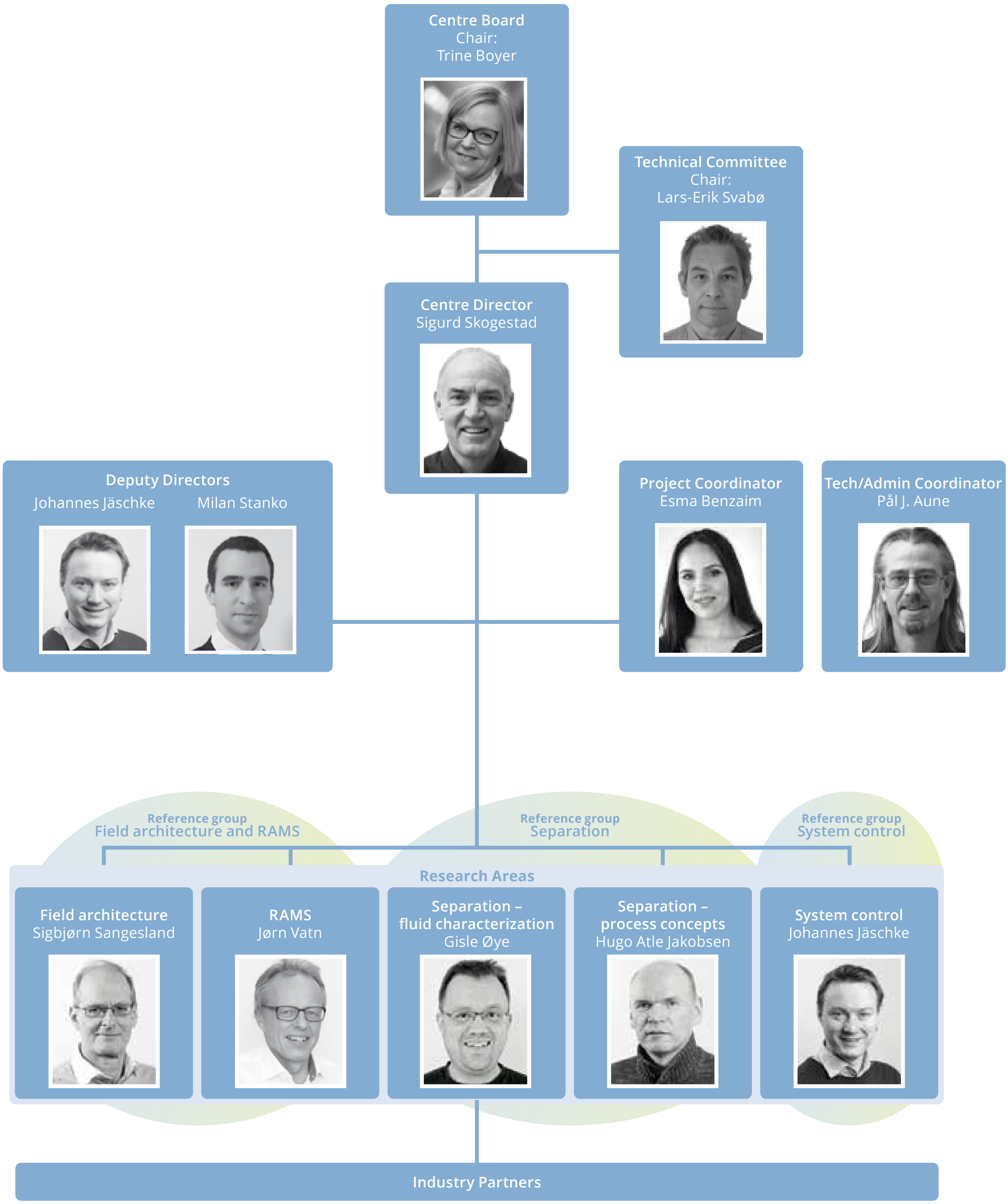
- Brazil-Norway Subsea Operations Consortium2 (BN-SOC2), the project was supposed to continue again from January 2021, but due to travel restrictions the project was put on hold in 2021. The project will start again with normal activities in 2022.

- In addition to Germany, China and Brazil, SUBPRO has cooperated with researchers from Denmark, Indonesia and USA.



Organization of the Centre

GOVERNANCE STRUCTURE (2022)



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.

THE SUBPRO DAY: TECHNICAL CONTRIBUTIONS TO THE RESEARCH ACTIVITIES
The SUBPRO day is a yearly meeting held in the month of October, where SUBPRO staff, industry partners and other interested parties get an overview of ongoing and new projects and give their input and comments.

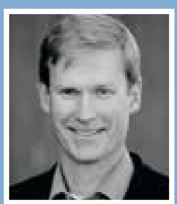
INDUSTRY PARTNER INVOLVEMENT IN RESEARCH PROJECTS
The industry partners are actively involved in the research projects all year through technical discussions and technical knowledge transfer through advice, co-supervision of PhD students and co-authoring of scientific papers, through industrial cases and by providing field data for testing models and software.

In addition to the two adjunct professor positions at NTNU for Audun Faanes and Gunleiv Skofteland from Equinor, a new professor (RAMS) Shen Yin from DNV was assigned at SUBPRO/NTNU starting from 2020, to enhance the collaboration between the Centre and the industry.

INNOVATION PROJECTS: RESEARCHERS FROM SUBPRO WORKING WITH THE INDUSTRY PARTNERS ORGANIZATIONS
An Innovation project is an extension of a PhD project, funded by SUBPRO, to enable implementation of project results in the industry. In 2021 several of our PhD's and Postdoc's had 3-6 month innovation grants:

- PhD-student Nanda Zikrullah started an Innovation Project in August 2019 (See page 29).
- PhD-student Mishiga Vallabhan started an Innovation Project in August 2019 (See page 74).
- Postdoc Jose Matias started an Innovation Project in February (See page 78).
- In addition, PhD-student Liu Haoge started an Innovation Project in February 2022 (See page 18).

CENTRE BOARD 2021-2022


Frank Børre Pedersen
DNV
Chair until 31.12.2021


Trine Boyer
TotalEnergies, Chair
from 01.01.2022

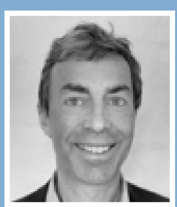

Kristin Moe Elgsaas
Aker BP


Jostein Kolbu
Aker Solutions

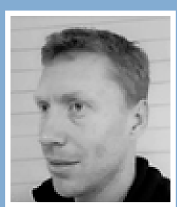

Audun Faanes
Equinor


Lars-Erik Svabø
Kongsberg Digital

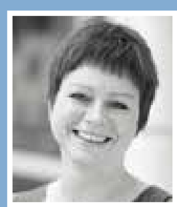

Tom Widerøe
Lundin Norway,
until 31.12.2021


Espen Gjørv
Lundin Energy
Norway, from
01.01.2022


Olav Dolonen
Neptune Energy
Norge


Lachlan McKenzie
TechnipFMC,
until 15.09.2021


Ola Jemtland
TechnipFMC,
from 15.09.2021


Kimberly C. Mayes
Research Council
of Norway, observer


Øyvind Weiby
Gregersen
NTNU


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

Health Security and Environment

During 2021, two HSE related incidents have been reported to SUBPRO.

The first incident was related to flies/moths in the laboratories in Block K5. Windows and doors were closed, and it is suspected that the insects had entered the rooms through the ventilation system.

The second incident was about bad smell in the laboratories in K5, reported by SUBPRO personnel. The smell was not related to lab activity but has come from outside the building. It is suspected that it had been brought into the lab through the ventilation system.

The two incidents were followed-up by the HSE engineer and the Campus service office.

The ventilation system will be renovated in the near future, as a part of a larger building renovation in Block K5.

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

HSE PROCEDURES FOR SUBPRO ACTIVITIES

All PhD students, Postdoctoral 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.

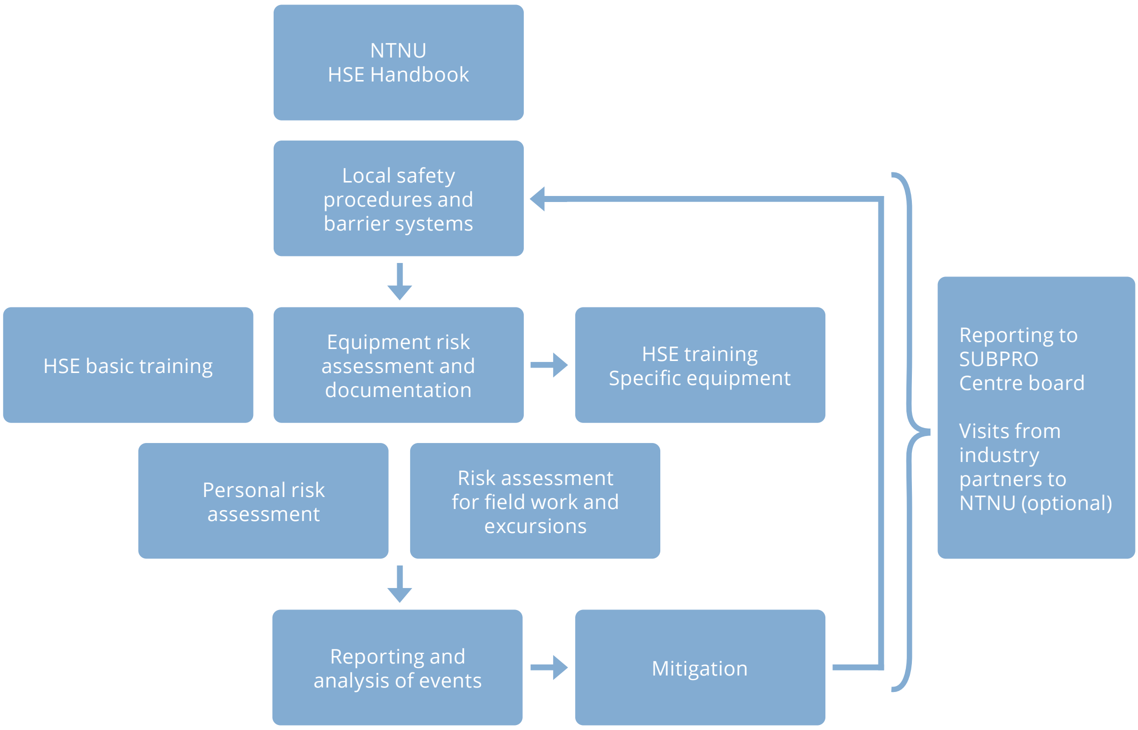


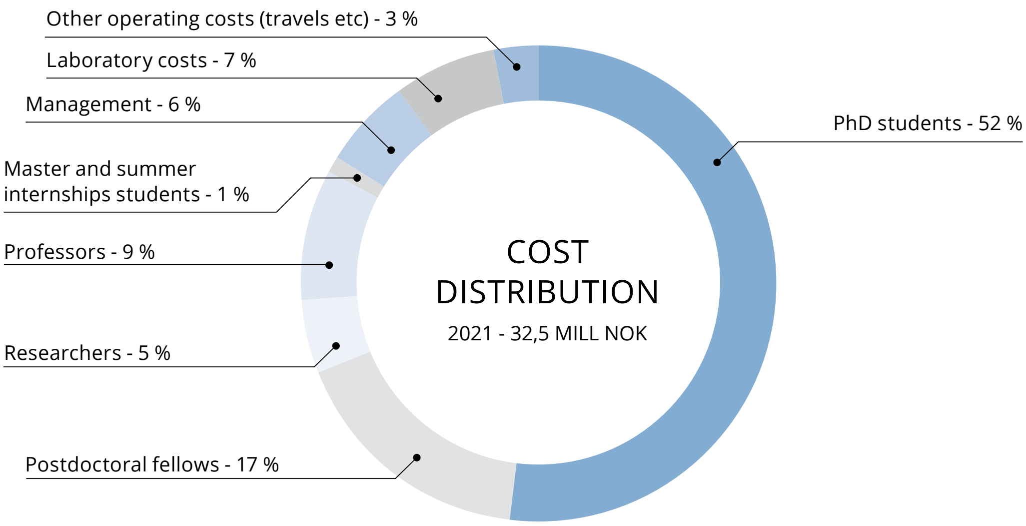
Figure 1: NTNU/SUBPRO HSE system

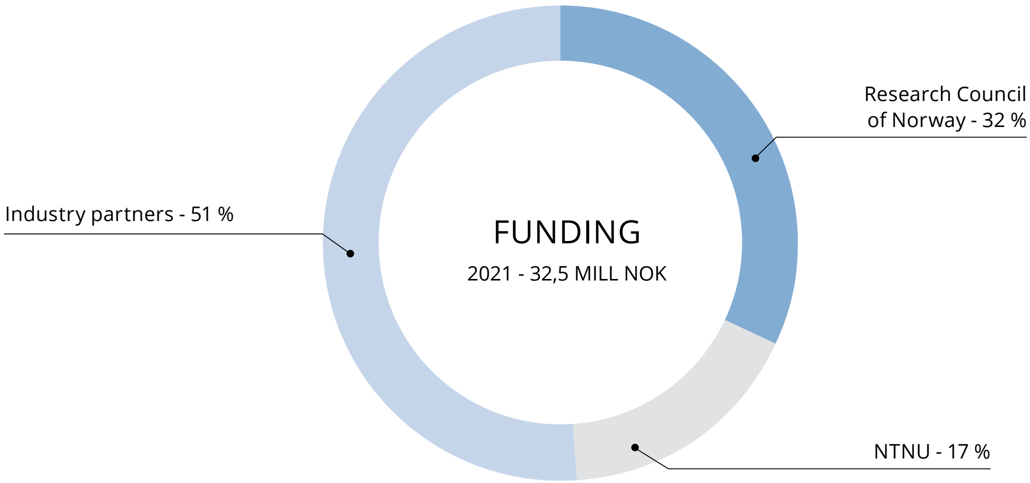
Key figures 2021

PROJECT DURATION	AUGUST 2015 – DECEMBER 2023		
Total annual budget (annual average, 2015-2023)	32 mill. NOK		
Personnel	Planned 2015-2023	Currently engaged 2021	Female percentage
PhD students	35[1]	17	24 %
Postdoctoral fellows	11[1]	6	17 %
Researchers (full or part time)	7[1]	2	0 %
Professors	25[1]	21	14 %
Master students educated (per year)	20	17	41 %

[1] Accumulated over 8 years

PUBLICATION 2021	
Journal and conference papers	30





Publications

Journal papers and conference papers published in 2021

FIELD ARCHITECTURE

Angga, I Gusti Agung Gede; Stanko Wolf, Milan Edvard.
"Automated decision support methodology for early planning phase of a multi-reservoir field".
Journal of Petroleum Science and Engineering 2021; Volume 205.

Diaz Arias, Mariana JC; dos Santos, Allyne Machado; Altamiranda, Edmary.
"Evolutionary Algorithm to Support Field Architecture Scenario Screening Automation and Optimization Using Decentralized Subsea Processing Modules".
Processes 2021; Volume 9.(1)

Liu, Haoge; Gjersvik, Tor Berge; Faanes, Audun.
"Subsea field layout optimization (Part I) – directional well trajectory planning based on 3D Dubins Curve".
Journal of Petroleum Science and Engineering 2021; Volume 208. (B)

Liu, Haoge; Gjersvik, Tor Berge; Faanes, Audun.
"Subsea field layout optimization (part II)–the location-allocation problem of manifolds".
Journal of Petroleum Science and Engineering 2021; Volume 208. (A)

Liu, Haoge; Gjersvik, Tor Berge; Faanes, Audun.
"Subsea field layout optimization (part III) --- the location-allocation problem of drilling sites".
Journal of Petroleum Science and Engineering 2021; Volume 208. (B)

Mirza, Bilal; Pant, Millie; Stanko, Milan; Sales, Leonardo.
"Differential evolution for early-phase offshore oilfield design considering uncertainties in initial oil-in-place and well productivity".
Upstream Oil and Gas Technology 2021; Volume 7. p. 1-16

Sales, Leonardo de Pádua Agripa; Jäschke, Johannes; Stanko, Milan.
"Early field planning using optimisation and considering uncertainties - Study case: Offshore deepwater field in Brazil".
Journal of Petroleum Science and Engineering 2021; Volume 207.

Sevillano, Lucas Cantinelli; Sangesland, Sigbjørn; Gjersvik, Tor Berge; Faanes, Audun.
"Enabling technologies for low cost subsea field development".
Proceedings of the ASME 2021 40th International Conference on Ocean, Offshore, and Arctic Engineering.Volume 4: Pipelines, Risers, and Subsea Systems. Virtual, Online. June 21–30, 2021. ISBN: 978-0-7918-8514-7. https://doi.org/10.1115/OMAE2021-62862

RELIABILITY, AVAILABILITY, MAINTENANCE AND SAFETY (RAMS)

Björklund, Ludvig; Glaser, Markus; Skofteland, Gunleiv; Lundteigen, Mary Ann.
"A Comparison of Different Approaches for Verification and Validation of Software in Safety-critical Systems".
I: Proceedings of the 31st European Safety and Reliability Conference.
Research Publishing Services 2021 ISBN 978-981-18-2016-8. p. 2878-2885

Lee, Tae Hwan; Skofteland, Gunleiv; Lundteigen, Mary Ann.
"Performance Management of Safety Instrumented Systems for Unmanned Facilities Using Machine Learning: Decision Support System for SIS".
I: Proceedings of the 31st European Safety and Reliability Conference.
Research Publishing, Singapore 2021 ISBN: 981-973-0000-00-0.

Liu, Xingheng; Assumpcao Matias, Jose Otavio; Jäschke, Johannes; Vatn, Jørn.
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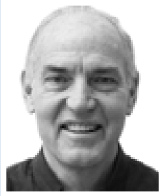
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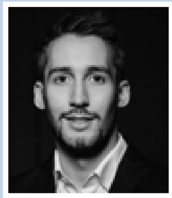
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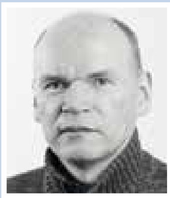
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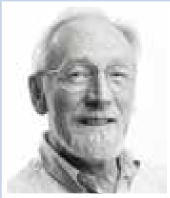
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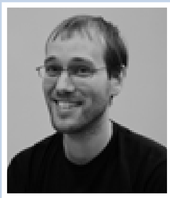
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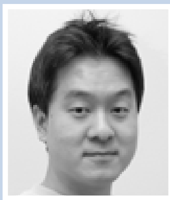
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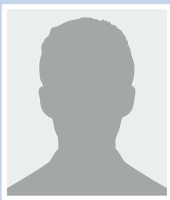
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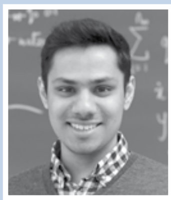
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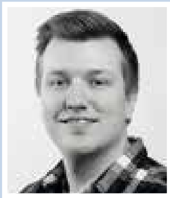
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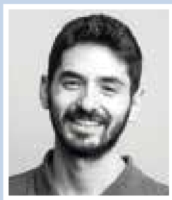
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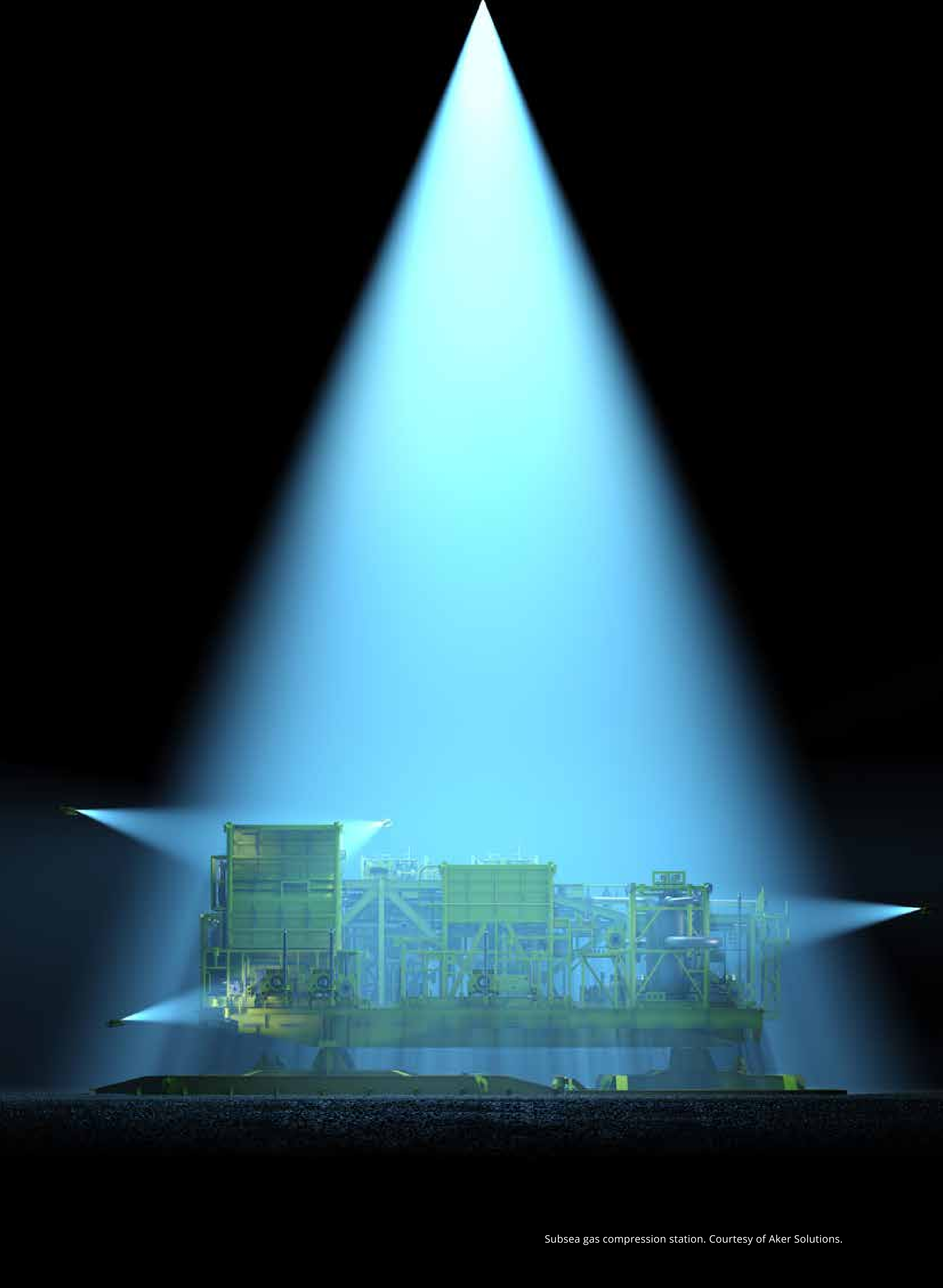

Subsea gas compression station. Courtesy of Aker Solutions.

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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