SUBPRO

SUBSEA PRODUCTION AND PROCESSING

Annual Report

2022

2023

sfi = Centre for Research-based Innovation

Established by the Research Council of Norway

NTNU

Norwegian University of Science and Technology

What is SUBPRO?

SUBPRO is a centre for research-based innovation (SFI) funded by the Research Council in Norway and nine industrial partners. The Norwegian oil and gas industry has 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
- Fluid characterization and flow assurance
- Separation process concepts
- Systems control

SUBPRO started up in August 2015, so we are now at the final 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 16 full time PhD students and Postdoctoral fellows in 2022. In addition, about 22 professors and associate professors, 9 researchers and 4 associated PhD students 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

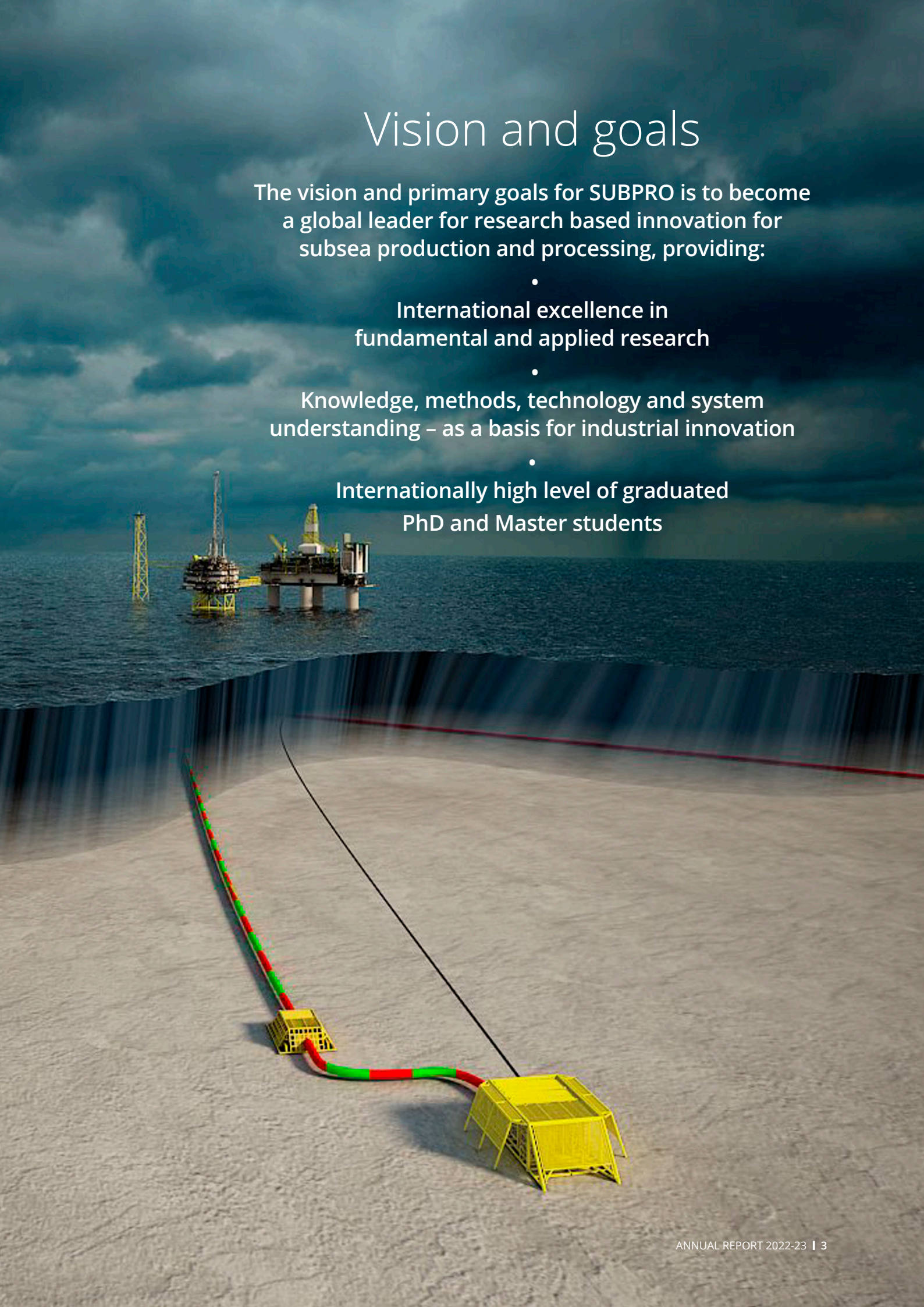
Front page picture: Njord-field after upgrade of Njord A and Njord Bravo.
Photo credit: Even Fløgstad / Equinor.
Illustration of subsea operation, Courtesy of Equinor.

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**



Chair of the Board

VANESSA RICHON

R&D Asset Decarbonization Manager,
Stavanger Research Center,
TotalEnergies EP Norge AS

Eight more months and SUBPRO will come to an end. Looking back at what has been accomplished in the last 8 years, I feel proud to have been part of this journey. There aren't many places in the world where groundbreaking research on subsea technologies is taking place and we can all agree that SUBPRO is one of them.

46 PhD/post-docs and more than 90 master students educated, 246 journal or conference publications, a few numbers that demonstrate how successful SUBPRO has been.

From field architecture to reliability, maintenance and safety, from fluid characteristics to process concepts without forgetting subsea control, the main building bricks of subsea systems have been studied, innovative solutions, methodologies have been developed. Several Innovation projects have also been conducted, leading to the industrialization of the research outcomes. That is also a proof of success and shows the strong link between academical research and industrial partners that has been put forward by the SUBPRO consortium. The rapid deployment and implementation of newly developed solutions or methodologies is of prime importance for our industry, and this has been addressed very well by SUBPRO.

Now it is time to think about the future and about the challenges ahead of us. The world will need more energy in the future, but an energy that needs to be affordable and sustainable. How can we achieve this? The industry needs to continue developing new Oil and gas fields as hydrocarbon-based fuels are still the major source of energy, especially for transportation for many years to come. Low costs and low emissions will be key for the future and as a research group we need to ensure that the right technologies will be available to the industry, trying to get further into the simplifications, margin reductions...

At the same time, we need to prepare the energy transition towards carbon free energy and the expertise developed in subsea for O&G developments can be extremely relevant for several of the key subjects like Carbon Capture and Storage or floating offshore wind.

We can already see today, looking at ongoing CCS projects that in Europe, that most of the carbon storage reservoirs will be located offshore and will rely on subsea developments. To have a sustainable CCS business, it will be essential to reduce both the operational and developments costs. As an industry, together with the regulators, we need to better understand the specifics of such developments in terms of safety or operations and adapt to ensure the sustainability of this business.

The aim of SUBPRO Zero is to build a SUstainable Bridge PROgram towards Zero emissions for the offshore industry, building on the expertise developed through 8 years of research on subsea technologies. Many topics are to be addressed to prepare the energy transition and SUBPRO Zero will help the industry to deliver the required bricks that will make this energy transition a reality, enabling low-cost CCS developments and providing economical solutions for the deployment of renewables offshore.

Centre director

SUBPRO is now into the final year of its eight-year duration. The activity in 2022 reached 16 fulltime PhD and postdoc projects. Because we are approaching the end, we did not start any new PhD and postdoc projects in 2022. Instead, we started nine shorter one-year researcher projects and gave four 6-months innovation grants to ongoing PhD and postdoc projects. Through the new SUBPRO Zero project, financed by industry, a large part of the activity in SUBPRO will continue for at least three more years.

PROFESSOR SIGURD SKOGESTAD

SUBPRO Centre director
NTNU, Department of Chemical Engineering

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.

Six projects have been finalized this year (final project documentation is included in this report):

- **Leonardo Sales** (PhD) Developing methods and obtaining insights for design optimization of fields and subsea processing systems (page 17 -19)
- **Lucas Cantinelli Sevillano** (Postdoc), Enabling technology for low-cost subsea field development (page 20 -23)
- **Xingheng Liu** (Postdoc) Estimation and optimization of remaining useful life (page 36 -39)
- **Ilgar Azizov** (PhD) Re-injection of produced water – dispersions in porous media (page 47 -49)
- **Moein Assar** (PhD) A digital twin library for oil/water emulsion separation and transport processes (page 50 52).
- **Mahdi Ahmadi** (Postdoc) Natural gas dehydration with the use of membranes (page 63 -65)

Nine one-year researcher projects started in 2022/2023:

- **Haoge Liu:** Subsea Field Layout Optimization- Innovation Project (page 14 -15).
- **Abraham Parra:** Operation and design of offshore oil and gas fields subject to power constraints (page 16).
- **Xingheng Liu:** Towards safety and security of autonomous systems against cyberphysical attacks (page 34 -35).
- **Husnain Ahmed:** Re-injection of produced water – co flow of particles and droplets visualized using microfluidic and advanced image analysis methods (page 46).
- **Nicolas La Forgia and Suparna Paul:** High speed image processing of single oil droplet breakage helps to improve models for phase distribution in oil-water separation (page 58 -59).
- **Niloufar Keshavarz Rezaei:** Natural gas dehydration with the use of membranes (page 60 -61).
- **Diego Di Domenico Pinto and Juliette Limpach:** Feasibility study of blue H2 (page 62).

During 2022-23, SUBPRO funded five innovation projects involving Haoge Liu, Tae Hwan Lee, Hamidreza Asaadian, Risvan Dirza and Halvor Arnes Krog.

I usually write a little about the oil price in my summary of the year, as it has a large impact on the priorities of our partners. The oil price has increased since it reached a low point of less than 20 USD per barrel when the Corona crisis hit in April 2020. It peaked at more than 110 USD per barrel in June 2022, but has since then dropped and is now about 70 USD per barrel. With the current war in Ukraine, it is expected to remain high for some time. All of this means that the oil and gas companies have record profits. It is of course difficult to predict the future, but with the increased focus towards sustainability and zero emissions of CO2, it is likely that demand for oil will drop in the long-term future. For natural gas the case may be different because it is seen by many as a temporary replacement for coal.

SUBPRO is now in its final year, although a few PhD projects will continue into 2024. The industrial partners are generally very happy with the SUBPRO project, and most of them have decided to join the new SUBPRO Zero project which starts in August 2023. In SUBPRO Zero, the aim is to help prepare Norway and the oil and gas industry for a more sustainable and greener future.

Partners

(Until 01.09.2022)

(Until 31.12.2022)

Statement from industry partners

AUDUN FAANES
Task Leader CO2
Transport Technology

Equinor

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

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

JOSTEIN KOLBU
Senior Manager
Subsea Compression

Aker Solutions

Aker Solutions has a long history of working with subsea production and processing systems. Through SUBPRO, we have the opportunity to collaborate with the partners on developing solutions to meet our common challenges.

The strong academic resources of the Centre, and the Master and PhD candidates that are joining our industry, make us better positioned for developing the solutions and products which are key parts of the energy transition.

Project structure

RESEARCH AREA

Field architecture
Prof. Sigbjørn Sangesland

Reliability, Availability, Maintenance and Safety
Prof. Jørn Vatn

Separation – fluid characterization
Prof. Gisle Øye

Separation - process concepts
Prof. Hugo Jakobsen

System control
Prof. Johannes Jäschke

PROJECTS

1.1 Subsea gate box
Postdoc Mariana Diaz
Prof. Sigbjørn Sangesland

1.1.b Optimization of field development and subsea layout
PhD Leonardo Sales
Assoc. Prof. Milan Stanko

1.1.c Enabling technology for low-cost subsea field development
Postdoc Lucas C. Sevillano
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 Gonzalez
Assoc. Prof. Milan Stanko

1.3 Multiphase boosting models
Gilberto Nunez, PhD
Prof. Sigbjørn Sangesland

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

1.4 Subsea field layout optimization
Reasercher Haoge Liu
Prof. Tor B. Gjersvik and adjunct Prof. Audun Faanes

1.1.e Subsea field layout optimization – innovation project
Reasercher Abraham Parra
Assoc Prof. Milan Stanko

3.1 New safety and control philosophy for subsea systems
Postdoc HyungJu 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
Yun Zhang, PhD
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

3.3.d Safety and security of autonomous systems against cyberphysical attacks
Researcher Xingheng Liu
Prof. Jørn Vatn and Prof. Shen Yin

Spin-off: SAFETY 4.0 – Ensuring functional safety of novel technologies
Nanda Zikrullah, PhD
Prof. Mary Ann Lundteigen

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

2.1.c Re-injection of produced water – co flow of particles and droplets visualized using microfluidic and advanced image analysis methods
Reasercher Husnain Ahmad
Prof. Gisle Øye

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.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

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

2.4.c Natural gas dehydration with the use of membranes
Reasercher Niloufar Keshavarz Rezaei
Prof. Magne Hilstad and Dr. Eivind Johannessen

Feasibility study of blue H2
Reasercher Diego Di Domenico Pinto and Juliette Limpach
Prof. Hanna K. Knuutila

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 un-measured variables
PhD Tamal Das
Prof. Johannes Jäschke

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

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

3.9 Production optimization under uncertainty
Dr. 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
Prof. Johannes Jäschke

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

Current PhD/postdoc projects

Finalized projects

One-year research projects

Associated / Spin-off projects

SUBPRO Zero

SUstainable Bridge PROgram towards Zero emissions

Johannes Jäschke, Professor, Dept. of Chemical Engineering and
Milan Stanko, Associate Professor, Dept. of Geoscience and Petroleum

SUBPRO-Zero is a new 3-year research project (Aug. 2023-2026)

The basis for SUBPRO Zero is the highly successful SUBPRO Center for Research-based Innovation (SFI) on Subsea Production and Processing (2015-2023) which was funded by industry, NTNU and the Research Council of Norway. As funding for SUBPRO expires in 2023, the consortium decided to organize a follow-up project with a more sustainable focus, SUBPRO-Zero (SUstainable Bridge PROgram towards Zero emissions).

In SUBPRO-Zero, NTNU and industry partners join forces to establish a common research program. Our mission is to conduct fundamental and applied research to contribute to net-zero emissions in the offshore industry. Embedded in a framework of a Value Chain Approach, our activities focus on the following areas:

- Low complexity blue hydrogen production (e.g., for offshore applications), gas treatment, and carbon capture (zero emission to air)
- Water treatment, including re-injection (zero emission to water)
- Field architecture, optimization, and energy efficiency
- Digitalization, Systems Control, and RAMS (Reliability, Availability, Maintenance and Safety)

The new SUBPRO-Zero activities are planned to start up in Autumn 2023 and are organized similar to the SUBPRO SFI, i.e. the research is performed mainly by PhD students and Postdocs at NTNU. There are currently 10 PhD and Postdoc projects planned for execution. The strategic decisions about research activities are made by a board consisting of representatives of the partners.

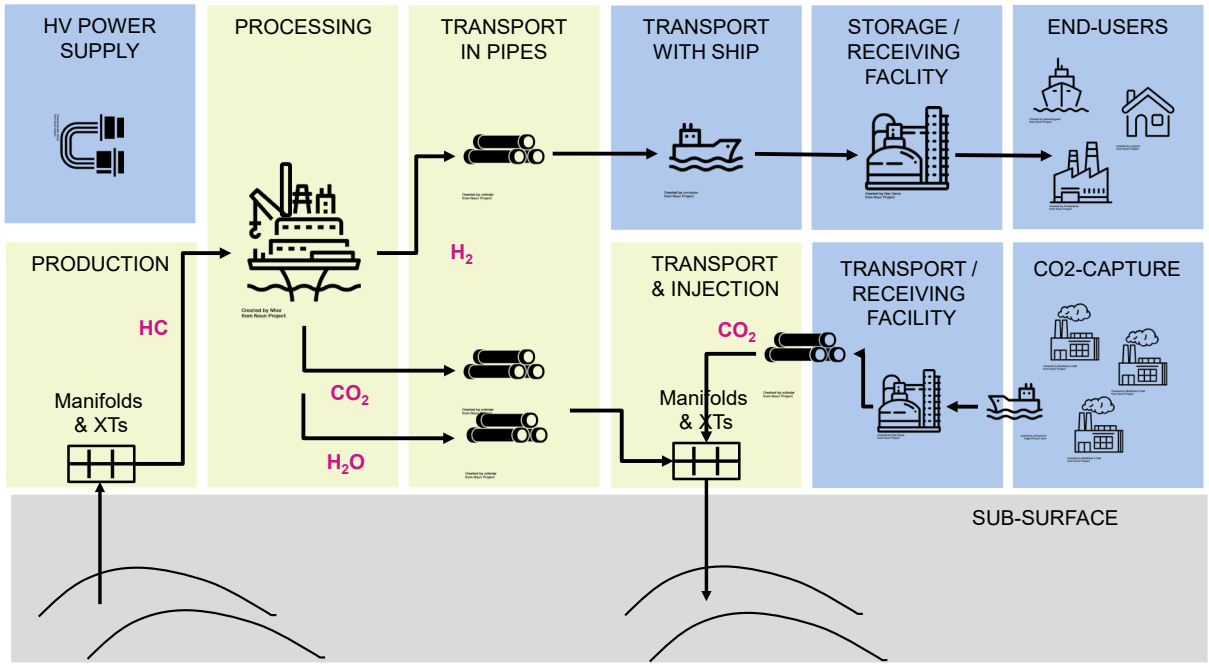
The following projects will be realized in the first round, and more may be started, for example if new partners join:

- Low CO2 emission platforms (PhD)
- Gas Flotation for Subsea Produced Water Treatment II (PhD)
- Decision-support methods for holistic water management - water value chain (Postdoc)
- Complete subsea separation (PhD)
- Lean designs for carbon dioxide subsea injection systems (Postdoc)
- Multi-scale Virtual Flow Metering for optimal decision-making (PhD)
- Design and operation of subsea oil and gas fields powered by renewable sources (Postdoc)
- Systematic methods for smart management of CO2 transport and injection systems (PhD)
- Optimal flow regime control in oil transport (PhD)
- Incorporating artificial intelligence in Safety-critical systems for CO2 capture, injection, and storage (PhD)

SUBPRO Zero will be funded by Industry and NTNU. Five operator companies and two supplier companies have so far agreed to join the consortium during this first period: Equinor, Aker BP, Neptune Energy, TotalEnergies, Vår Energi, Aker Solutions, Kongsberg Digital.

In the longer term, we are looking into the possibility for a further extension where also the research council is included (for example, through an FME or SFI project). For more information see

https://www.ntnu.edu/subpro-zero



Value Chain Approach: The scope of SUBPRO-Zero is shown in yellow.

RESEARCH AREA

Field architecture

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

Professor Sigbjørn Sangesland
Research Area Manager
Department of Geoscience and Petroleum

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

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

SPECIFIC INDUSTRIAL AND RESEARCH CHALLENGES AND GOALS:

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

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

ONGOING PROJECTS DURING 2022:

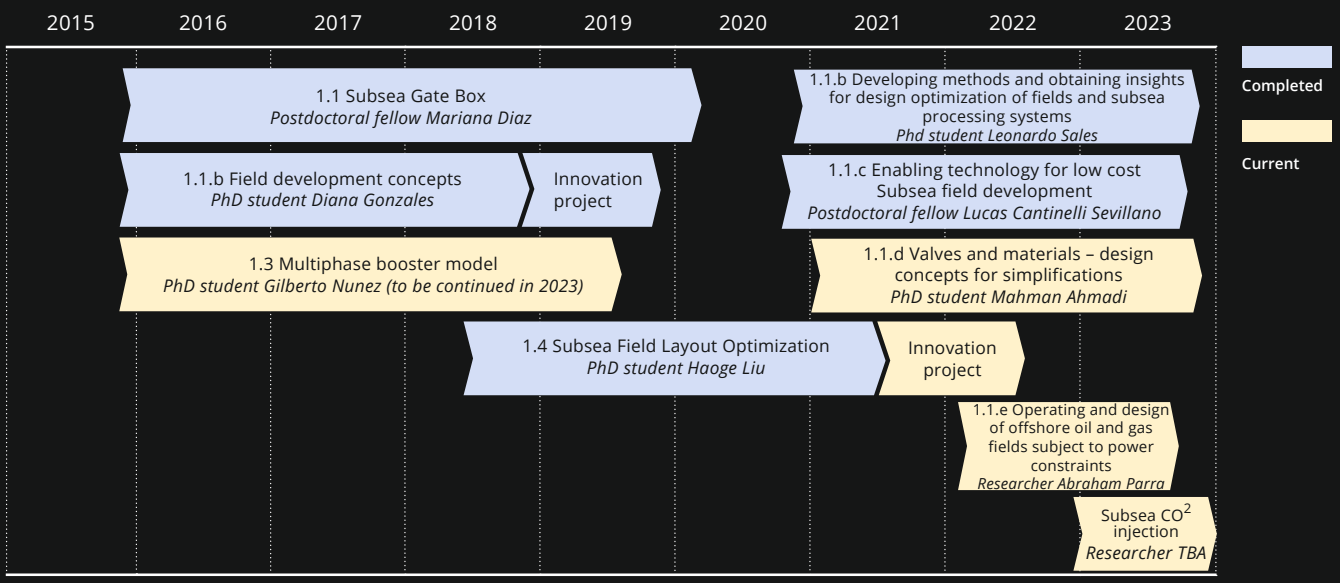
PhD project:
- Valve and materials- design concepts for simplification
- Optimization of layout of subsea production systems with subsea processing
- Multiphase booster models

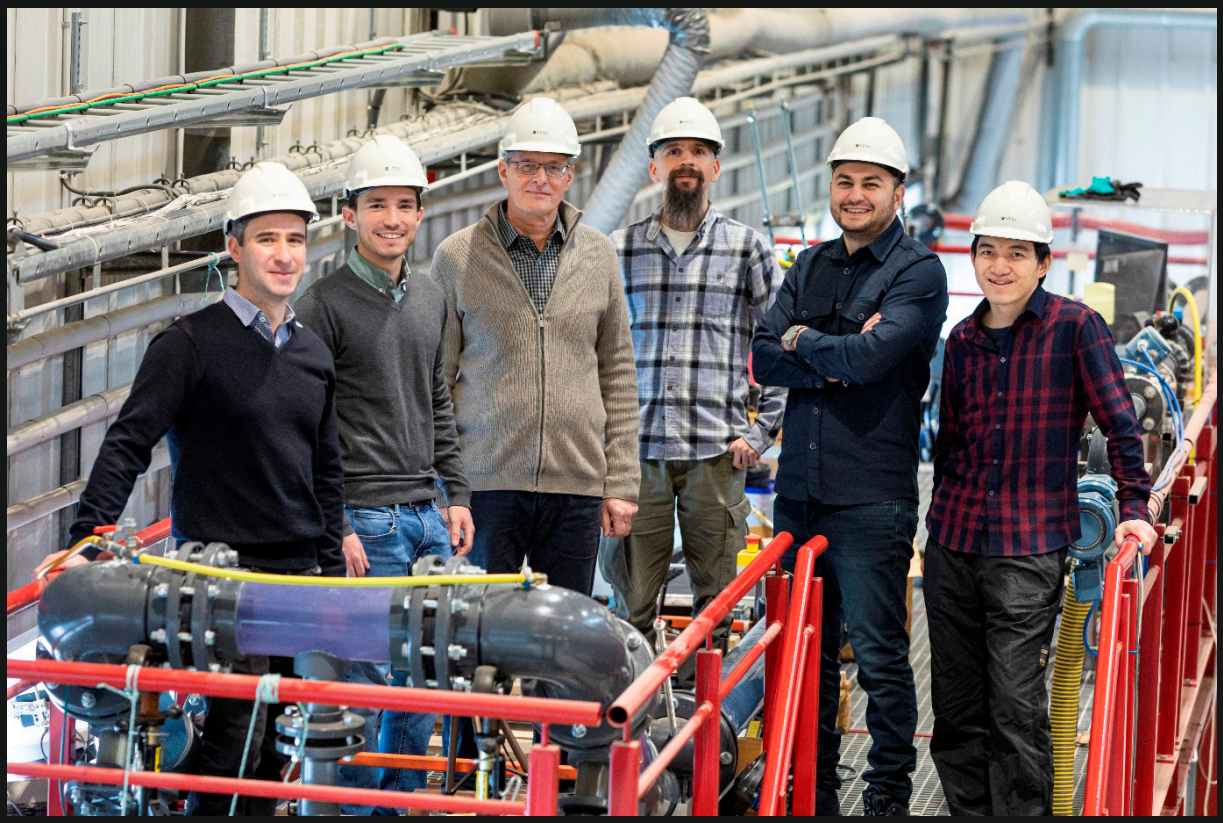
Innovation project:
- Optimizing subsea field layout to minimize risk and cost

Postdoc project:
- Enabling technology for low-cost subsea field development (The candidate started in a new position on September 1)

Researcher project (One year):
- Operation and design of offshore oil and gas fields subject to power constraints (started September 2022)
- Subsea CO_2 injection (start early 2023)

Completed, current and planned projects





***The Field Archicture 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 Ahmadli and Researcher Haoge Liu.

Professor Tor Berge Gjersvik and Researcher Abraham Parra were not when the photo was taken.

Valves and materials – design concepts for simplifications

Investigating new possibilities for valves and actuators assuming an 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 valve & valve control systems, optimizing subsea valve design, and simplifying the maintenance operations.

PhD student: **Mehman Ahmadli**
Start date: 16.08.2021
Planned end date: 15.08.2024
Project manager and supervisor: Professor Tor Berge Gjersvik
Department of Geoscience and Petroleum
Project nr: 1.1.d

1. BACKGROUND

In a situation where the oil 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 coming transition from electrohydraulic to all-electric control system constitutes an important contributing part. However, just changing the control system platform without simultaneously also 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 onto manifolds reduce the 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 DELIVERABLES

3D model simulation: A 3D model of the barrier valve is created in the Ansys® software, and in the simulation the subsea conditions are created. The output of the simulation is the total friction force and the required stem force function of the stroke length. The results of the numerical method are verified with the analytical method's results, which allows to assume the liability of the further results of the simulation with changed coating material and geometry.

Alternative material for coating: The effect of the coating material change is studied in the simulation model, but the laboratory experiment will be carried out to learn the sliding friction movement of poly crystalline diamond (PDC) coated pair contact surfaces under the same subsea environment.

*Replacement of subsea barrier valve: E*asy replacement subsea of critical components like valve actuators; possibly also the valve itself will be investigated to minimize the operational costs and profit loss due to production stop.

Challenging design margins: Current margins based on non-retrievability and the lack of control of forces in actuators (with spring) over the lifetime of the XT. All electric systems allow such control, and thereby the movement of the valve stem will be investigated to optimize the actuating power.

Eliminating the actuator spring: The possibility of the eliminating the actuator spring will be investigated and the effects of this on loading will be calculated (potentially up to 80%).

3. INDUSTRIAL PARTICIPATION

TotalEnergies is actively involved in the project alongside 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.

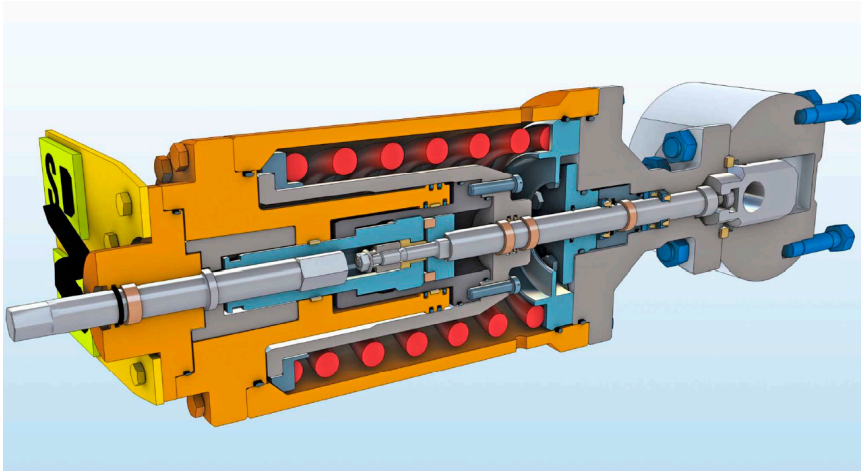


Figure 1: FSC subsea valve. The valve is in a closed position (Courtesy of Aker Solutions)

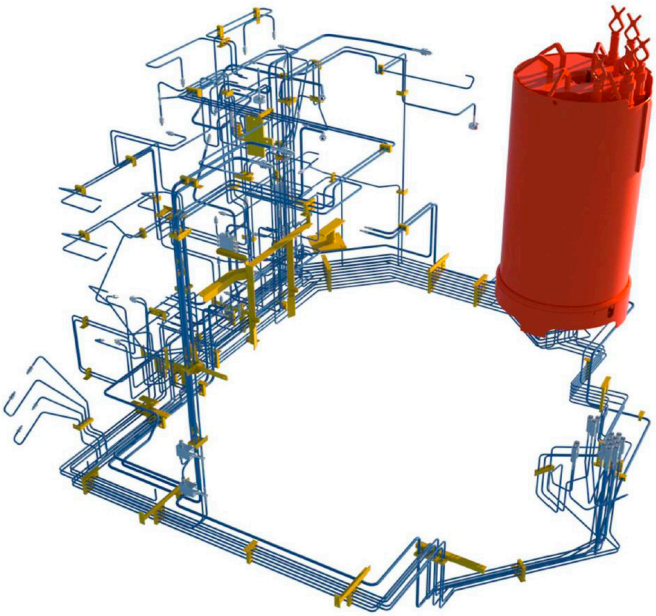


Figure 2—Small Bore Tubing on XT [FMC]

Figure 2: Small Bore Tubing on XT [TechnipFMC]

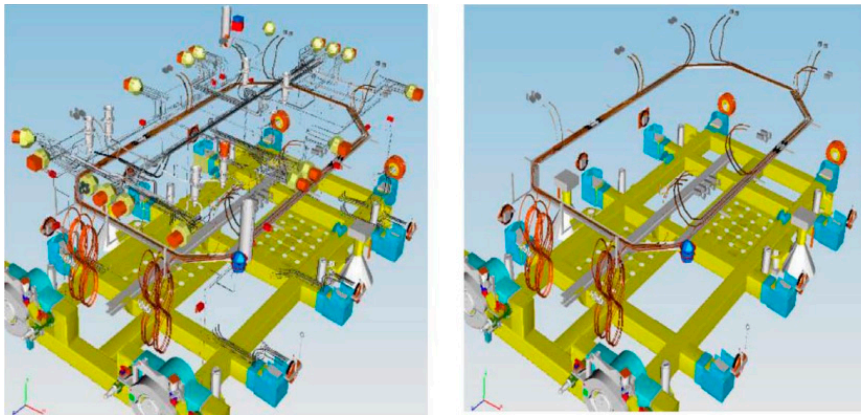


Figure 3: A 4-slot manifold with electro-hydraulic controls to the left and with electric controls to the right [TechnipFMC]

Subsea Field Layout Optimization

Exploration of possible commercialization.

Researcher: **Haoge Liu**
Start Date: 08.02.2022
Planned end Date: 09.08.2023
Supervisors: Professor Tor Berge Gjersvik, Adjunct Professor Audun Faanes
Department of Geoscience and Petroleum
Project nr: 1.4

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. During my PhD work, we have successfully developed a global optimal method with high efficiency for subsea field layout optimization to reduce the overall cost under various engineering constraints. We hope to promote our method into the industry.

2. WHAT WE HAVE DONE

We have taken further field tests with Equinor. In the field tests, two main issues in the application of our method have been discovered. The first issue, which is to decide the optimal direction for a horizontal well in the optimal layout, has been perfectly solved. The second issue, which is to design the optimal well trajectory to fulfil complex layers' constraints, still needs further study. The following Figure 1 shows the 2-point well trajectory (simple structure) cannot fulfil the layers' constraints, therefore we must have a more complex well structure. However, with a more complex structure applied, the dimension of the variables increases sharply leading to numerical issues, as the Figure 2 shows. As the well trajectory design method is not the core of our method for layout optimization, we suggest that if this issue cannot be solved perfectly in the near future, we can resort to the existing trajectory design software to get the cost contour of each well under the complex constraints, then feed the cost contours into the BLP model to decide the optimal layout.

We have discussed the two possible business models for our method: 1. stand-alone app; 2. plug-in package for an existing platform. As the Figure 3 shows to the right.

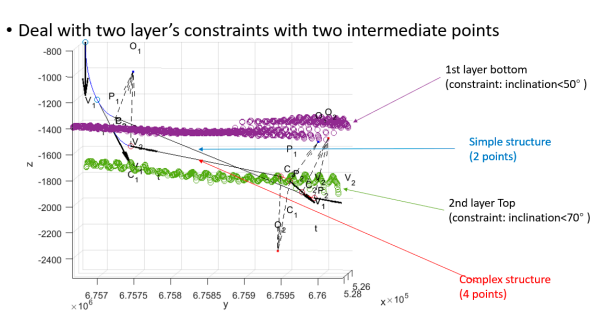


Figure 1 Trajectories for Complex Underground Scenario

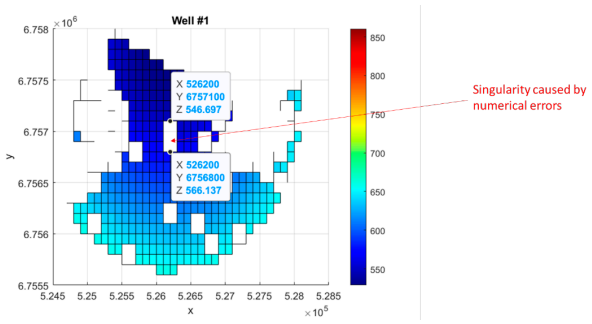


Figure 2 Numerical Issues in Complex Trajectory

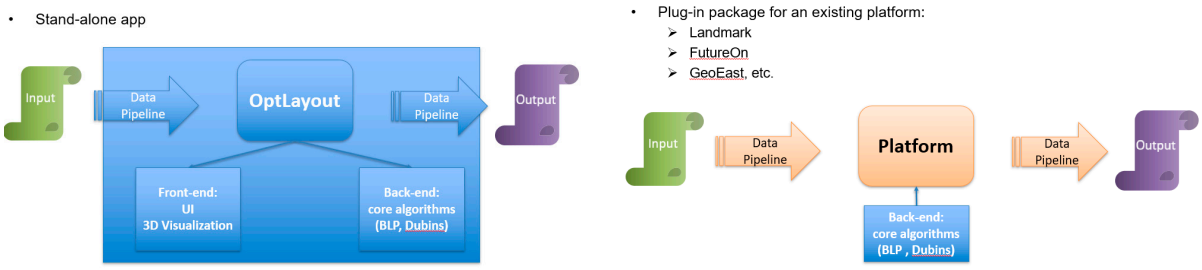


Figure 3 Business Models

Based on the 1st possibility, a demo app (as shown in Figure 4) with a user manual has been developed to better demonstrate and promote our work. Based on the 2nd possibility, we have reached out to search possible cooperation with two platforms such as FutureOn and GeoEast. We have also contacted a possible future investor/client – Abu Dhabi National Oil Company (ADNOC)

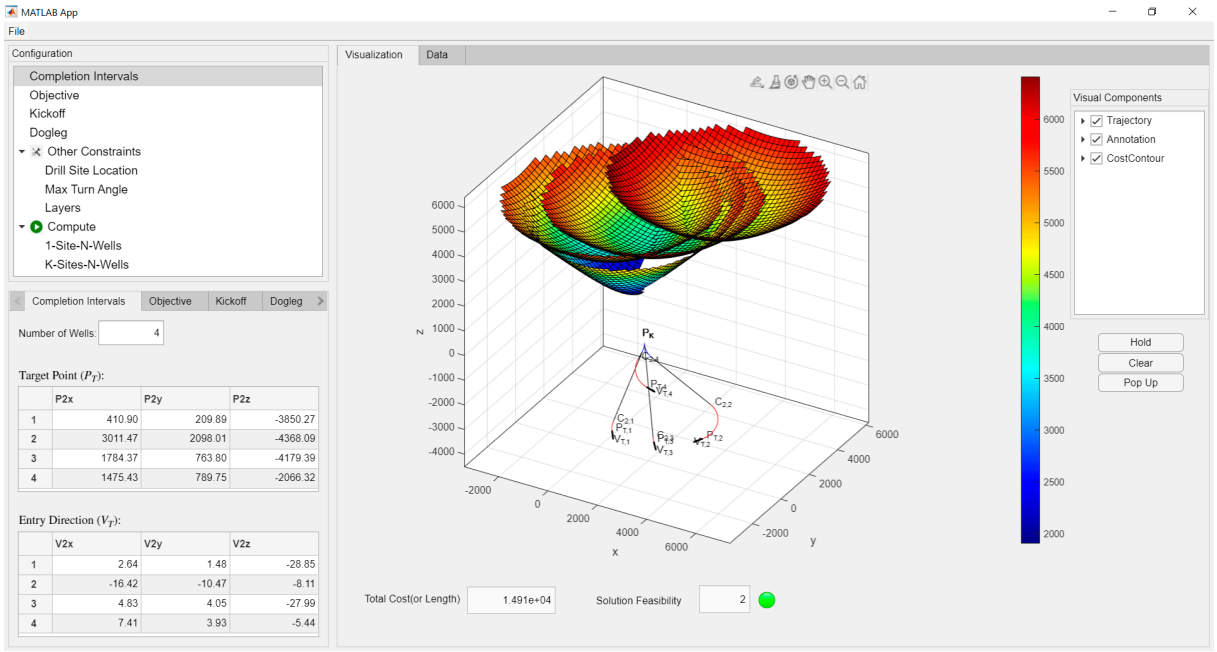


Figure 4 Demo App

3. MAIN DELIVERABLES

By the end of the innovation project, we shall have the following results:

1. A decision on the business model.
2. A demo app with a detailed user manual to demonstrate the functionalities of our method.
3. A journal paper regarding the new issues we have encountered during the field tests.

Operation and design of offshore oil and gas fields subject to power constraints

How to design and operate oil and gas fields using fluctuating variable energy inputs (e.g., from renewable energies sources) and adapting the field to the available power, and stabilizing the output by using energy storage (e.g., Hydrogen).

Green Shift Impact: The research reduces the need for fossil fuels to operate oil and gas offshore fields, thus reducing the carbon footprint of the gas and oil industry.

Researcher: **Abraham Parra**
Start date: 26.09.2022
Planned end date: 25.09.2023
Project manager and supervisor: Associate professor Milan Stanko
Department of Geoscience and Petroleum
Project nr: 1.1.e

1. DESCRIPTION OF THE PROJECT INCLUDING COOPERATION WITH PARTNERS

Future offshore oil and gas field developments in the Norwegian Continental Shelf may use power from renewables (e.g., windfarms). The power supply from such sources is often periodic, with daily and seasonal variations. This project investigates ways to deal with this issue, e.g.:

- Produce the field in a fluctuating manner to adapt to the variation in available power and stabilize the output by using different storage methods e.g., the storage capability of export gas pipelines and oil tanks.
- Design auxiliary systems to stabilize the power supply in O&G fields powered by renewables (e.g. electrolysis, hydrogen storage and fuel cells)

In addition, this project studies the consequences of these two approaches regarding economic value and risk from the field operation and field design perspective.

2. DELIVERABLES INCLUDING POSSIBLE PUBLICATIONS

The main tool to use in the project is numerical simulation. Some issues to study are:

- Design and operation of gravity separators and compressors for short term variation of inlet flow conditions
- Processing facilities stabilization times
- Compensation of oil and gas production using oil export tanks and line-pack in gas export flowline
- Technical and economic feasibility study on auxiliary power systems with energy storage to ensure steady state operation

DOCUMENTATION:

- Two technical reports, and one article for publication in conference or journal

Final Project Report

Developing methods and obtaining insights for design optimization of fields and subsea processing systems

PhD candidate: **Leonardo Sales**
Start date: 13.01.2020
Planned thesis defense date: Spring 2023
Project manager and main supervisor: Associate professor Milan Stanko
Co-Supervisor: Associate Professor Johannes Jäschke
Department of Geoscience and Petroleum
Project nr: 1.1.b

1. FIELD DEVELOPMENT AND SUBSEA PROCESSING ARE CHALLENGING

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 high level of expertise and effort, 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. Therefore, they are a good alternative for decision support. While most of the previous studies focused on topside or field development, here we develop different subsea layout optimization methods to maximize project net present value (NPV) considering subsea processing equipment.

The design of the subsea layout and the evaluation of processing equipment is usually performed at late stages of the field planning process, when preparing the plan for development and operations, or performed years after the field is producing. Therefore, these activities are influenced by field development decisions taken at earlier stages, such as the production and drilling schedule, based on uncertain information and that entail massive investment. Some of these uncertainties are also present when designing field layouts, for example cost uncertainties, oil price uncertainty, reserves in place, etc. Thus, it is also important to understand the repercussions of the early field development phase in the subsea layout decisions, and to understand what uncertainties are inherited from earlier stages and how to quantify them.

This project builds on the research projects within SUBPRO of "Superstructure Optimization of Early Stage Offshore Oil Field Development with Subsea Processing" (Dag Krogstad), "Subsea gate box" (Mariana Diaz), and "Methodologies to determine cost-effective development strategies for offshore fields during early-phase studies using proxy models and optimization" (Diana González).

2. FINDING THE BEST WAY TO DESIGN FIELDS AND SUBSEA LAYOUTS

In the first stage of this PhD, we employed non-linear numerical optimization, latin hypercube sampling and the Schwartz & Smith oil price model to compute analytically the probability distributions of the optimal number of wells, plateau rate and project value. The uncertainties considered are in-place oil volumes of oil, well productivity and oil price (Figure 1a). Then, we generated estimates of how do these distributions change from an early field planning standpoint until when the field is abandoned, when uncertainties are reduced to a minimum (Figure 1b). We found that early-phase designs based on the modes of the probability distributions have an economic performance close to one made with full "clairvoyance". We found that is possible to determine optimum field designs with both high ultimate recovery factor and NPV using a multi-objective optimization and a genetic algorithm. Two papers documenting these works are published in journals.

Afterwards, we proposed a mixed-integer non-linear (MINLP) method to optimize subsea production system design using superstructures (Figure 1c). The subsea layout, equipment capacity, oil and gas production rates, and system pressures are optimized as NPV is maximized (Figure 1d shows the optimal layout). One paper documenting this work was submitted to a journal. We then expanded the model to include reliability and maintenance aspects, and this affected greatly the optimal subsea layout (Figure 1e).

Lastly, with the objective of speeding up the solving of the subsea layout problem, we proposed a hybrid method (Figure 1f) consisting of a genetic algorithm optimizing the structure, while the gradient method part solves the continuous non-linear variables (flow rates, reservoir deliverability, equipment capacities, etc.). Figure 1g shows the optimization time required by the hybrid method and the original MILP when solving a synthetic case based on the Goliat field in Norway. A paper was published in OMAE 2022 on this.

Currently, in partnership with AkerBP, we are studying a subsea case for optimal scheduling and placement of subsea equipment using a commercial black-box model and considering uncertainties.

3. MAIN RESULTS

Based on the cases studied, our main contributions are as follows. Regarding the early-phase field planning problem considering uncertainties:

- Both exact and heuristic approaches are fast and robust to determine the probability distribution of the optimal number of wells, plateau rate and project NPV.
- Early-phase designs based on the modes of the probability distributions are different but have an economic performance close (3-15% different) to one made with full "clairvoyance" (Figure 1b).
- The use of LHS in both models allows to drastically reduce the sampling size.
- The multi-objective heuristic optimization proposed allows to find optimum field designs with both high ultimate recovery factor and NPV.

For the subsea layout optimization problem:

- The optimization model successfully finds the best subsea processing design in the study case analyzed (Figure 1d). The optimal solution is found quickly, but a large amount of time is spent converging.
- It is important to include maintenance and reliability aspects in the model since it greatly affects the optimal layout (Figure 1d versus Figure 1e).
- A hybrid method consisting of a genetic algorithm and a nested non-linear optimization was proposed that successfully finds the optimal field layout of the case study in a much shorter time (Figure 1g).

4. INNOVATION AND INDUSTRY COLLABORATION

We obtained some feedback and suggestions from TotalEnergies about the field development optimization studies. Through cooperation with Equinor, we managed to improve the subsea layout model by including reliability and maintenance and then obtained better and more realistic solutions. Lastly, in cooperation with AkerBP, uncertainties and the use of a black-box model were studied and addressed for the subsea gatebox design problem, which gives insights about the applicability of this new technology.

5. FUTURE WORK

The research contained in this thesis can be extended in many directions. Some future work is suggested below:

- Flexibility for the field development problem could also be addressed, i.e. starting the design with the best-known solution and improving it along time with real options theory.
- The values of capital expenditures and maintenance costs are highly uncertain and have, in general, a significant impact on the results. Better input is required, or, alternatively, a robust method to quantify the effect of these uncertainties.
- In the optimizations, a large part of the search space has similar values regarding NPV, flow-rates, system pressure and equipment capacity. Additionally, long times are spent to achieve convergence. Some heuristics or enumeration techniques based on practical engineering guidelines could be implemented and exploited to find solutions faster.
- Some key performance indicators that might be relevant to include in the studies are: internal rate of return, payback time and environmental performance factors such as CO_2 footprint, CO_2 emissions and energy consumption.
- Finally, the proposed methods were applied for specific fields only. More studies with other fields are required to guarantee the applicability and generality of the conclusions shown here.

6. COMPLETE LIST OF PUBLICATIONS

Leonardo, Sales; Johannes, Jäschke; Milan, Stanko.
"Designing Subsea Processing Systems Using a Hybrid Genetic Algorithm".
41st International Conference on Ocean, Offshore and Arctic Engineering (OMAE2022); 2022-06-05 - 2022-06-10

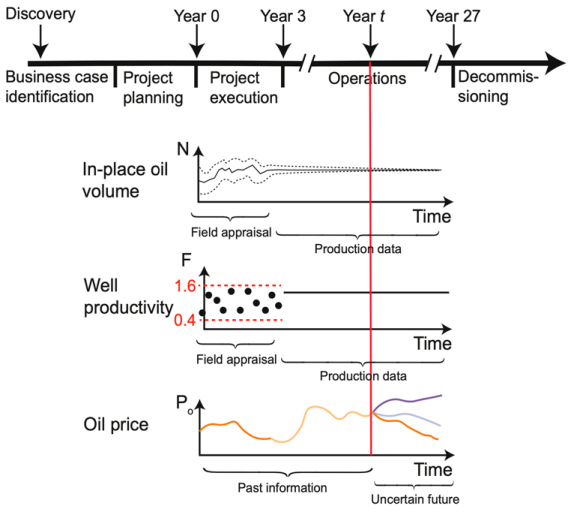
Leonardo, Sales; Milan, Stanko; Johannes, Jäschke.
"Superstructure optimization of subsea processing layouts".
Journal of Petroleum Exploration and Production Technology; Volume 13; Page 1575–1589; 2023

Leonardo, Sales; Milan, Stanko; Johannes, Jäschke.
"Early field planning using optimization and considering uncertainties".
Journal of Petroleum Science and Engineering; Volume 207; 2021.

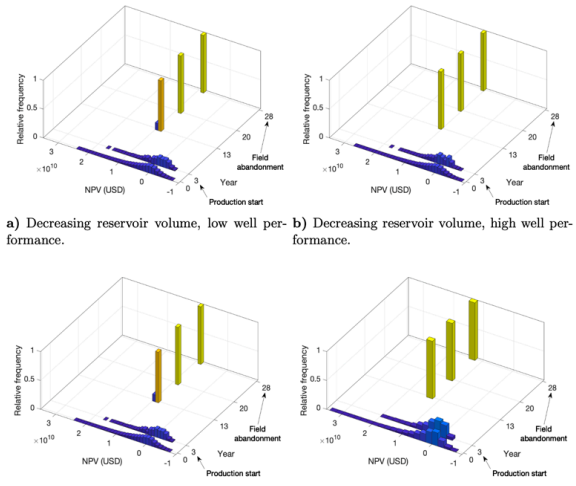
Leonardo, Sales; Thomas, Stolpnes; Milan, Stanko, Audun, Faanes.
"Subsea Processing Optimization Considering Reliability and Maintenance".
42nd International Conference on Ocean, Offshore and Arctic Engineering (OMAE2023); 2022-06-11 - 2022-06-16

7. MY NEW JOB

Company/Institution:	Wood PLC
Position/Area of work:	Subsea Engineer



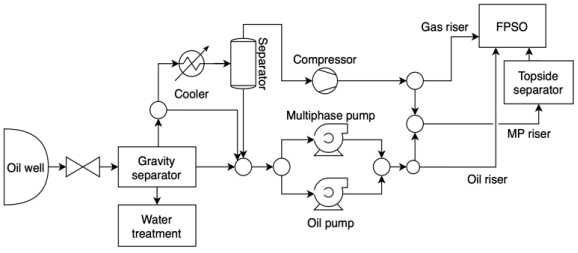
(a)



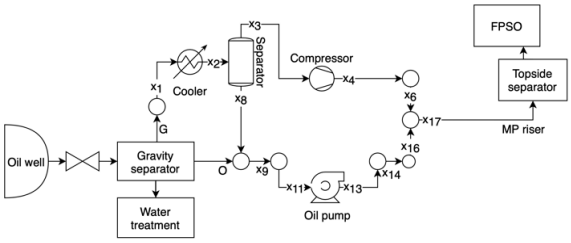
a) Decreasing reservoir volume, low well performance. b) Decreasing reservoir volume, high well performance.

c) Increasing reservoir volume, low well performance. d) Increasing reservoir volume, high well performance.

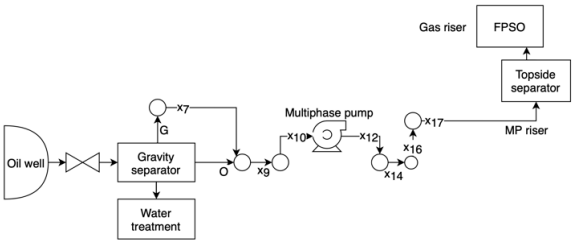
(b)



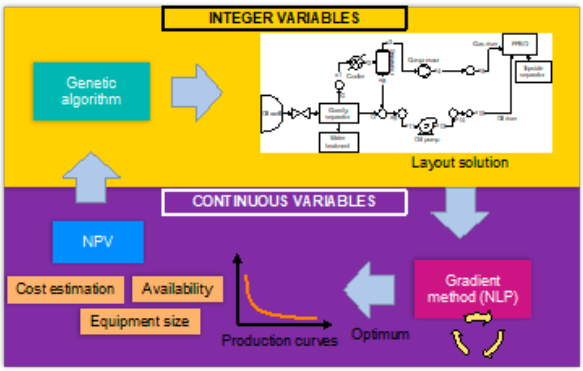
(c)



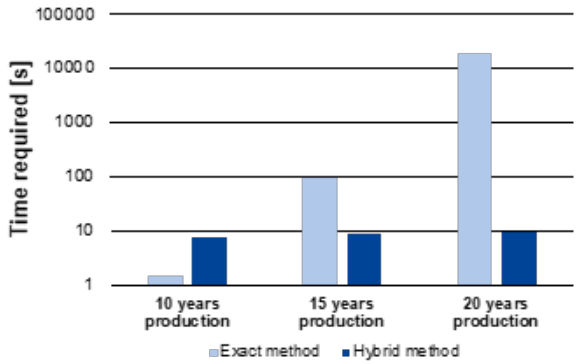
(d)



(e)



(f)



(g)

Figure 1: (a) Uncertain variables in field development. (b) Resulting histograms from field development optimization considering uncertainties. (c) Superstructure used in field layout studies. (d) Solution A, optimal layout using a simplified reliability and maintenance model. (e) Solution B, optimal layout considering RAMS aspects. (f) General hybrid model. (g) Computational effort comparison for the exact and the hybrid model.

Final Project Report

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 graduate: **Lucas Cantinelli Sevillano**
Start date: 01.11.2020
End date: 31.08.2022
Project manager and supervisor: Professor Tor Berge Gjersvik and Adjunct Professor Audun Faanes (Equinor)
Department of Geoscience and Petroleum
Project nr: 1.1.c

1. BACKGROUND FOR THE PROJECT

Worldwide the oil and gas industry is committed to reduce carbon emissions, and to achieve that it has to look beyond the scope of the traditional solutions applied to subsea field architecture. In this sense, subsea production and processing technology may be a key enabler for the continuous exploitation of oil and gas resources. It is therefore essential to evaluate the impact of subsea technology developments to identify technical and economic opportunities for design simplifications, and cost- and emission reductions.

Costs and emissions of subsea production systems must account for the whole service life of the equipment, instead of focusing solely on the initial capital expenses. Therefore, this project has aimed to investigate design solutions which could influence the overall offshore system performance, i.e., subsea equipment plus support vessels, throughout the decades of planned operations. Among other benefits this design approach could enable smaller, less pollutant, more readily available, and cheaper vessels to perform needed intervention jobs.

2. WHAT I HAVE DONE

- ***Identified and mapped readiness level of various subsea technology developments.*** The work was aimed to evaluate existing technologies. The evaluation was based on the API's technology readiness level scale. Selected technologies were the subject of further study cases.
- ***Design and simulated the performance of alternative valve types.*** Valve with alternative geometries, such as a cylindrical rotary valve (See figure 1) may take advantage of all-electrical control architecture since an electric motor can be connected directly to the valve through a gear transmission, and potentially show improved performance of the valve/actuator system.
- ***Compared approaches for estimating fluids needed when pressure testing of subsea Xmas tree valves.*** Proper estimation of the amount of MEG needed when testing valves may optimize the refilling strategy of subsea chemical storage tanks.
- ***Concept definition of a modular subsea Xmas tree***. The work addressed drawings and barrier evaluation of a modular Xmas tree. A modular design concept may reduce costs associated with handling of equipment during subsea interventions, since service vessels with lower specifications and lower day rates could be used to retrieve the smaller modules.
- ***Investigated the potential for a subsea flushing tool***. Before retrieval of subsea hardware, the production fluid trapped inside the equipment must be flushed to prevent hydrocarbon leakages to the environments. The proposed subsea tool can deliver higher flow rates of flushing fluid, increasing the efficiency of the operation.

- ***Conducted stress analyses of the subsea wellhead***. The study analyzed stresses on the wellhead for different installation configurations. The proposed solution for installing the wellhead in a caisson may further reduce the costs associated with mitigating wellhead fatigue and increase the service lifetime of subsea wells.

3. MAIN RESULTS

The literature review on the topic of emerging subsea technologies has identified and mapped the TRL of multiple ongoing technology developments which can be implemented together to optimize the design of SPSs. It has also identified the necessary steps to further develop these technologies.

The results of FEM simulations conduced for the novel rotary cylinder valves has indicated that the frictional force opposing crack opening of the cylinder valve is smaller than the frictional force developed in gate valves used in bores of the same diameter.

The study cases used for comparing the performance of the EOS (Equation of states) approach and the ideal gas approach when estimating the amount of MEG needed to equalize the pressure across gate valves has showed considerable disagreement between the two approaches (see Figure 2), which might indicate the need for adopting the EOS approach when designing the required capacity of a Subsea chemical storage and injection system (SCSIS). The EOS model has been implemented in a spreadsheet to calculate the volume needed of MEG throughout the life service of a field, according to the reservoir's fluid composition and other relevant parameters.

The modular XT architecture spreads the valve functionalities around the well (See Figure 3), and this design concept has been evaluated regarding the well barrier elements in place during different operational phases. Detailed schematics (see Figure 4) have been presented to demonstrate the modular concept's compliance with the 2 barriers principle during IMR (inspection, maintenance, and repair) operations. The relocation of the wing valves to a separate module has shown to reduce the number of components that could become leakage paths during wireline or coiled tubing operations. Modular architecture also enables for equipment retrieved to be carried out by smaller and less costly vessels (See Figure 5).

The calculations performed to evaluate the subsea flushing tool have shown the benefits of reducing the flow rate of MEG from the surface during a flushing operation. Namely, that it may be possible to reduce pumping pressures. Thus, enabling smaller injections lines to be used and reducing costs associated with manufacture and handling of equipment.

Finite element analyses have been used to evaluate the stress distribution in subsea wellheads with different geometric configurations. The results of the simulations (See Figure 6) indicate that installing the well inside a caisson can considerably reduce the stresses on major fatigue hot spots, like the HP housing weld to the surface casing, while stresses on other less vulnerable points of the system may increase. Thus, resulting in an overall gain of equipment service life (Increased BOP days).

The project results comprise a collection of technical reports and scientific papers which present the different approaches for improving the design of subsea production systems. Such a collection could be used as reference material for future lines of research.

4. INNOVATION AND INDUSTRY COLLABORATION

The research topics addressed with most potential for innovation are the rotary cylindrical gate valve and the modular XT design architecture. The analyses conduced at the design concept level (TRL 1) indicate the potential improvements of performance but would require in-depth analyses in collaboration with industry partners, such as Aker Solutions, TechnipFMC, etc., regarding further development

The methodology proposed for estimating MEG volumes when testing Xmas tree valves, and the method for wellhead installation in a caisson could be further developed with an operator partner like Equinor or AkerBP and could be implemented in a shorter timeframe compared to the cylindrical gate valve concept or the modular XT design architecture.

5. FURTHER WORK

- Use fluid and operational (pressure, temperature) data from a real field case scenario to assess the volume estimation of MEG used to equalize the pressure across vales when performing pressure tests.
- Perform a cost-analysis of the modular Xmas tree design concept, regarding the extra hardware costs with the multiple modules versus the savings obtained in workover operations performed by smaller support vessels.
- The proposed modular Xmas tree design concept requires a dedicated RAMS analysis, particularly to determine the reliability of the additional connections between the different modules.
- Estimate the technical specifications of the actuator mechanism needed to operate the proposed rotary cylindrical gate valve, based on the initial values obtained for friction force when opening the valve.
- The calculations performed for the flushing system tool were based on small-scale lab experiments and simulations of said experiment. It would be relevant to model the flushing of an actual subsea production system to confirm the findings.
- The study on wellhead installation in a caisson could be extended to analyze other parameters such as the diameter of the caisson and different kind of soils, which could offer either less or more resistance to the wellhead motions.

6. COMPLETE LIST OF PUBLICATIONS

Sevillano, Lucas Cantinelli; Sangesland, Sigbjørn. *"Assessment of power requirements for alternative vertical transportation system for deepsea mining".* 41st International Conference on Ocean, Offshore, and Arctic Engineering (OMAE2022); 2022-06-05 - 2022-06-10.

Sevillano, Lucas Cantinelli; Sangesland, Sigbjørn; Gjersvik, Tor Berge; Faanes, Audun.
"A more accurate approach for the design of subsea chemical storage systems regarding volume requirements of valve leakage tests".
41st International Conference on Ocean, Offshore and Arctic Engineering (OMAE2022); 2022-06-05 - 2022-06-10.

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; 21-30 June 2021.

7. MY NEW JOB

I am currently employed as a subsea engineer at Wood Group Norway AS, based in their Stavanger office. I may be reached at lucas.sevillano@woodplc.com.

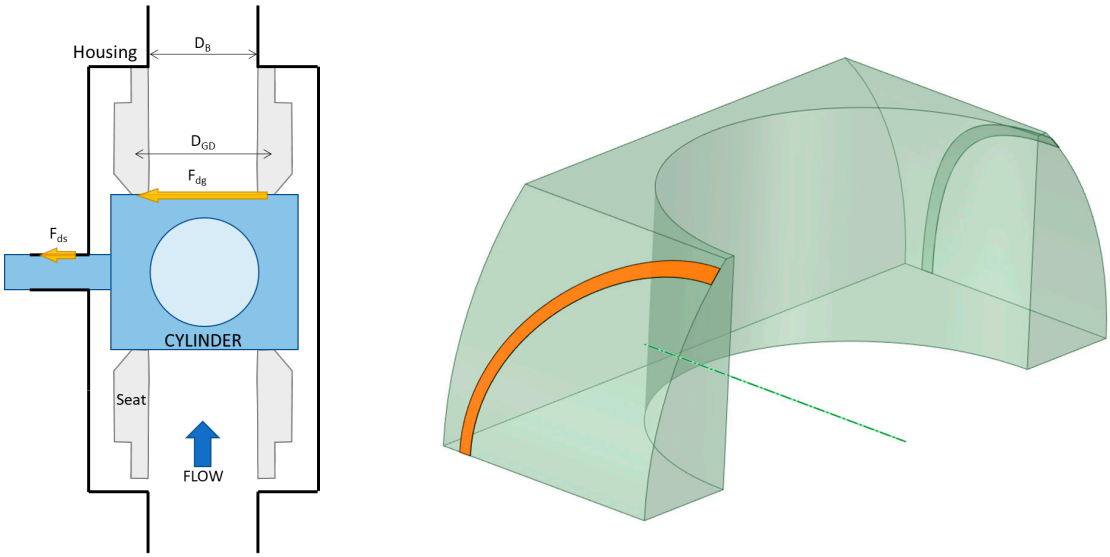


Figure 1 – Left: Force Balance in Cylinder Valve to Crack Open the Valve. Right: 3D Models of Half-Cylinder Used in FEA. Valve in Closed Position. Seat Not Depicted for Clarity. Highlighted in Orange the Contact Surface Between Cylinder and Seat.

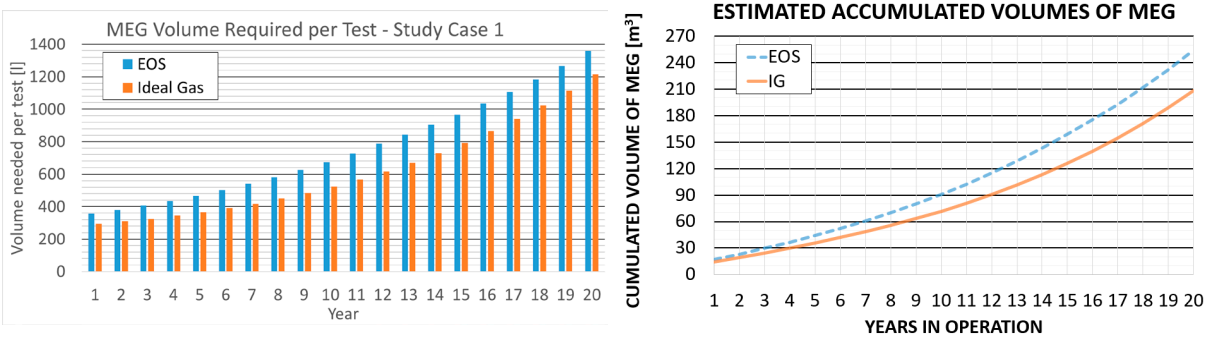
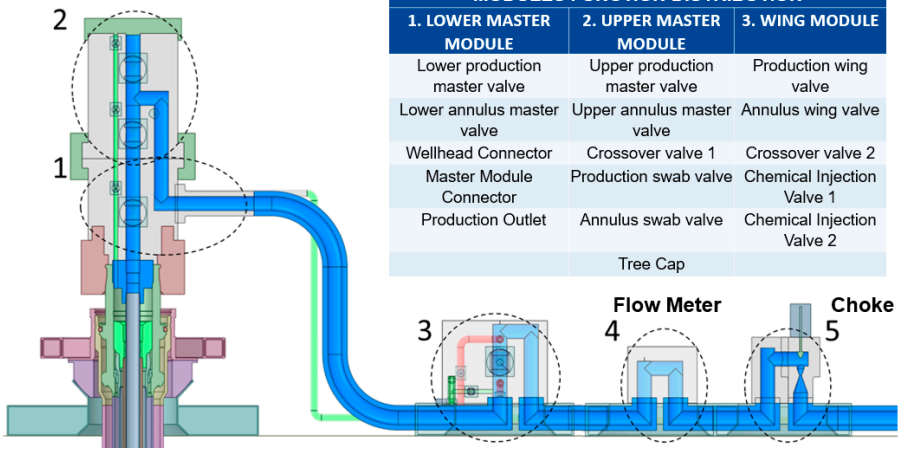


Figure 2 – Comparison between MEG volumes estimated according to the EOS approach and the ideal gas approach. The IG approach consistently underestimates the amount of MEG needed per year (top). Which reflects on the accumulated volume of MEG used (bottom) and the scheduling of refilling operations for the subsea chemical storage tanks.



MODULES FUNCTION DISTRIBUTION		
1. LOWER MASTER MODULE	**2. UPPER MASTER MODULE**	**3. WING MODULE**
Lower production master valve	Upper production master valve	Production wing valve
Lower annulus master valve	Upper annulus master valve	Annulus wing valve
Wellhead Connector	Crossover valve 1	Crossover valve 2
Master Module Connector	Production swab valve	Chemical Injection Valve 1
Production Outlet	Annulus swab valve	Chemical Injection Valve 2
	Tree Cap	

Figure 3 - 3D model of modular Xmas Tree and description of functionalities distribution. Modules 1 and 2 sit on top of the wellhead, while modules 3, 4 and 5 are installed around the wellhead. Easier access to modules 2, 3, 4 and 5 simplify their retrieval operation.

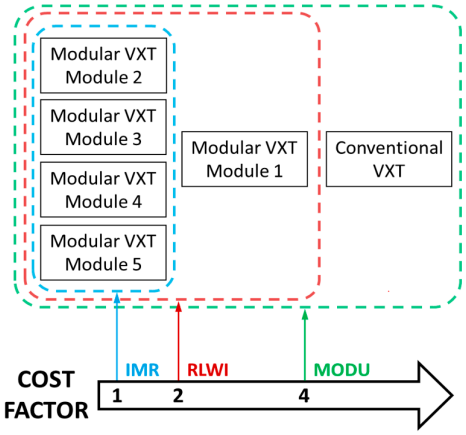


Figure 5 – Intervention Cost Reduction Potential of Modular XT Architecture

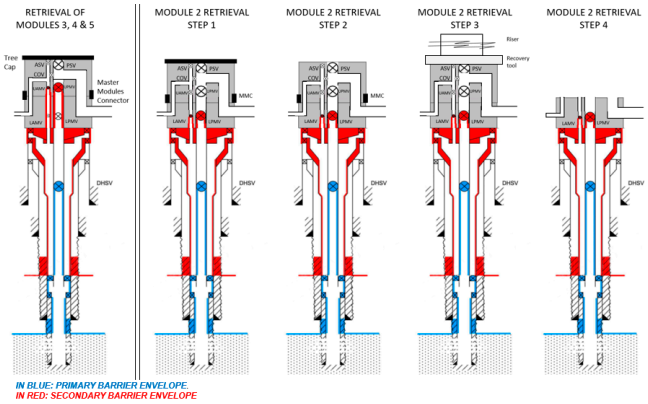


Figure 4 - Sketch of barriers in place during retrieval of modules. And also a FEM simulation of a subsea wellhead

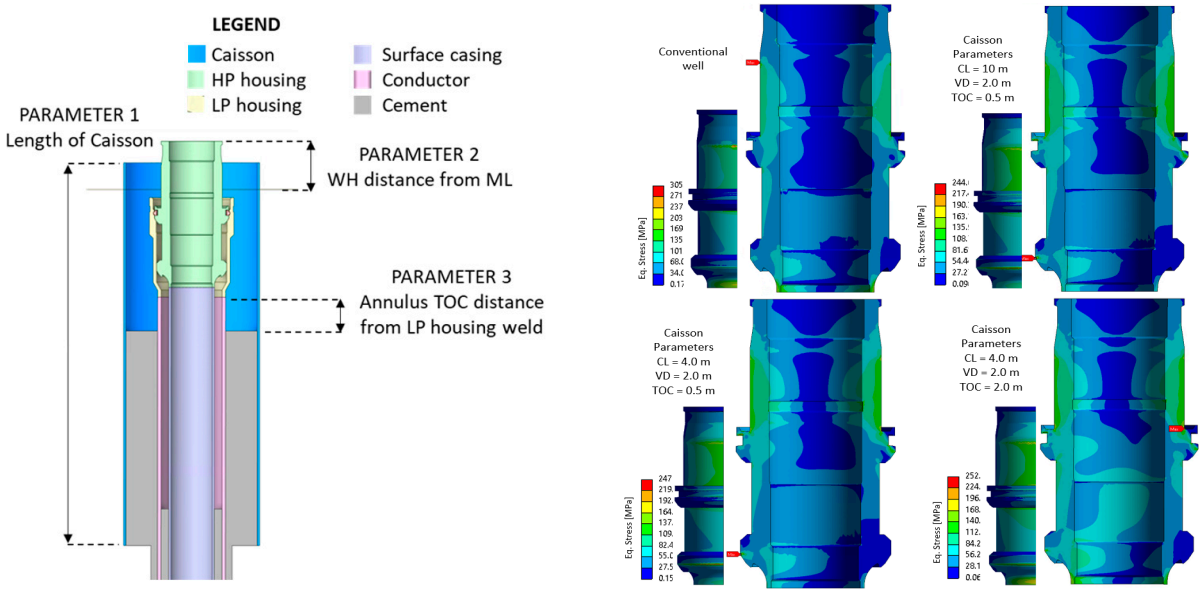


Figure 6 – LEFT: 3D FEM of wellhead and caisson. RIGHT: von Mises stress distribution in high-pressure housing for different design parameters

RESEARCH AREA

Reliability, Availability, Maintenance and Safety (RAMS)

Cost efficient solutions without compromising safety and environment.

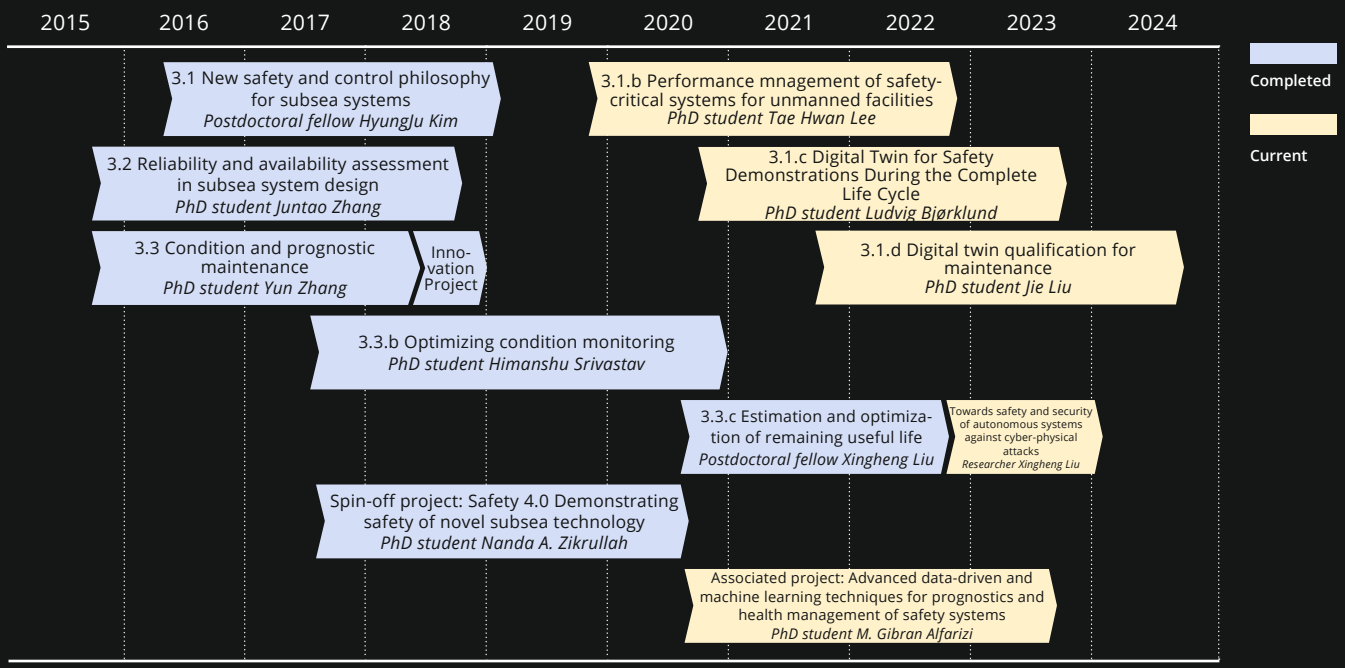
Professor Jørn Vatn
Research Area Manager
Department og Mechanical and Industrial Engineering

2022 was a year for the continuation of ongoing research within the established topics of the RAMS research area. There is no new PhDs started up in 2022, but Xingheng Liu completed his postdoctoral position and entered into a one-year researcher project towards safety and security of autonomous systems against cyber-physical attacks . PhD candidate Nanda Anugrah Zikrullah defended successfully his thesis on 24.02.2022 and is now employed in DNV.

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”. For 2023 Xingheng Liu will present maintenance modelling on the production optimization workshop arranged by BRU21 in March 2023.

SUBPRO is aiming to continue the research beyond the original time frame of the SFI om the SUBPRO-Zero project initiative. Several SUBPRO partners have indicated the interest for such a follow up project which hopefully at a later stage could develop into an FME (Research centre for environmental friendly energy). From the RAMS area we have proposed five candidate PhD projects covering safety, production assurance, security and machine learning. Final decision on these project will be march 2023. As a warm up for this new initiative three master students are investigating needs for research on production assurance/reliability modelling in relation to blue hydrogen production. The aim is also to obtain synergy with the FME HYDROGENi.

Completed and current projects



The RAMS team, from the left, around the clock: PhD student Tae Hwan Lee, Profesor Jørn Vatn, PhD student Jie Liu, Professor Mary Ann Lundteigen, Researcher Xingheng Liu and associated PhD student Muhammad Gibran Alfarizi.
***Professor Shen Yin,** Adjunct Professor Gunleiv Skofteland (Equinor), Professor Markus Glaser (Aalen University), Senior Principal Researcher Tore Myhrvold (DNV) and PhD student Ludvig Bjørklund were not present when the picture was taken.*

Performance management of safety-critical systems for unmanned facilities

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: **Tae Hwan Lee**
Start date: 28.10.2019
Planned end date: 11.02.2023
Project manager and main supervisor: Professor Mary Ann Lundteigen
Co-Supervisor: Adjunct professor Gunleiv Skofteland (Equinor), Adjunct professor Frank Ove Westad
Department of Engineering Cybernetics
Project nr: 3.1.d

1. BACKGROUND

Performance management of safety instrumented systems (SIS), automatic control systems to ensure safe condition even at accidental situation, 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 DELIVERABLES

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 European Safety and Reliability (ESREL) 2021 conference.

In SIS advisor, not only existing operation data is used to build a classification model, but the data generated from dynamic process simulation software is also used to com-

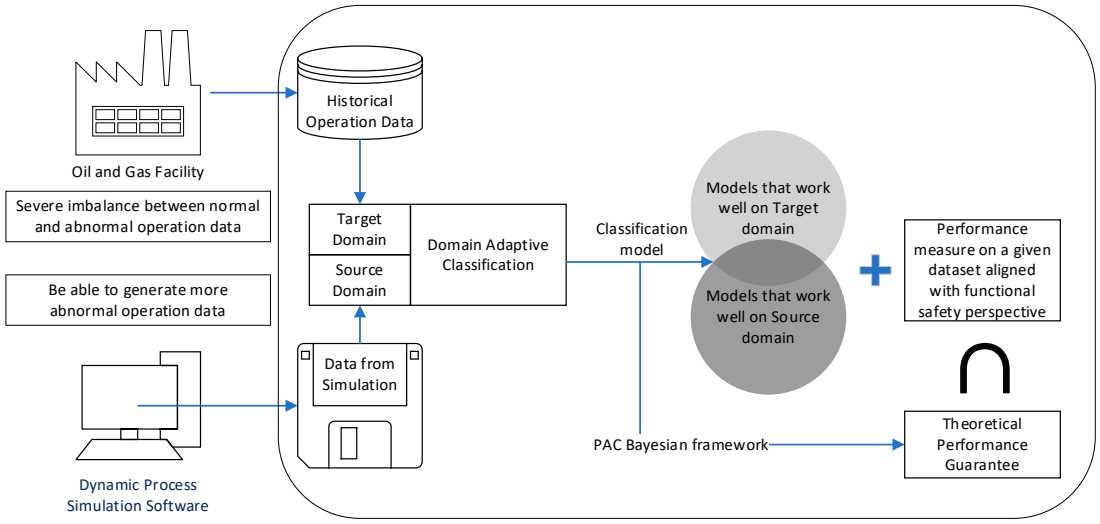


Figure 1. SIS advisor framework

plement the completeness of data distribution. By having simulation data based on hazardous event scenarios, it is possible to reduce the impact of sample selection bias in machine learning which happens often by having insufficient coverage of actual data distribution as well as the impact of class imbalance by having more data in dangerous operating condition.

In 2022, research activities were focused on following items:

- Reformulated the problem into several distinct issues
  - o Simulation-generative oversampling
    - . To overcome a sample selection bias due to incomplete sampling on the data
    - . To minimize the effect of class imbalance due to intrinsic characteristic of SIS
  - o Domain adaptive approach
    - . To minimize the effect of covariate shift between actual field data and simulation data
  - o PAC Bayesian approach
    - . To provide quantitative measure on performance guarantee of a SIS advisor
- Performed an experiment on simulation-generative oversampling part and compared its performance with several class imbalance reduction techniques with a measure of ROC AUC (Area Under Receiver Operating Characteristic (ROC) Curve). Figure 2 shows the result of experiment, and it can be confirmed that simulation-generative over-sampling method shows the best performance in average on 100 repeated experiments.

During 2023, which is the final year, implementation on PAC Bayesian approach as well as domain adaptive approach is planned. Publication plan is as follows:

- Simulation-generative over-sampling + PAC Bayesian generalization error bound
- Domain adaptive simulation-generative over-sampling + PAC Bayesian domain adaptation error bounds

Innovation project, as an extended project from original PhD project, is planned to be performed to investigate applicability on an industrial case.

3. INDUSTRY PARTICIPATION

Currently, Equinor and DNV are participating actively in this project, and collaboration is established with Kongsberg Digital (KDI) 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 KDI. Open simulation platform and K-SPICE were introduced to NTNU students and professors for discussing how such products can be utilized in their research.

4. INNOVATION

Innovation project is planned to be performed as an extension of this project to find its applicability in an actual field environment, and to figure out practical challenges in the application. Currently, due to lack of actual field data and immature status of technology itself, only data generated through K-SPICE, a dynamic process simulation software, is used. By having an experiment in more realistic configuration, industry partners can get more confidence on adopting machine learning or data analysis tool as a hazard detection or situational awareness as well as an idea on how such technology needs to be applied in safety critical applications.

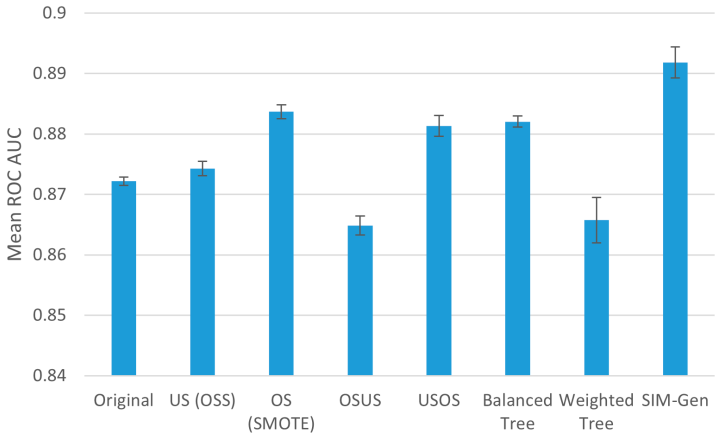


Figure 2. Result of experiment on simulation-generative over-sampling technique and its comparison to other class imbalance reduction techniques (Mean ROC AUC score with standard error on test data set). US means under-sampling, OS means over-sampling, and SIM-Gen means simulation-generative over-sampling method.

Digital Twin for Safety Demonstrations During the Complete Life Cycle

Towards a complete framework for demonstrating the safety of an all-electric actuated subsea valve using a Digital Twin.

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 and reduce the amount of experimental verification activities.

PhD student: **Ludvig Björklund**
Start date: 28.08.2020
Planned end date: 31.03.2024
Project manager: Professor Mary Ann Lundteigen
Supervisors: Prof. Mary Ann Lundteigen, Prof. Markus Glaser (Aalen University) and Prof. Gunleiv Skofteland (Equinor)
Department of Engineering Cybernetics
Project nr: 3.1.c

1. BACKGROUND

Shifting from electro-hydraulic-based actuation to all-electric systems enables cost reductions and potentially also increased safety. The potential increase in safety level relates to improved diagnostics and technical health monitoring of critical components. Due to novelty of concepts with battery assisted valve closure, it is vital to demonstrate the safety before acceptance. With the reliance on programmable systems, it is necessary to align the safety demonstration with the functional safety requirements in standards like IEC 61508. The aim of this project is to introduce a digital twin (DT) framework for use in safety demonstration, containing modeling approaches and sample models, which can efficiently interface the control logic at different stages of the development process.

DIGITAL TWINS AS A OPPORTUNITY FOR IMPROVED SAFETY DEMONSTRATION

Simulation-based approaches of verification activities can scale up the testing of the functional safety. The concept of DTs becomes an interesting extension by considering the complete lifecycle of each unique physical iteration of the asset. Varying physical parameters within the underlying models and inputs, as illustrated in Figure 1, will enable a high-test coverage and analytical potentials of the behavior of the mirrored physical asset, including the software applications. A DT would additionally enable verification activities of software updates to cover the lifespan of the physical asset. To facilitate simple and scalable DT-based testing of safety-logic, control algorithms and diagnostic tools, for which the safe execution of the all-electric is dependent upon, modeling transparency and iteration time of simulations are important research topics.

2. WHAT HAVE I DONE

FITTING THE DIGITAL TWIN ACCORDING TO THE INTENDED PURPOSE

A transparent modeling approach of defining physical parameters to be included or excluded in the mathematical models, proposed, and evaluated on the models of the gate valve and stem, of which the DT is built upon. The results were published in conference proceedings and presented at ESREL 2022.

PREPARING THE DIGITAL TWIN FOR REAL-TIME

A key value identified with using DTs for safety demonstrations are the potential of mitigating the time required for testing of the functional safety of the system, including the software-enabled functionalities. Interfacing the underlying models with software intended for implementation in hardware target devices, relying on electrical wiring, is of utmost importance for the DT to improve safety demonstrations. In Figure 1, the dashed line illustrates the interfacing issue that is discussed. Interfacing the software application with the DT, focusing on the realization of control algorithms implemented (or describing) as logical circuits.

An article addressing this issue is currently in the final stages, tackling the potential of three potential interfacing solutions and predictions on the performance of each in relation to derived criteria of varying importance.

3. MAIN RESULTS

This approach for demonstrating safety could scale up the verification activities and cover scenarios hard to emulate in experimental test benches. The deliverables of the project will consist of

A prototype DT which covers the safety relevant behaviour of the case study

A DT-based approach for simple and quick verification activities

A test suite which enabling operators and other actors to evaluate scenarios covering failure modes and degradation effects.

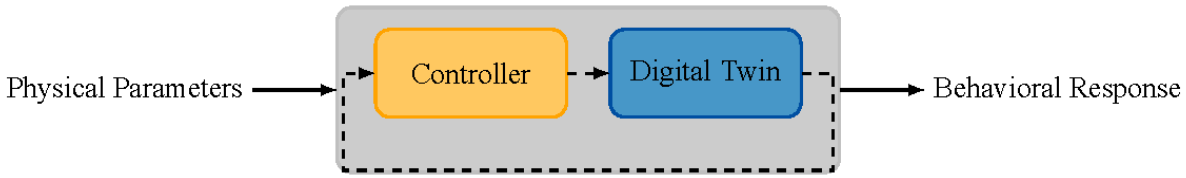


Figure 1: Testing the behavior of software-reliant functional safety system by means of varying inputs and parameters. A set of parameters and inputs results in a response both from the Digital Twin mirroring a physical asset, but an overall behavior of the system, enabling evaluation of the safe/unsafe actions of the controller.

Digital Twin Qualification for Maintenance

A new method to qualify and assure the 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**
Start date: 01.09.2021
Planned end date: 31.08.2024
Project manager and supervisor: Professor Shen Yin
Co-supervisor: Prof. Jørn Vatn
Department of Mechanical and Industrial Engineering
Project nr: 3.1.d

1. BACKGROUND

In November 2020, SUBPRO hosted a Digital Twins seminar where this PhD project was suggested and supported. Since they can continuously estimate the state and trend of the processing system and aid in the optimization of maintenance plans, digital twins are thought to play a significant role in maintenance engineering and optimization. Before digital twins can be used in the industry, there are still a few obstacles to be overcome, such as how to guarantee model quality and that the models' output is consistently reliable.

The "DNV-RP-A204 Qualification and assurance of digital twins" Recommended Practice (RP) was released by DNV in 2020 [1]. The RP fully outlines high-level requirements for the assurance and qualification of digital twins. Real-time interactions between physical and virtual things are the focus of certain researchers. Depending on the data flow, DT can have varying levels of integration, and a model is only regarded as a digital twin when both automatic data flows are present [2]. However, automatic data flow from the digital item to the physical object is often not needed for maintenance models because engineers or operators tend to base most decisions on safety standards. Additionally, end users could use digital twins to identify system states, predict system growth, and display system behaviors. The utilization of digital twins may be related to the capacity level of digital twins, which is hypothesized to have six levels and can be either separated from or connected to the physical system [3].

The three domains or categories of maintenance models are fault diagnosis, failure prognosis, and maintenance optimization. All of these models were developed using probability theory and the underlying techniques for diagnostic and failure prediction. Therefore, determining how trustworthy the models are is difficult. The same is true for digital twins for maintenance built using these models. The PhD project aims to present methods for keeping competent and reliable digital twins.

2. RESEARCH ACTIVITIES AND DELIVERABLES

Essential courses, like System Resilience and Digital twins for sustainable manufacturing, were taken as part of the PhD academic training. Two conference papers have also been written and submitted independently to ESREL 2022 and IFAC 2023. The article, which was published in ESREL 2022, offers approaches for assessing the models used for predicting the remaining usable life from a resilience perspective. In November 2022, the second conference paper is submitted to IFAC 2023. The paper suggested an index for evaluating digital twins, which is depicted in Figure 1. The index is also tied to and evaluated against prior related research.

3. INDUSTRY PARTICIPATION

The PhD project's initial starting point is the DNV publication. It is planned to collaborate with DNV and other industry partners who create or utilize digital twins for maintenance over the phase of the project in order to discuss and confirm the suggested methodologies and carry out testing using real-world data.

4. MAIN RESULTS

The project targeted results are paramount to ensure confidence that the digital twin will function as specified and that the information and decisions can be trusted. Lack of trust will limit the value provided by the digital twin.

5. REFERENCE

[1] DNV-RP-A204 (2020). Qualification and assurance of digital twins. Recommended practice, DNV.

[2] Kritzinger, W., Karner, M., Traar, G., Henjes, J., and Sihn, W. (2018). Digital twin in manufacturing: A categorical literature review and classification. IFAC-PapersOnLine, 51(11), 1016–1022.

[3] Altamiranda, Edmary, and Eliezer Colina. "A system of systems digital twin to support lifetime management and life extension of subsea production systems." OCEANS 2019-Marseille. IEEE, 2019.

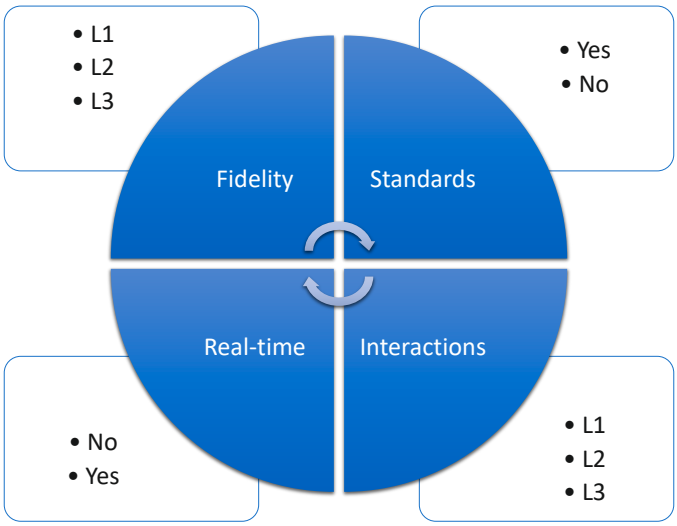


Figure 1: Proposed index for digital twins' evaluation.

Advanced data-driven and machine learning techniques for prognostics and health management of 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**
Start date: 16.08.2020
Planned end date: 31.07.2023
Project manager and main supervisor: Professor Shen Yin
Co-Supervisor: Professor Jørn Vatn
Department of Mechanical and Industrial Engineering

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 published in Journal IEEE Transactions on Artificial Intelligence.

In the field of prognostics, we have investigated the use of random forest and Bayesian optimization for predicting remaining useful life of experimental bearings. The study shows superior RUL prediction compared to RUL prediction with stochastic Wiener process. The study has been published in Journal IEEE Transactions on Industrial Informatics. In addition, random forest can also be used to predict liquid hydrogen release characteristics, which can help to select effective safety barriers and adopt the most appropriate safety measures in case of liquid hydrogen leakage. The study has been submitted to Journal Reliability Engineering and System Safety.

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.

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

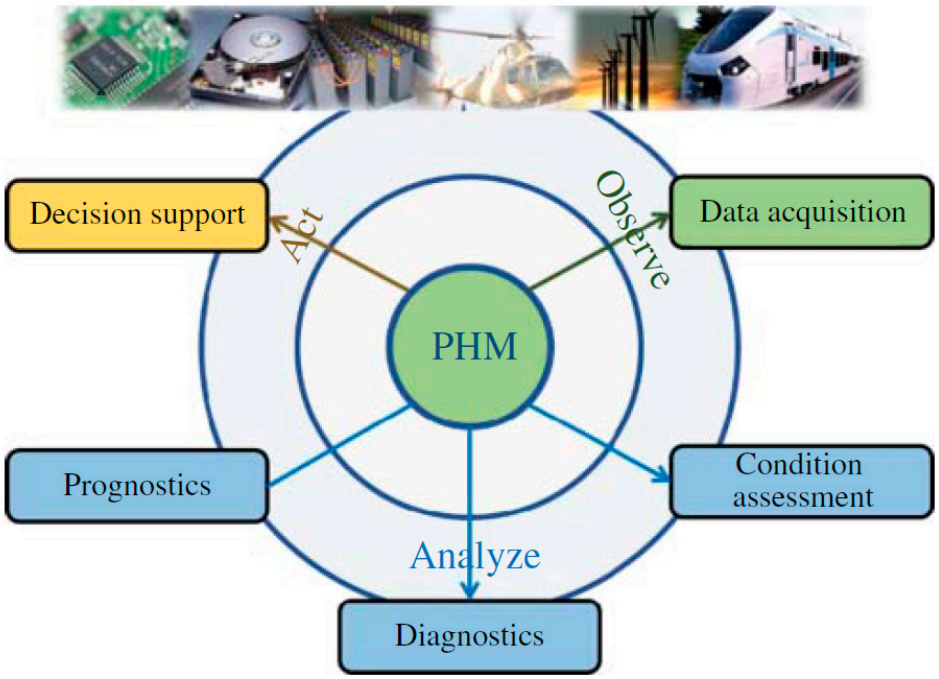
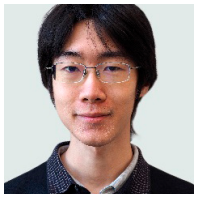


Figure 1. Framework for prognostics and health management.

Towards safety and security of autonomous systems against cyber-physical attacks

A systematic study of defence strategies against cyber-physical attacks on autonomous systems

Green Shift Impact: Enhance the safety and security of cyber-physical systems to prevent loss and accidents while optimizing the use of defence resources.



Researcher: **Xingheng Liu**
Start date: 01.10.2022
Planned end date: 30.09.2023
Supervisor/Co-supervisor: Prof. Jørn Vatn and Prof. Shen Yin
Department of Mechanical and Industrial Engineering
Project nr: 3.3.d

1. BACKGROUD OF THE PROJECT

Cyber-physical systems integrate sensing, computation, control and networking into physical objects and infrastructure, connecting them to the Internet and to each other. With its increasing use in all aspects in our daily life, such as smart grid, autonomous automobile systems, medical monitoring, industrial control systems, robotics systems, and automatic pilot avionics, an appropriate risk assessment for CPS is in urgent need. This project is dedicated to a systematic study of defense strategies against cyber-physical attacks on autonomous systems, from a perspective of systems and control, and RAMS.

2. RESEARCH ACTIVITIES AND DELIVERABLES

This research initiates a systematic study on the common aspects of the differences in system configurations and attack surfaces. The scientific objectives include (i) a theoretical framework on reliability and safety of autonomous systems, and (ii) an integrated theoretical framework where the complete lifecycle of attack prevention, attack-resilience, and attack detection & identification is considered (iii) detection and resilient control schemes that are applicable to all types of integrity attacks, and (iv) a comprehensive framework for state estimation and health monitoring using sensor data under diverse types of cyber-physical attack. It will contribute as the very first effort towards a generic solution to dealing with all types of integrity attacks at the bottom-level of measurement and control systems. In particular, the following activities have been or will be carried out:

A Setup of RAMS laboratory. Consisting of multiple autonomous vehicles (see Figure 1 and 2), the Autonomous Vehicles Research Studio (AVRS) is a start point for research in autonomous robotics, resilient control, fault detection and isolation, and infrastructure inspection. The setup has been accomplished early November, and the coordinated motion control of multiple vehicles has been successfully demonstrated.

B Special session organization. Currently the target conferences include IEEE ISIE (32nd International Symposium on Industrial Electronics) and IECON 2023 (49th Annual Conference of the IEEE Industrial Electronics Society). A special session proposal on the sustainability of industrial CPS has been submitted to IEEE ISIE.

C Publish research and review papers on the sustainability, safety and security of cyber-physical systems. New attack and defense strategies for cyber-physical systems, as well as robust and resilient control will be addressed and validated using the RAMS LAB.

D Internal collaboration with project 3.1: Digital twin qualification. We aim to provide new methods and metrics for the evaluation and quantification of the resilience of cyber-physical systems facing internal failure/external attacks of different severity.

3. POTENTIAL RESULTS

This work will contribute to new methods and tools for systematic risk assessment, by identifying and evaluating system vulnerabilities, attack scenarios and countermeasures. Considerations for safety and security will be addressed simultaneously in a unified framework with the ultimate goal to avoid failures. The developed method shall be used in conceptual design phases for new systems (e.g., SCADA for wind turbine control) to establish safety barriers and select attack countermeasures in a cost-effective way. It can also be used to evaluate and validate existing protections on a system, examining the potential vulnerabilities and proposing improvement measures to enhance safety and security.

Figure 1: drones, vehicles, and robots in the autonomous vehicle research studio. They are equipped with embedded computers, cameras and sensors that enable the sensing of operation environment and network communication.

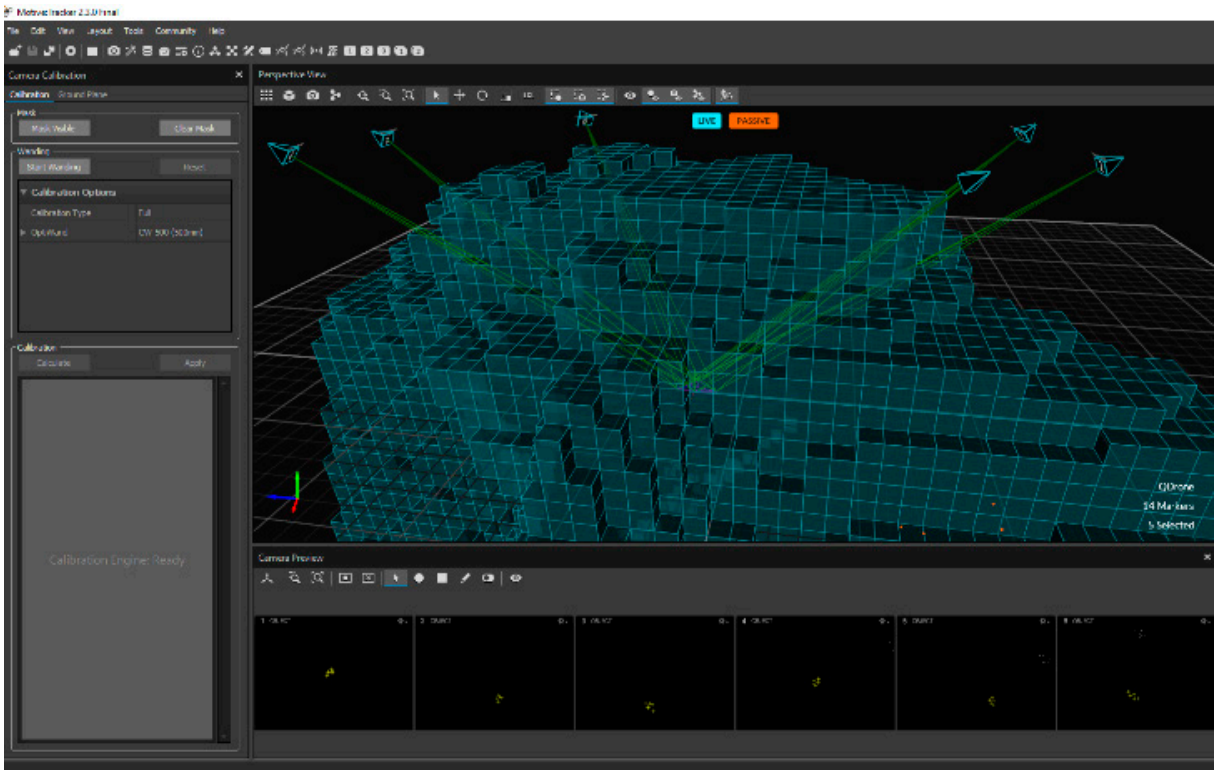


Figure 2: Calibration of OptiTrack, the motion capture system.

Final Project report

Estimation and optimization of remaining useful life

Develop prototype simulators for prediction and optimization of remaining useful life for subsea choke valves.

Postdoctoral graduate: **Xingheng Liu**
Start date: 01.10.2020
End date: 30.09.2022
Project manager and supervisor: Professor Jørn Vatn
Department of Mechanical and Industrial Engineering
Project nr: 3.3.c

1. BACKGROUND FOR THE PROJECT

Subsea systems are vulnerable to degradation and failure. In addition, field inspections and maintenance on subsea systems are typically complicated, expensive, and time-consuming due to limited accessibility. Thus, there is a benefit in tracking system health and calculating its remaining useful lifetime (RUL) from both a safety and financial standpoint. A choke valve lowers the well pressure, controls production rate, and creates downstream or back pressure by limiting the flow to a narrow aperture or orifice. Given the possibility of high flow velocities produced by the pressure let-down over the choke, the valves stand out as the parts of oil & gas production systems most vulnerable to erosion. As a result of sand production, drilling, and hydraulic fracturing, the abrasive well stream frequently contains oil, gas, water, sand, and other particles such as calcite and proppants. Moreover, the operating condition, i.e., percent travel of a choke valve, is constantly changing, which makes it even more difficult to obtain intuitive and easily interpretable health indicators. **The industrial challenge is, therefore, estimating the RUL of a choke valve working under complex environment and time-varying operating conditions.**

2. WHAT I HAVE DONE

The common belief is that the erosion of a production choke is monotonic and irreversible. Indeed, the actual opening of a valve at a given percent travel shall increase with time due to constant erosion, although clogging may sometimes cause a temporary decrease of the effective pass area. My research is driven by the fact that the recorded health indicator, namely the flow coefficient Cv, is rarely monotonic which contradicts the physical reasoning. The research then proceeded into three directions. First, we simply assume that non-monotonicity results from noise. Under this assumption, the research question becomes how to effectively estimate the true degradation when it is masked by noise. Second, we consider the influence of percent travel (operating condition), and explicitly model its effect on the observed health indicator. More specifically, we assume that when the percent travel changes, both the Cv value and its changing rate are perturbed. Moreover, noise level is also assumed to be influenced by the percent travel. This leads to sophisticated modeling approaches to describe the degradation process and to estimate the model parameters. Finally, we consider the health indicator at any time as a function of the percent travel. In this way, traditional degradation models that consider the evolution of 1- (or N-) dimension scalar health indicator(s) become inappropriate since the degradation is characterized by a curve slowly drifting away from its baseline values. Eventually, a degraded surface is formed. From this perspective, the degradation modeling is treated in an interpolation and extrapolation framework. Diverse methods, including spatio-temporal approaches, have been examined in terms of their suitability in describing the degradation process and their capability in forecasting the degradation evolution.

To answer the first research question, in Early 2021, I reached out to Jose Otavio Assumpcao Matias, former postdoc in the Department of Chemical Engineering supervised by Prof. Johannes Jäschke. He worked on RUL estimation from a production optimization and control perspective. Having setup an experimental rig in his department, Jose collected erosion monitoring data, which exhibited the non-monotonicity due to measurement noise. I then designed and tested new filtering algorithms. Despite the fact that the lab environment was not able to simulate the erosion environment in a real production

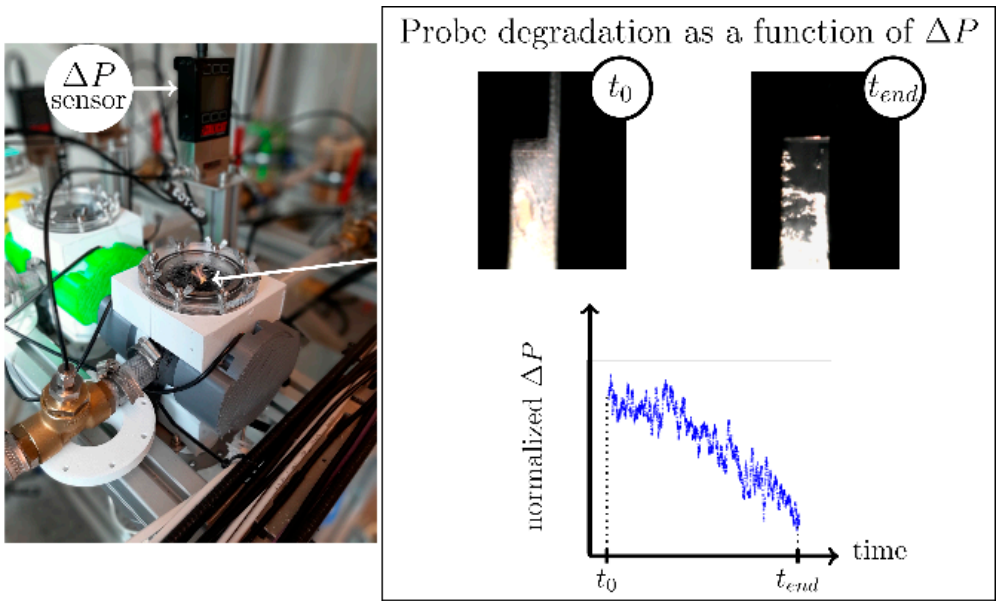


Figure 1: Eroding sample (top right), the container (left) and the degradation measurement pressure drop (bottom right). The whole experimental rig is not shown here.

well, we managed to build filtering algorithms based on Gibbs sampling, and published a research paper in Reliability Engineering & System Safety.

The second and third research questions are triggered by observed patterns in the field data provided by Equinor. The resulting articles are still under review. Apart from research on the choke valve, I also worked together with BRU21 participant, PhD candidate Tom Ivar Pedersen, who is pursuing a doctor degree in maintenance optimization. We worked together on developing advanced and realistic quantitative maintenance strategies for the silicon industry, with case studies on real plant. There were also international collaborations with researchers in City University of Hong Kong. Particularly, with Dr. Aibo Zhang, former PhD candidate in RAMS group, we together proposed a novel hierarchical maintenance framework to incorporate the information density into maintenance/inspection modeling. The above-mentioned research activities are quite recent, so the papers are still under review.

(INDUSTRY COOPERATION: CONTRIBUTIONS, FROM WHICH COMPANIES)

Equinor is the most active industrial partner in this project. Our contact in Equinor, Mr. Erling Lunde, has provided us valuable field data and helped me understand the technical context and details. That was the starting point of my second and third research questions: the real data has shown more complex pattern then those collected in an experimental environment, and thus, required more complex models and assumptions. Apart from Equinor, there have also been meaningful discussion and exchanges with DNV, Lundin, Kongsberg.

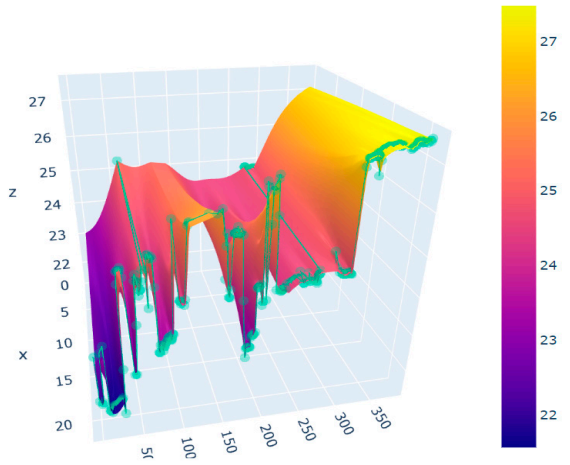


Figure 2: interpolated Cv. The green points are actual observations. x, y and z axis represent percent travel, time and Cv, respectively. Using kriging, we can obtain a Cv surface which shows the erosion at any time and any percent travel.

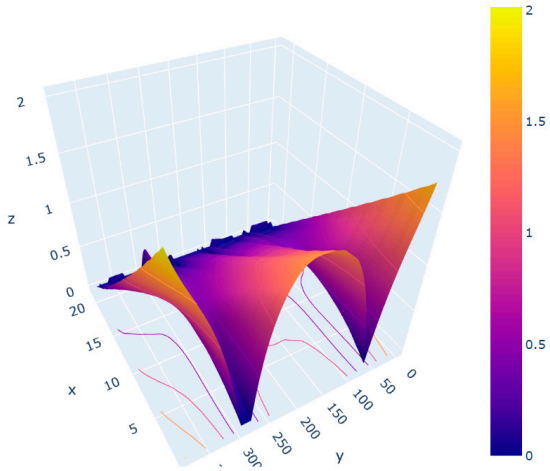


Figure 3: the standard deviation (axis z, also the color bar) of the interpolated Cv in Figure 2. Depending on the density of actual observations, the model has less confidence in its interpolated Cv at locations where few Cv data are collected.

3. MAIN RESULTS

We have advanced the scientific community of degradation modeling and RUL estimation in different ways. The main academic contributions are listed below:

A Proposed a Gibbs sampling-based filter to estimate the degradation when the original health indicator is perturbed with noise.

B Proposed a state space model to incorporate time-varying operating condition into degradation modeling and used particle filter to estimate the underlying model parameters.

C Proposed a spatio-temporal interpolation/extrapolation framework to model two-dimension degradation. Methods such as Kriging have shown their strength in exploiting the 2D data, and their forecasting capabilities are tested and proved to outperform traditional methods such as time series analysis.

The bullet points below highlight new insights health management for subsea choke valves:

- The percent travel is a factor that should never be overlooked when considering the degradation of a valve, as it defines the baseline behavior.

Predicting the RUL requires more data than the Cv and percent travel. Flow rate, sand data and event log are crucial for explaining the fluctuations of the health indicator. In our work, we did not manage to get those data.

Developing RUL estimation model requires active participation of flow assurance expert.

A prototype for RUL prediction has been built using Python. The prototype requires historical Cv and percent travel data as input, and predict the estimated Cv for different valve opening and its confidence interval as output. A demonstration was shown in a workshop in September 2022, where most participants (Equinor, DNV, Lundin...) work on flow assurance.

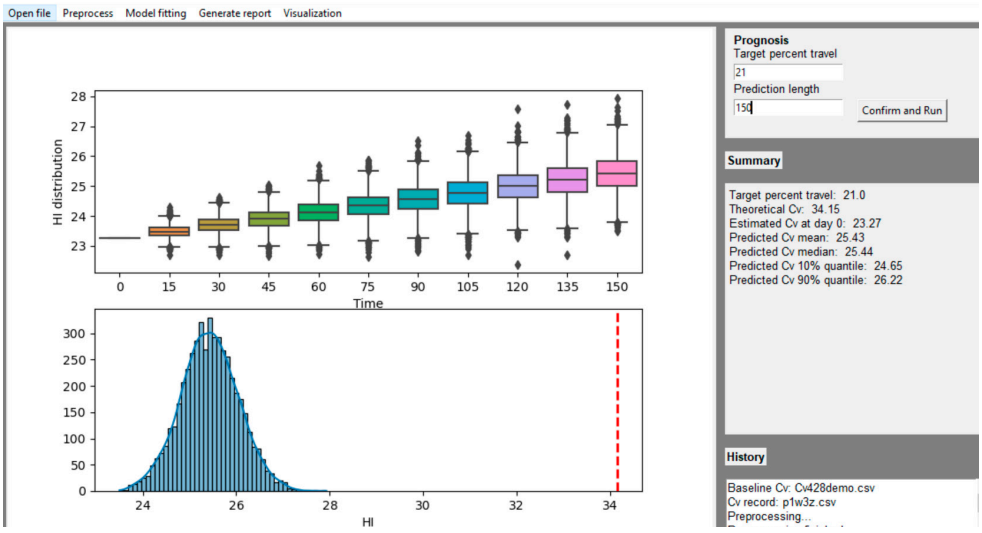


Figure 4: a snapshot of the toolbox for RUL estimation.

4. INNOVATION AND INDUSTRY COLLABORATION

The prototype for RUL prediction can reveal the Cv trend and variations based on historical Cv and percent travel information. To what extent the result is credible is still unclear, due to lack of large amount data for validation, as well as few feedback from industry partners.

5. FURTHER WORK

The results of my research highlight the importance of understanding/using the correct data for building a RUL estimation model. Below are some research directions worth exploiting:

From a data scientist perspective, the current model can be further improved by considering more process data, including the flow rate, sand data, sand event, maintenance log, etc. In fact, the erosion itself is driven by production, which in turn determines the intensity of the flow and the impact of diverse particles.

From a physician's perspective, it is important to understand how the impact from sand, water and oil may influence the inner geometry of the valve (effective pass area). Experiments are required to establish relations between sand impact and choke geometry, and between choke geometry and Cv. For this, building realistic experimental rigs to simulate the erosion for a real choke is indispensable.

6. COMPLETE LIST OF PUBLICATIONS

Xingheng, Liu; José, Matias; Johannes, Jäschke; Jørn, Vatn.
"Gibbs sampler for noisy Transformed Gamma process: inference and remaining useful life estimation".
Reliability Engineering & System Safety; Volume 217; 108084, 2022.

Xingheng, Liu; Jørn, Vatn.
"Filtering noisy Gamma degradation process: Genz transform versus Gibbs sampler"
31st European Safety and Reliability Conference (ESREL 2021); 19-23 September 2021.

Xingheng, Liu; Jørn, Vatn.
"Erosion state estimation for subsea choke valves considering valve openings"
32st European Safety and Reliability Conference (ESREL 2022); 28th August - 1st September 2022.

Xingheng, Liu; Jørn, Vatn; Aibo, Zhang.
"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 & The 4th International Conference on Reliability Systems Engineering (QR2MSE2021 and ICRSE2021); October 27-29, 2021.

7. MY NEW JOB

Company/institution: NTNU
Position/area of work: Researcher at SUBPRO.

RESEARCH AREA

Separation - Fluid characterization

Enhancement of separation efficiency and flow assurance

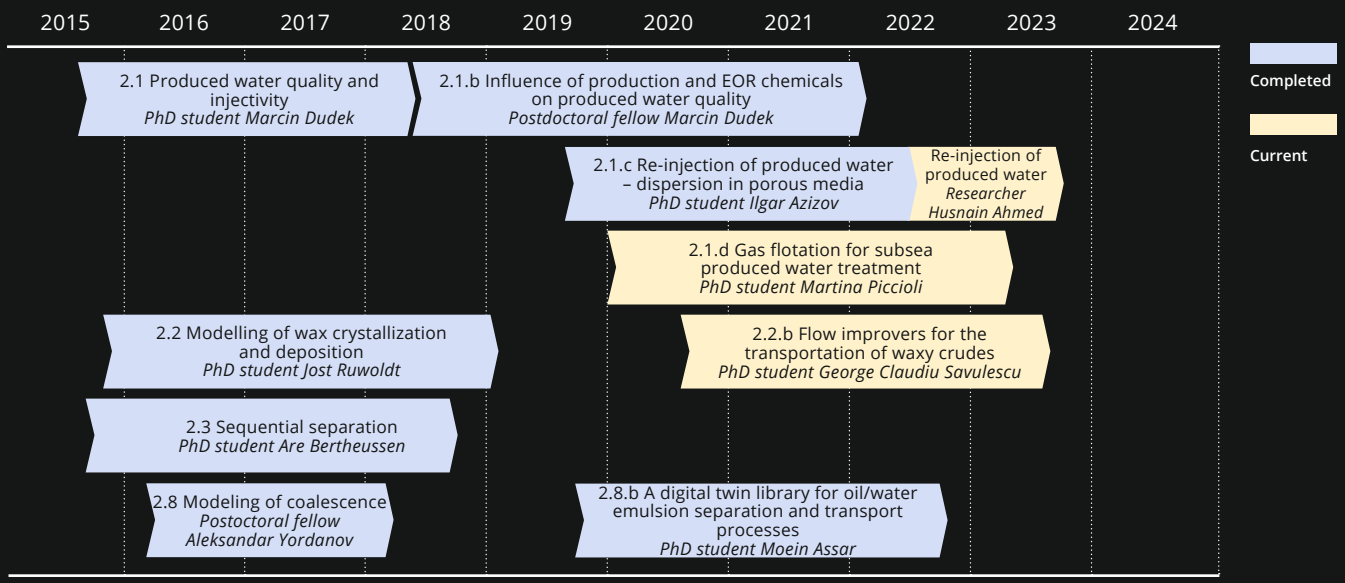
Professor Gisle Øye
Research Area Manager
Department of Chemical Engineering

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, particularly focusing on microfluidic and NMR methods, for advanced fluid characterization at conditions relevant for subsea processing.

There were in total five projects within this area in 2022, see the overview of completed and current projects. The PhD projects “Re-injection of produced water – dispersion in porous media” and “A digital twin library for oil/water emulsion separation and transport” ended in fall 2022, while the former is continued in a researcher project. The two remaining PhD projects will continue until fall 2023.

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

Completed and current projects



The Fluid Caracterization 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, PhD student Martina Piccioli and Researcher Husnain Ahmed were not present when the picture was taken.

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**
Start date: 06.01.2020
Planned end date: 30.10.2023
Project manager and main supervisor: Professor Gisle Øye
Co-supervisors: Doctor Marcin Dudek and Svein Viggo Aanesen (Equinor)
Department of Chemical Engineering
Project nr: 2.1.d

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 higher outer 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 AND RESULTS

HIGH-PRESSURE AND HIGH TEMPERATURE GAS FLOTATION

Experiments regarding the oil removal efficiencies at the expected seabed conditions (e.g. high pressure and high temperature) were carried out with a gas flotation high-pressure rig at the Ugelstad lab (Figure 1). The experiments were performed up to 80 bar and 80˚C at three different retention times. In Figure 2 some of the experimental results are shown. The best oil removal was found at 80˚C in combination with high pressure. Temperature had the most significant impact on enhancing the separation due to improved oil drop – gas bubble, gas bubble – gas bubble, and oil drop – oil drop coalescence due to the increased film thinning rates caused by lowered viscosity of the water, all leading to enhanced creaming. The pressure effect was attributed to more and smaller bubbles with increased pressures at a given temperature, increasing the available area for drop-bubble attachments.

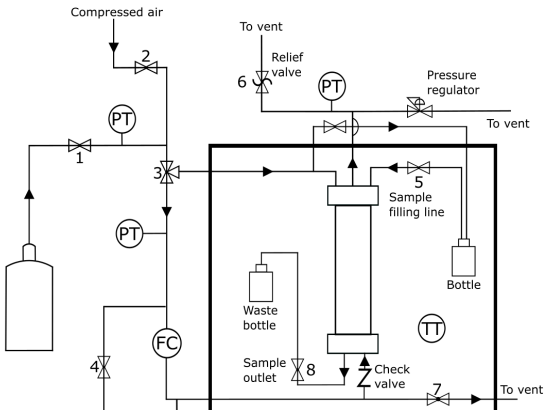


Figure 1: High-pressure rig in operation at Ugelstad lab at NTNU.

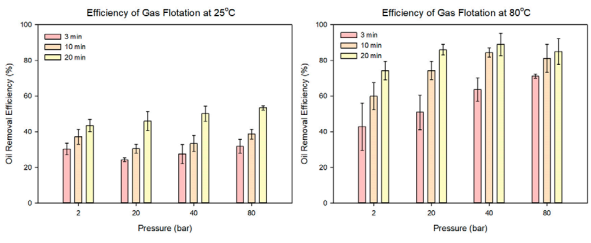


Figure 2: Oil removal efficiency after gas flotation at 50˚C and 80˚C. The experiments were performed at four different pressures and three residence times.

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 (Figure 2). A microfluidic method to study the drainage time, i.e., the time required for the liquid film to reach the critical thickness until it ruptures, has been developed at Ugelstad lab. Compared to other methods usually used for this purpose, e.g., droplet-bubble micromanipulator, where one event at a time can be studied, microfluidics allows to have a larger number of events for different conditions in a relatively short time. An example of the results is shown in Figure 4, where the distribution is related to more than 200 attachment events.

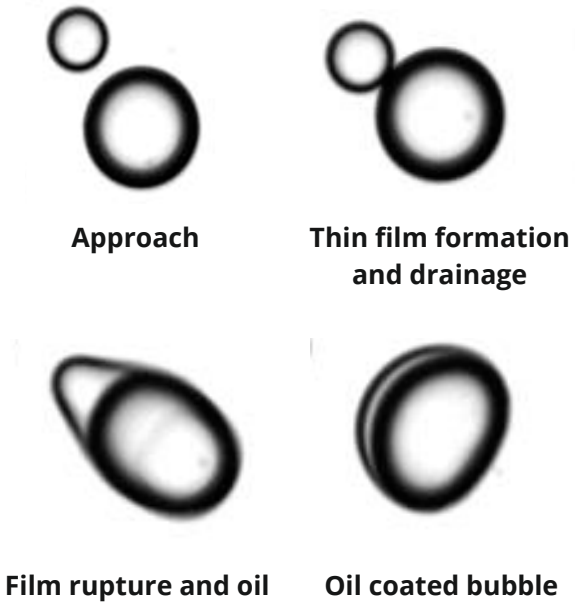


Figure 3: Drop-bubble interaction stages as observed in the microfluidic test rig.

3. INNOVATION GRANT – GAS FLOTATION WITH SOLID PARTICLES

Solid particles in PW can contribute to flow assurance problems or to the stabilization of emulsions. One important property of solids is their wettability, which is quantified by the contact angle (θ). Hydrophilic particles (θ<90˚) can adsorb at the oil-water interface, with the result of creating steric hindrance that can prevent both drop-drop and drop-bubble coalescence. Moreover, solid particles can block the pores in the reservoir and decrease the permeability of the formation. For this, their removal, together with the understanding of their effect of the oil removal is of high concern.

Regardless the recognized importance of the topic, in the literature gas flotation studies focus on the removal of dispersed oil, and the influence of solids on the oil removal efficiency is not investigated yet. The aim of this innovation grant is to investigate the solid particles removal during gas flotation together with their influence on the oil removal.

The grant lasts for 6 months, and it starts in January 2023.

4. INDUSTRIAL COLLABORATION

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.

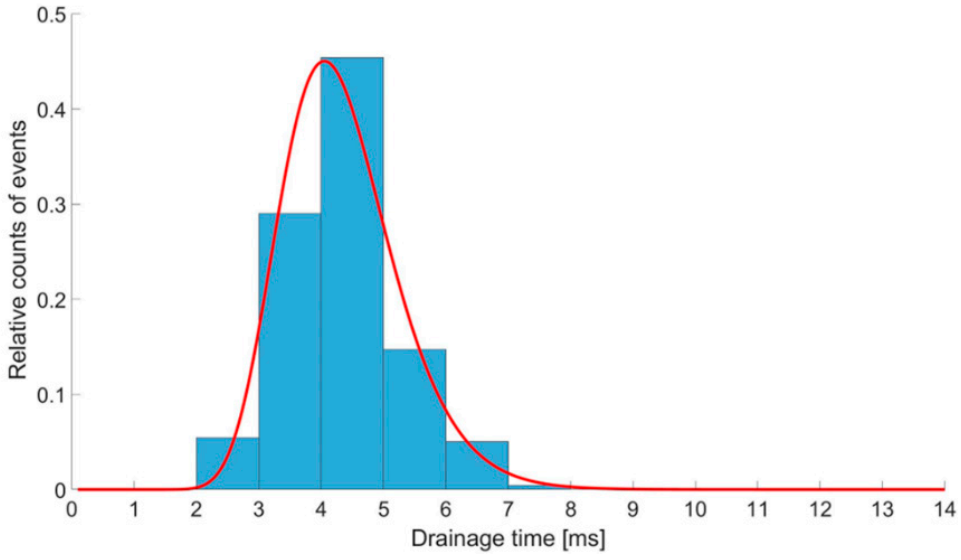


Figure 4: Probability density function of drainage times studied with microfluidics.

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**
Start date: 31.08.2020
Planned end date: 31.08.2023
Project manager: Professor Gisle Øye
Supervisors: Prof. Gisle Øye, Prof. Sébastien Simon and Prof. Geir Sørland
Department of Chemical Engineering
Project nr: 2.2.b

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. Wax crystallization can be modified by asphaltenes present in the crude oils or by the addition of pour point depressants (PPD). This project, which started in autumn 2020, is the continuation of the activities performed in the project "Prevention of Wax Deposition" (Jost Ruwoldt). We are currently developing and implementing new techniques and procedures to characterize and quantify the interactions between waxes and asphaltenes or PPDs.

2. EXPERIMENTAL APPROACH

Low field and high field nuclear magnetic resonance (NMR) was used from August 2020 until June 2022, while Atomic Force Microscopy (AFM) has been used since July 2022 and is planned to be the main technique until the end of the project.

Equinor is collaborating to the project by providing selected samples for the PhD project.

3. MAIN RESULTS

NMR methods have been developed and tested in 2022 to focus on the following determinations:

- Evolution of asphaltene aggregation state with asphaltene concentration and the effect of the aggregation state on wax crystallization
- Quantification of free and restricted diffusion of a model solvent inside the wax crystal network and the effect of inhibitors (Figure 1)
- Measurements of wax precipitation curves using 2 different low field NMR approaches
- Demonstration of wax-asphaltene and wax-PPD co-crystallization, using high resolution NMR

This year, I also undertook a 3-month research visit at TU Eindhoven in the Netherlands under the supervision of Professor Maja R*ücker. AFM techniques were developed to facilitate the following determinations:*

- Quantification of surface features on solid samples, evaporated from wax and wax-inhibitor solutions (Figure 2)
- Determination of tip-surface interactions on wax and wax-inhibitor solid surfaces in solvent

4. OUTLOOK

AFM research will be continued in the Nanolab at NTNU in the first 6 months of 2023. The developed techniques will be applied on a broader range of wax and wax-inhibitor systems, with temperature control when needed. The project is expected to finish in November 2023.

5. POTENTIAL APPLICATIONS OF THE RESULTS, TRANSFER KNOWLEDGE TO INDUSTRY

This project developed new methods quantify wax precipitation rate with temperature, using NMR. A high focus has been placed for developing knowledge about the mechanism of wax crystallization. This will facilitate the understanding of wax-related processes in crude oils with known asphaltene content and the tailoring of a suitable inhibitor in specific industrial circumstances. Transfer to the industry will be performed both through scientific articles and presentations.

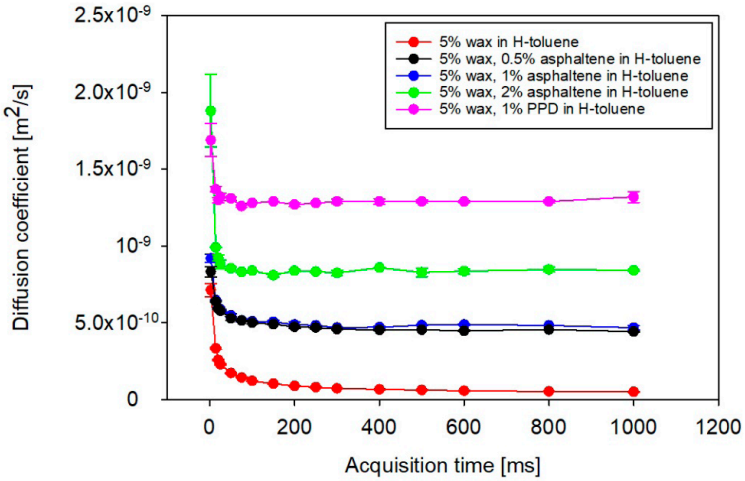


Figure 1 presents diffusion data acquired with low field NMR for wax, wax-asphaltene and wax-PPD systems. The restricted diffusion of the toluene can be determined when the time tends to infinity, while the free diffusion of the toluene can be determined when the time tends to 0. One can notice that the higher the asphaltene concentration is, the higher the restricted diffusion coefficient is. This indicates that the toluene has less restrictions in the wax-asphaltene crystal network, which is in line with previous determinations at SUBPRO (project 2.2.a), where smaller and more dispersed crystals were detected with cross-polarized microscopy (CPM) when asphaltene or PPD is added.

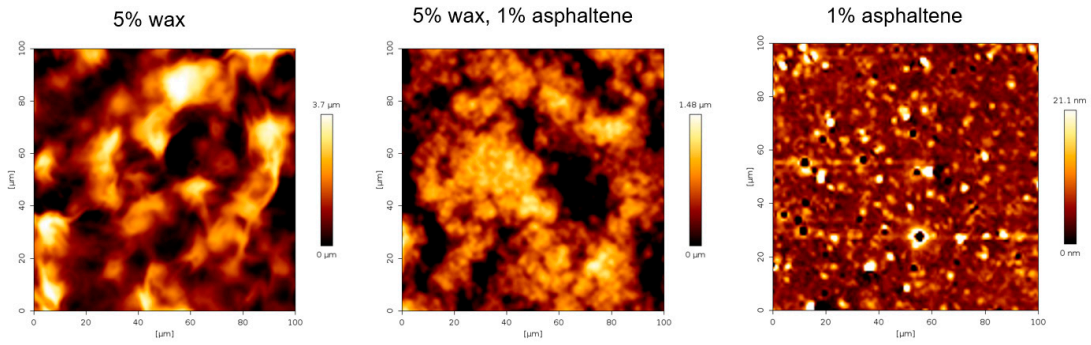


Figure 2 presents height data from AFM scans of solid wax, wax-asphaltene and asphaltene samples, dried by evaporation from 5% wax, 5% wax 1% asphaltene and 1% asphaltene solutions in toluene, respectively. Surface features display high heights for the wax system (3.7 µm maximum variation), while they display low heights for the asphaltene system (21.1 nm maximum variation). The surface features are larger and higher in amplitude for wax than for asphaltene. When wax and asphaltene are precipitated from the same solution, an intermediate height range is obtained (1.48 µm maximum variation), with larger structures of lower amplitude than for wax. Asphaltenes most likely act as wax nucleation sites and then they become incorporated in the wax crystal network during gelation. Consequently, the orientation and shape of the dried wax-asphaltene crystals is different than for the wax-only crystals.

Re-injection of produced water – co-flow of particles and droplets visualized using microfluidic and advanced image analysis methods

Researcher: **Husnain Ahmed**
Start date: 17.10.2022
Planned end date: 31.12.2023
Project supervisor: Gisle Øye
Department of Chemical Engineering
Project nr: 2.1.c

1. DESCRIPTION OF THE PROJECT:

Produced water re-injection (PWRI) is an environmentally attractive way of handling the large amounts of water produced along with oil and gas production, as it decreases discharges to sea. It can also be economically attractive, since it may limit the need for processing large amounts of produced water towards strict discharge regulations, and secure extra injection water. PWRI is possibly the preferred way of handling produced water in particularly environmentally sensitive locations and when using subsea production and processing facilities. Implementation of PWRI faces several challenges, including the risk of scaling, reservoir souring, biofouling, and corrosion control of installations. However, a main limitation for implementing PWRI is often the risk of permeability decline during simultaneous injection of particles and droplets in porous structures which is poorly understood. Current models can account for the water quality, the injection pressure required to maintain injectivity and thermal effects leading to fracture growth in the reservoirs, while lack of detailed understanding of transport, plugging and deposition mechanisms at the pore scale is a shortcoming in the models. The goal in this project is to use recently developed microfluidic methodologies and image analysis tools to improve this understanding and thereby facilitate better produced water re-injection specifications.

2. DELIVERABLES:

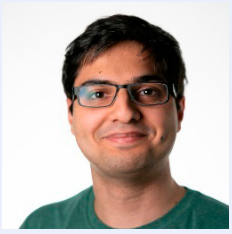
- Fast experimental method for evaluating pore scale formation damage
- Experimental data on transport properties and permeability reduction during co-flow of particles and droplets
- Two possible research articles from this project.

Final project Report

Re-injection of produced water – dispersions in porous media

New methodology for understanding of transport and retention phenomenon.

Green Shift Impact: Cleaner oil and gas production by minimizing discharges of produced water



PhD graduate: **Ilgar Azizov**
Start date: 19.08.2019
Thesis defense date: 29.09.2022
Title of thesis: A Microfluidic Study of Droplet and Particle Retention: A Path from the Rationale to Pore-Scale Experiments.
Thesis committee members: Associate Professor Michael Duits, University of Twente, The Netherlands. Dr. Karen Louise Feilberg, DTU Offshore, Denmark.
Project manager and main supervisor: Professor Gisle Øye
Co-supervisor: Dr. Marcin Dudek
Department of Chemical Enginerring
Project nr: 2.1.c

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 r*e-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 coreflooding) 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.

Microfluidics is a field of science that deals with transport and manipulation of fluids in confined microchannels. In contrast to coreflooding, 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.

2. WHAT I HAVE DONE.

The executed project is an experimental work that comprises development of the microfluidic method and image processing/analysis. Firstly, a review that identified the gaps in the literature and defined the rationale behind the implementation of microfluidics was performed. The review showed that microfluidics is a viable tool for produced water re-injection studies that provides pore-scale visualization of the retention, although it would require time and labour to develop the methodology. Secondly, the methodology to investigate retention of droplet only, particles only, and droplets and particles together in porous media using microfluidics was produced. Afterwards, a number of parameters such as injection rates, concentration of dispersed components as well as the effect of mono- and polydispersity, and water chemistry including salinity and surface-active components were studied. Moreover, significant effort was put into the image analysis part of the project where traditional image analysis methods and neural networks were used to analyse microscopy images.

3. MAIN RESULTS.

The results of the project can be divided into two parts: literature review and method development, which included microfluidic experiments and image analysis work. The literature review resulted in a paper that summarized physical and physicochemical parameters affecting retention of droplets, examined the gaps, and provided an

outlook on the future studies. The method development produced a methodology that allowed to systematically study the transport and retention of mono- and tailored polydisperse emulsions as wells as solely particles and the combination of particles and droplets. 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 a 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. When it comes to the retention of particles, it was identified that the salinity of water phase has great influence on the retention as well as the release of the particles upon exposure to the water with a lower salinity than during the retention. Moreover, the effect of production chemicals, e.g., flocculants was examined, which demonstrated that flocculants could have a significant effect on the retention, depending on the charge of the polymer molecules. Among the tested systems, a polycationic surfactant facilitated the retention of particles in in the system where both particles and pore space surface had a negative charge. Additionally, state-of-the-art pipeline for image analysis was developed to analyze the data/images obtained using the microfluidic method (Figure 1) [5]. The approach utilizes open-source computer vision libraries employing AI for image analysis. The summary of the developed method is visualized in Figure 1, while the reader is referred to the list of publications for more detailed information [2, 3, 4, 5].

4. INNOVATION

Understanding the parameters affecting the retention is essential to obtain models of injectivity decline and define injection water specifications. It is expected that the developed microfluidic methodology will help to improve the existing models and increase their effectiveness and help the industry to define more effective injection water specifications. The project was built on the microfluidics competence developed in SUBPRO project 2.1.a – "Produced water quality and injectivity". Equinor demonstrate interest in the project and contributed through several mentoring sessions helping to structure the project and identify the industry interests.

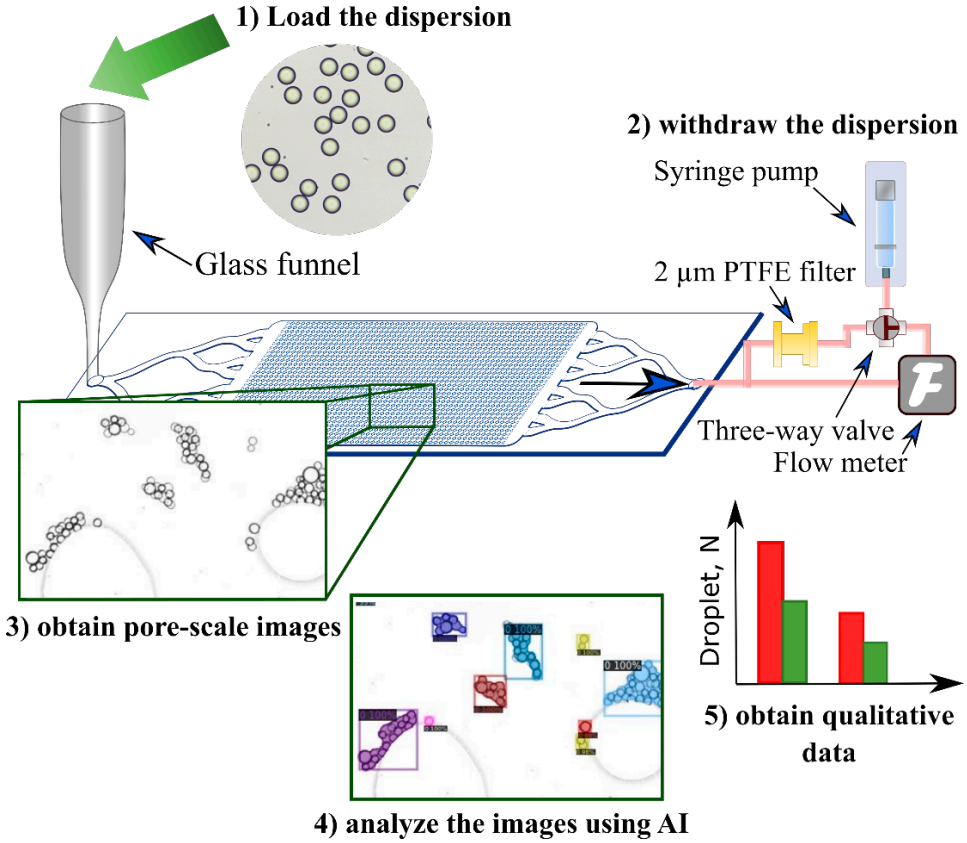


Figure 1. The schematic of microfluidic method. First a dispersion is loaded in the funnel. Then the pumping system is started to draw the dispersion through the microfluidic porous network. A microscope is used to obtain images of the retained droplet at the pore-scale. The AI-based image analysis is applied to recover information from the images and obtain qualitative data that can be analyzed.

5. FURTHER WORK

This project extended our existing microfluidics toolbox and established the building blocks for the future studies. By the end of the project, several issues remained unresolved and are recommended to be tackled in the future work in order to enable utilization of more realistic systems. Firstly, the usage of crude oil systems was not possible due to the phase separation of emulsions during the experiments; instead, density adjusted model oils were used. Secondly, droplet coalescence in porous media was not investigated as surfactant stabilized emulsions were used in the experiments to enable continuous supply of droplets to the microfluidic chip. Thirdly, it is recommended to continue automatization and digitalization of the microfluidic lab both when it comes to the hardware used for the experiments and the image analysis pipeline. Potentially, these improvements would provide the basis for more complex experiments utilizing systems that are more representative of the real conditions.

6. COMPLETE LIST OF PUBLICATIONS

Azizov, Ilgar; Dudek, Marcin; Øye, Gisle.
"Studying droplet retention in porous media by novel microfluidic methods".
Chemical Engineering Science (CES); Volume 248; 2022.

Azizov, Ilgar; Dudek, Marcin; Øye, Gisle.
"Emulsions in porous media from the perspective of produced water re-injection – A review".
Journal of Petroleum Science and Engineering 2021; Volume 206.

7. MY NEW JOB

Company: Equinor

Position: Reservoir Engineer

Final project Report

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 graduate: **Moein Assar**
Start date: 25.10.2019
Planned thesis defense date: 01.09.2023
Title of thesis: A Digital Twin Library for Oil/Water Emulsion Separation and Transport Processes
Project manager: Associate Professor Brian Arthur Grimes
Co-supervisors: Prof. Magne Hillestad and adjunct Prof. Audun Faanes (Equinor)
Department of Chemical Engineering
Project nr: 2.8.b

1. BACKGROUND FOR THE PROJECT

The separation and transport of multiphase fluids, particularly liquid-liquid dispersions in the form of crude oil and water emulsions, is an economically and environmentally crucial process in the subsea petroleum industry. Consequently, the development of fundamentally advanced yet simply implemented models for the separation and transport of multiphase fluids would be a valuable tool for process and system engineers tasked with developing, controlling, and optimizing new subsea transport and separation processes. The main objective of this project is to create a portable C++ class library based on the population balance approach for modeling of processes involving crude oil/ water emulsion. Population balance models (PBE) provide a theoretical framework to model processes involving interaction between droplets as well as sedimentation/skimming, which eventually leads to the evolution of droplet distribution size over time. The knowledge of droplet size distribution can play an essential role in predicting physical properties as well as determining the efficiency of separation equipment.

2. WHAT I HAVE DONE

A C++ model library for the fast and robust computation of PBMs with various complexities has been developed. Based on the level of sophistication and the external dimensions involved, three distinct modules are envisaged for simulating different applications, as shown in figure 1.

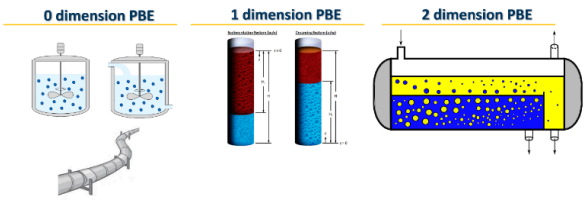


Fig. 1. 0, 1 & 2 dimensional PBE applications

These modules can be simultaneously used in a modular simulation to represent and model a complex process system in oil production, transport, and processing. This approach would allow tracking of the droplet size distribution from wells to production facilities, enabling a more realistic estimation of the separation efficiency of the separation equipment.

The models are programmed in C++ in a modular way using object-oriented features of C++. Special attention has been devoted to portability as well as the computational efficiency of the programs. The latter case is critical as these models can quickly become computationally demanding by increasing the number of dimensions considered for the model.

3. MAIN RESULTS

The main results of this project are divided into three parts, as follows:

ESTIMATION OF TIME AND LENGTH SCALES FOR PBE

The main challenge for solving PBEs is uncertainty regarding the infinity at the bound of the integrals in the governing equations which affects accuracy of the solution as well as stiffness of the equations. The common approach requires strong reliance on the user post interpretation of the result and refining the mesh and the domain bound in case of unexpected results. To tackle this, a new approximation method was proposed. It utilizes a closed-form analytical solution of PBE in form of a dimensionless group with simplified kernels. This new approach was successfully applied to estimate time and length scales of the system. The approximation method was further expanded for generating grid based on spectral-element orthogonal collocation for both steady-state and transient PBE. The new algorithm shows a lot of potential for efficient and robust grid generation that can guarantee reliable, grid-independent and less stiff solutions.

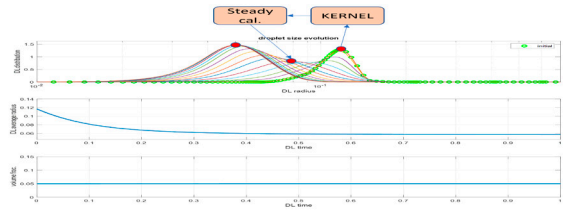


Fig. 2. Schematic of the proposed algorithm for estimation of a complex kernel time and length scales

A NEW INSIGHT TO MODEL GRAVITATIONAL SEPARATION AND DENSE PACKED LAYER

Theoretically, gravitational separation process is affected by binary coalescence of the droplets, hindered settling/rising of the droplets, and interfacial coalescence. 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, by considering the advection, dispersion and binary coalescence, a novel model is now 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. The described model is tuned versus the experimental data from TotalEnergies. Finally, the model was successfully extended to 3-phase separators for both steady-state and transient problems.

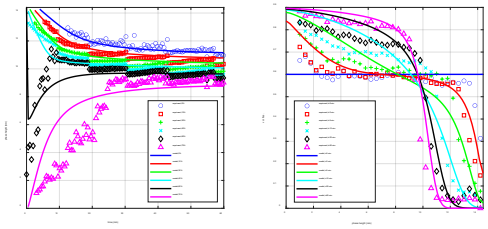


Fig.3. Comparison of experiment and model (initial volume fraction=60%), left: various water iso-volume-fraction curves, right: water volume fraction profiles at different elapsed times.

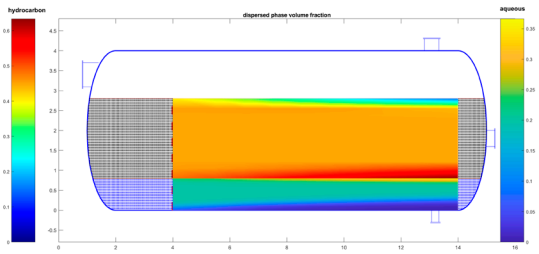


Fig.4. Dispersed phase volume fraction for a typical 3-phase separator.

GEOMETRICAL TRANSFORMATION TO SOLVE MULTI-PHASE FLOW IN CIRCULAR GEOMETRIES

Spectral discretization of 2D circular geometries via orthogonal collocation technique was studied using the geometrical mapping technique. In doing so, two analytical mappings between the circle and square geometries, namely, elliptical and horizontally squelched mappings, were employed. The developed techniques can address the problems of polar discretization for cases without symmetries in which the boundary condition at the center of the circle cannot be defined. Additionally, the squelched mapping technique enables spectral discretization of the circular segment geometries. This property can be utilized to tackle the irregular geometries formed in multiphase flow problems in pipes and separators. Accordingly, simple to implement while numerically efficient algorithms and procedures are developed for solving PDEs in circular geometries with different boundary conditions for both steady state and transient problems. Various implementation issues are thoroughly discussed, including vectorization and strategies to avoid solving the differential-algebraic system of equations. Additionally, several aspects of these techniques, such as error properties, condition number, and computational time were studied. Finally, the squelched mapping discretization was successfully employed to discretize and solve Navier-Stokes equations for the two and three-phase multi-fluid gravity flows in sloped pipes / separators.

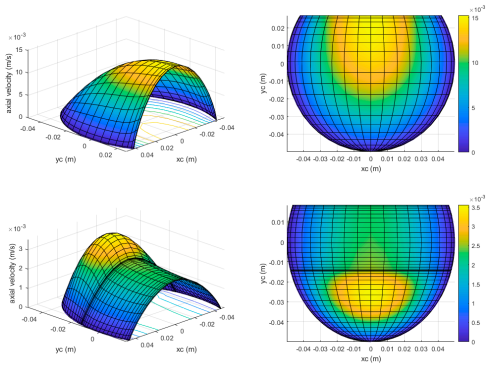


Fig. 5. Simplified Navier-Stokes Equation for multiphase flow, top: two phase stratified flow, bottom: three phase stratified flow

4. INNOVATION AND INDUSTRY COLLABORATION

Some areas in which this C++ model library can be used are production optimization/control, produced water treatment optimization/control, and improved flow assurance. The faster steady state solvers can be employed to design and optimize the existing/new processes. At the same time, the transient solvers can be readily used to study the systems dynamics and control system design.

5. FUTURE WORK

There is great potential to continue this project either by focusing on applying the developed models or extending the library to more complex/ realistic systems. Some of the possibilities to continue this project are listed below:

COMPREHENSIVE MODELING OF SUBSEA OIL WATER SEPARATION.

It is essential to consider different elements of the process in a comprehensive model. Here the main items are the choke valve, gathering subsea flowline, and finally pipe separator. The PBEmulib library enables us to build a modular model for steady state and transient conditions. The steady-state model would be used to study the effect of different operating parameters on the separation efficiency, such as choke pressure drop, level in the pipe separator, flow rate, volume fraction as well as pipe separator design parameters such as length and diameter. based on the mentioned studies, the optimum designs will be investigated for different operating conditions. Primarily, this work should be conducted in cooperation with the pipe separator project in Subpro, and the finding of that project should be used to tune the model. In the project's final phase, the effect of transient disturbances like flow fluctuations and possible slugs should be studied on the pipe separator performance using the transient model. Accordingly, the proper control system should be studied and proposed.

Extending the model library to more realistic pipe flow applications. Three new modules can be added as below:

- ✓ Fully turbulent oil/water vertical pipe
- ✓ Fully turbulent oil/water horizontal pipe
- ✓ Pressure changing element (e.g., pumps, valves, fittings, chokes, etc.) with variable turbulence intensity in the downstream piping

The mentioned modules can be used to evaluate the piping system's uniformity requirement, which is critical for the design and evaluation of autosamplers used for BS&W measurement in surface and custody metering facilities according to API MPMS 8.2 and ISO-3171.

A realistic 3D CFD-PBE model for a 3-phase separator

Solving Navier-stokes and PBE simultaneously for a 3D realistic separator will allow capturing the effect of the location of the nozzles (especially water outlet nozzle/arrangement) on the equipment separation efficiency

Developing PBE models for electrostatic dehydration and desalting process

6. COMPLETE LIST OF PUBLICATIONS

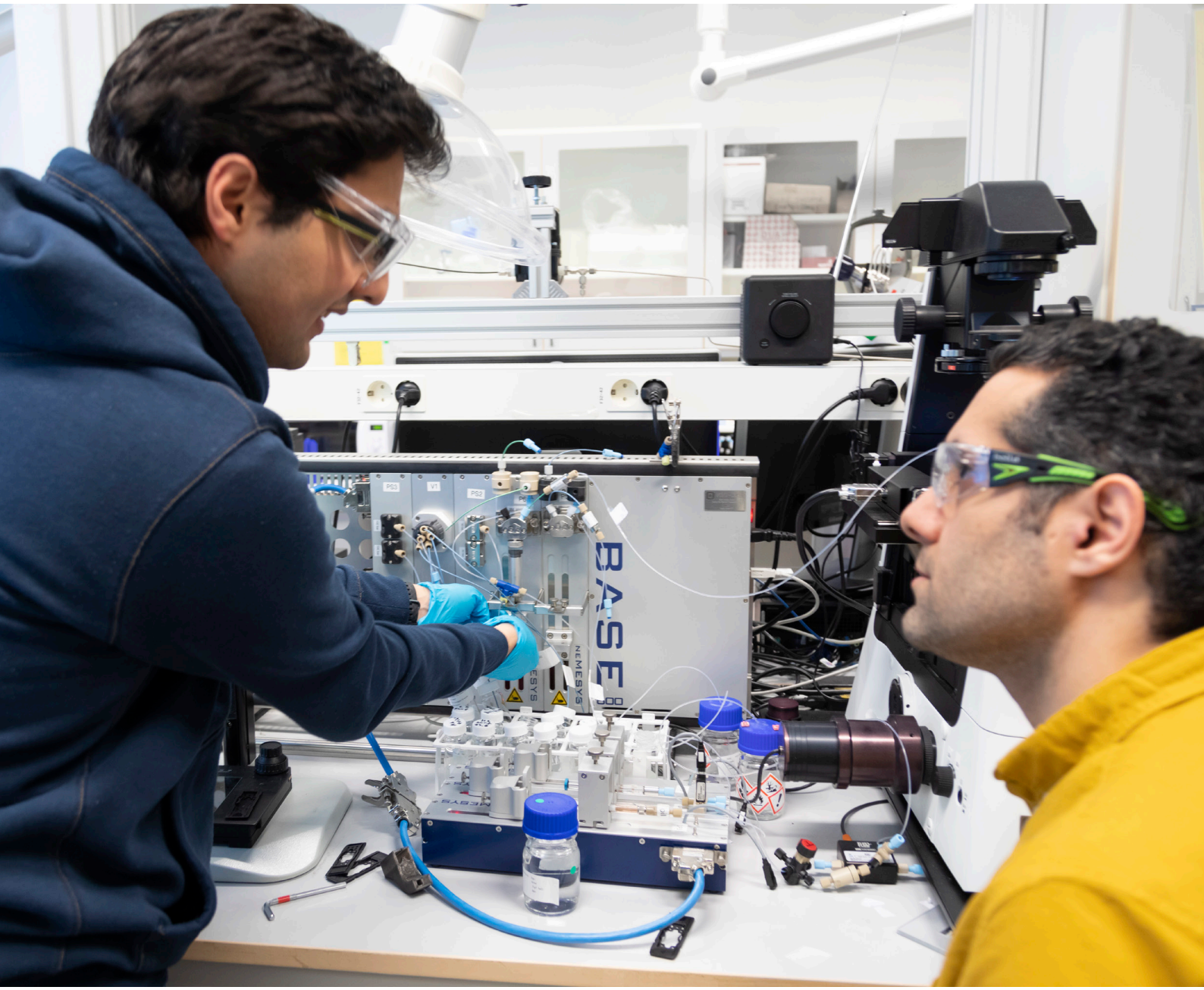
Assar, Moein; Grimes, Brian Arthur.
"A new approach to analyze the equilibrium and transient behaviors of particulate systems and the subsequent application to multiphase fluid systems".
Journal of Chemical Engineering Research and Design, Volume188; Page 1083-1096; 2022.

Assar, Moein; Simon, Sebastien Charles Roger; Sørland, Geir; Grimes, Brian Arthur.
"A theoretical and experimental investigation of batch oil-water gravity separation".
Chemical engineering research & design; Volume 194; Page 136-150; 2023.

7. MY NEW JOB

Company/Institution: AIBEL

Position/Area of work: Senior Process Engineer



From the left PhD student Ilgar Azizov and PhD student Moein Assar at the Microfluidic laboratory co-studying capture of droplets and particles in porous media

RESEARCH AREA

Separation - Process concepts

Enabling new solutions for subsea separation

Professor Hugo Atle Jakobsen
Research Area Manager
Department of Chemical Engineering

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.

ONGOING PROJECTS OF PROCESS CONCEPTS

PhD project:

- Subsea bulk oil-water separation: The PhD contract of Hamidreza Asaadian ends in March but he got a 6-months innovation scholarship The PhD contract

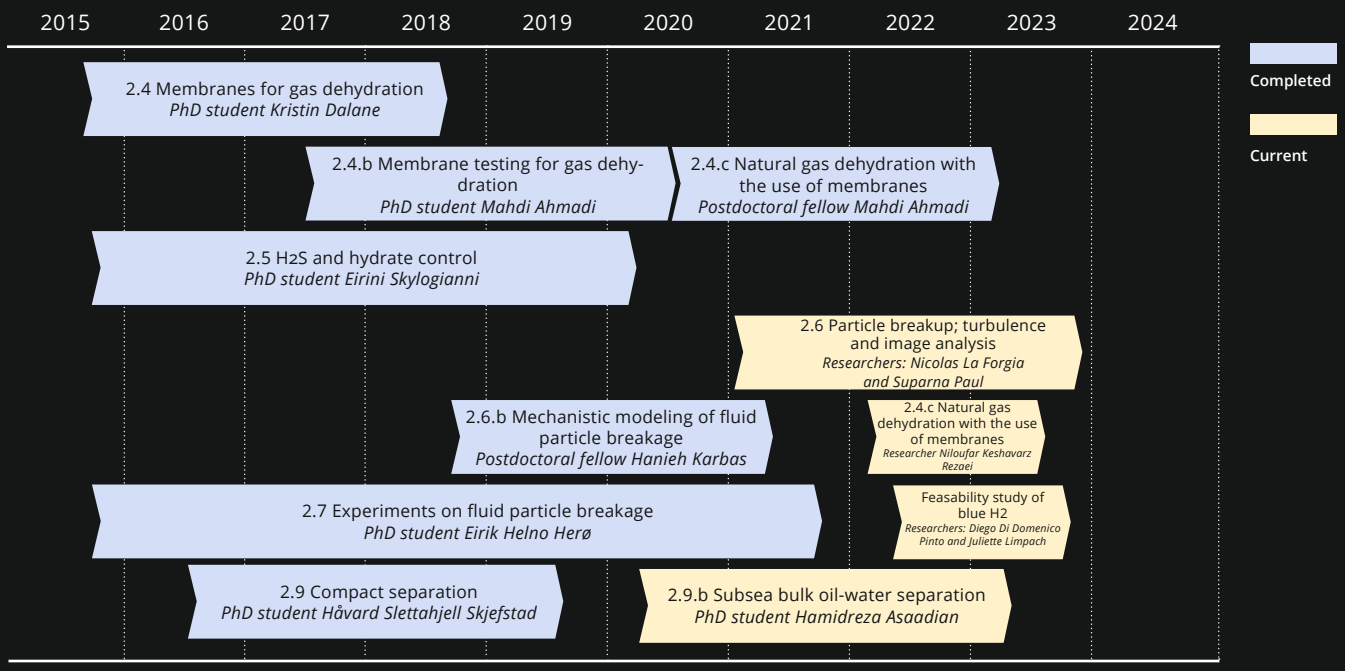
Postdoctoral project:

- Natural gas dehydration with the use of membranes: Post doc Mahdi Ahmadi did finish his project with SUBPRO. His final report is published at the end of this section.

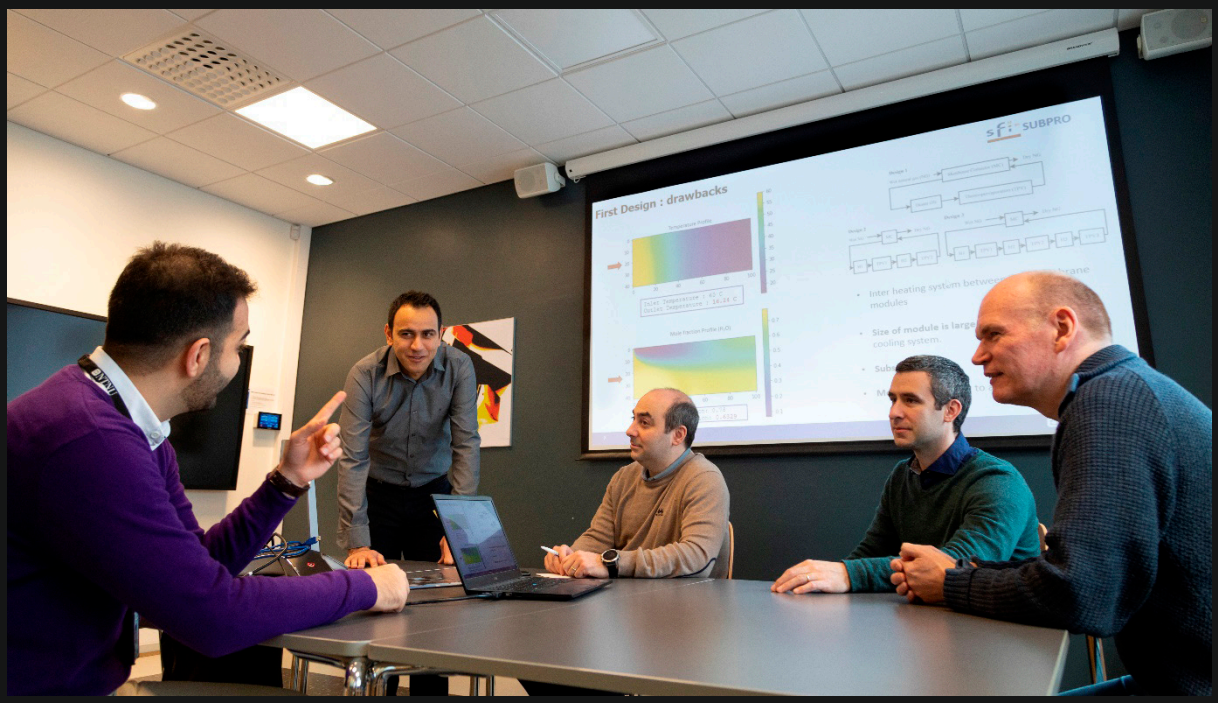
Researcher projects:

- Fluid particle breakage: one permanent researcher Nicolas La Forgia - For the period (01.01.2023-31.12.2023), in addition to a one year researcher Suparna Paul - For the period (01.09.2022-30.08.2023)
- Natural gas dehydration with the use of membranes: one year researcher Niloufar Keshavarz Rezaei - from 01.07.2022 to 31.07.2023.
- Blue hydrogen : One 1 year researcher: Diego Pinto and Juliette Limpach - Until 30.08.2023 and 31.10.2023

Completed and current projects



This figure shows an overview of all projects within the research area.



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, Researchers: Suparna Paul, Niloufar Keshavarz Rezaei, Diego Pinto and Juliette Limpach - were not present when the picture was taken.

Subsea bulk oil-water separation

To make more efficient subsea bulk oil-water separation by improving separation design, understanding multiphase flow fundamentals and preventing undesired phenomena during separation process.

Green Shift Impact: Subsea separation of produced water increases the recovery rates for brown field installations. Removing produced water on the seabed 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**
Start date: 04.03.2020
Planned end date: 04.03.2023
Project manager: Associate Professor Milan Stanko
Supervisors: Associate Prof. Milan Stanko and Prof. Gisle Øye
Department of Geoscience and Petroleum
Project nr: 2.9.b

1. BACKGROUND

One of the most crucial difficulties in oil production from mature oil fields is the management of produced water. This issue can be solved by subsea separation, which also has additional advantages. Therefore, it is important to create or to develop further subsea separator technologies that are affordable such that the business case for subsea separation may be strengthened. This project is a continuation of previous project "compact separation", conducted by Håvard Skjefstad. Håvard 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 on the separation efficiency and on the dispersion characteristics with or without inlet choking (Fig. 2)
- Experimental study of the effect of small amounts of gas (air) on separation efficiency
- Development of numerical methods for separations design (Fig. 3)

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.

4. INNOVATION GRANT PROJECT

We have planned to continue advancing on this topic to take it closer to application after the PhD period is completed through an innovation project. The focus of this project is to make user-friendly tools to design this type of pipe separator and to have meeting with the partners to transfer our results. We also plan to do a thorough documentation of some elements of the experimental rig, such as controller setup, communication system, startup and shut down procedures and polish the LabView interface.

Some of the activities are planned for 2023 are to provide the required material for fifth article:

- 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

Fig 1 - Set-up rig modifications

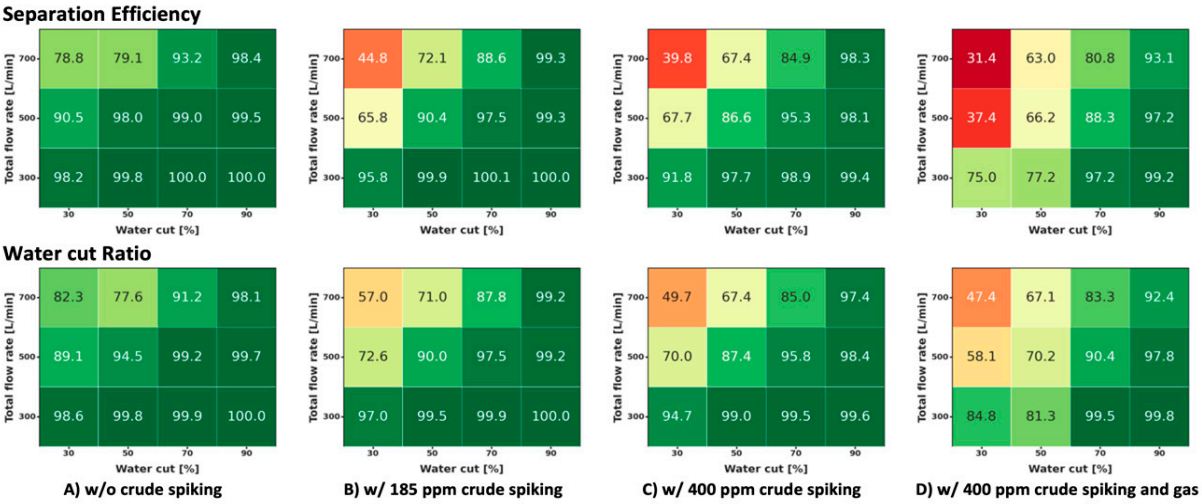


Fig 2 – Separation efficiency and water cut ratio of different fluid systems

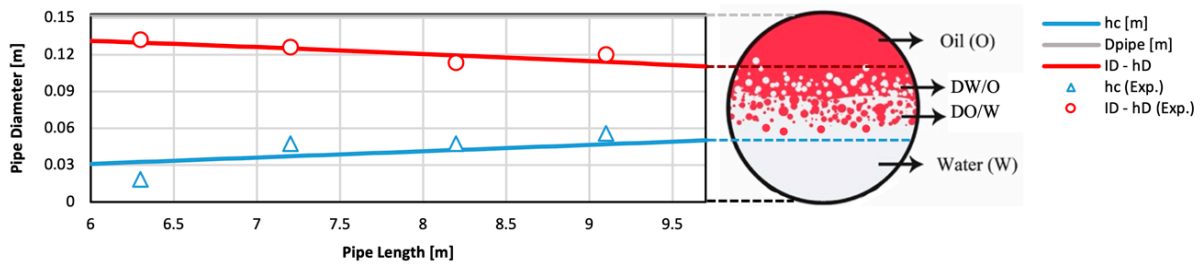


Fig 3 – Phase thickness model in pipe

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.

Researchers: **Nicolas La Forgia** and **Suparna Paul**
Start date: 01.01.2023
Planned end date: 31.12.2023
Project manager and supervisor: Professor Hugo Atle Jakobsen.
Department og Chemical Engineering
Project nr: 2.6

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 need 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 using newer estimation method is required to fully understand the breakage phenomena.

The main goals of these projects are:

- To develop the tools for the accurate interpretation of measurements from experiments on particle breakage, through image processing.
- To perform the statistical analysis and uncertainty evaluation of the measurements.
- To improve existing measurement methods and models for estimating and predicting breakage outcomes.
- 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 EXPECTED RESULTS

In these projects, the focus is set on two main parts; first on the experimental investigation of the breakage of oil droplet in water, and second on the develop of new methods and models for the estimation and prediction of breakage outcomes. 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 where our in-house developed software tracks the evolution of the position and deformation of the oil droplets, the breakage event, and the subsequent production of daughter droplets and the size distribution.

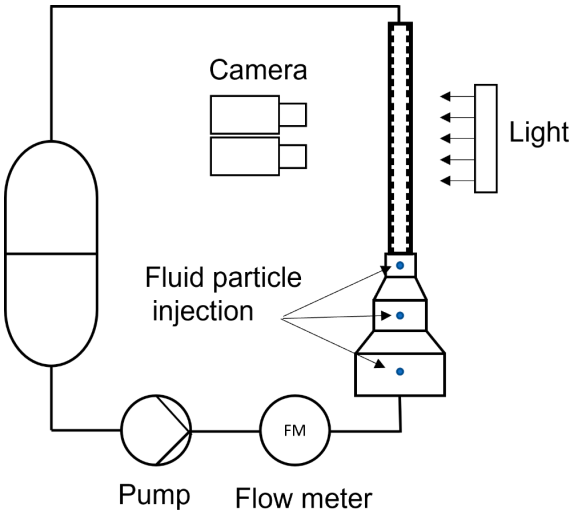


Figure 1: Experimental facility, consisting of a close loop of water, a pump, and a flow meter for controlling the flow conditions, a test section with high-speed cameras and backlight illumination and injection ports for the oil droplet incorporation. Profiles mounted on the tube walls of the test section were used to generate turbulent flow conditions, causing the particle breakage. The blue circles represent the location of the ports for injection of oil droplets into the water flow.

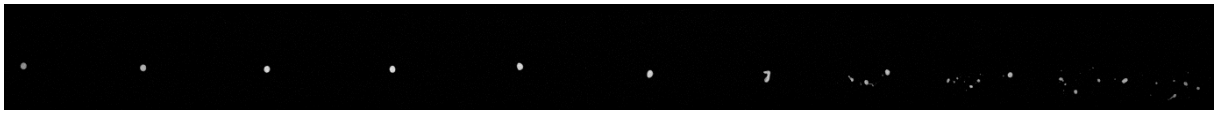


Figure 2: Example sequence of images of a single oil droplet travelling through the test section, deforming, and breaking into several daughter droplets.

In figure 2, an example of a droplet travelling in the test section is shown. As it travels through the test section (from left to right in the image), the droplets get deformed because of the turbulent flow conditions, and at some point, the deformation leads to the breakage into multiple daughter droplets.

The measurements obtained with these set-up follows a Lagrangian description of each individual breakage event, where the fluid particles are followed as they travel in the test section, observing how the interaction with the flow condition produce deformation on the droplets that leads to breakage. However, simulation models are based on an Eulerian description where breakage is analysed as functions of space and time. Then the accuracy of such models then follows the ability for estimating these Eulerian fields based on Lagrangian observations. Single oil experiments have been analysed using the Lagrangian framework where an estimation of the breakage frequency (an Eulerian field describing the amount of droplet breakage per unit of time at different position and for different droplet size), has been obtained through the ratio of the average of the fraction of droplet breaking and a measure of the breakage time (approximated as the time between breakage and the last point where the droplet was spherical). This estimation has been criticized in the literature due to not representing accurately the definition of the breakage frequency. As a consequence, we have been investigating a method for the estimation of the breakage frequency based on an eulerian representation of the breakage which can be formulated with the experimental data created with single oil experiments.

3. MAIN RESULTS AND POSSIBLE INDUSTRIAL USE

During the duration of these projects, several milestones have been accomplished:

- 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]).
- An Eulerian method for describing the breakage frequency has been developed and soon will be published. The publication shows the new methodology and compare it with traditional Lagrangian estimation of the breakage frequency based on measurement of breakage probability and breakage time.

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. The data collected for different oils and experimental condition will be used in this project to propose more accurate models for the prediction of breakage events. The outcome for these projects can be used for the design and prediction of industrial separators.

4. 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. (2018). 195. p. 159-178.

[2] La Forgia, N., Herø, E. H., Jakobsen H. A. *"Highspeed image processing of fl uid particle breakage in turbulent flow"*. Chemical Engineering Science: X. (2021). 12.

[3] Herø, E. H., La Forgia, N., Solsvik J., Jakobsen H. A., *"Single drop breakage in turbulent fl ow: 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 fl ow",* 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 breakage",* Chemical Engineering & Technology.(2019). 42, No. 4, 903-909.

Natural gas dehydration with the use of membranes

Subsea gas dehydration using membrane technology enables the direct transport of gas streams to pipelines.

Green Shift Impact: An environmentally friendly and energy-saving process that reduces methane loss.

Researcher: **Niloufar Keshavarz Rezaei**
Start date: 01.07.2022
Planned end date: 30.07.2023
Project manager and main supervisor: Professor Liyuan Deng
Co-supervisors: Professor Magne Hillestad, Dr. Eivind Johannessen (Equinor)
Department of Chemical Engineering
Project nr: 2.4.c

1. SUBSEA DEHYDRATION PROCESS CONCEPT AND INDUSTRIAL OBJECTIVES

The main objective of this project is to implement a robust membrane-based technology for subsea natural gas dehydration. Water vapor is the primary cause of corrosion and hydrate formation in pipelines. Despite conventional methods, membrane technology offers high modularity, compact design, and less methane loss. A viable membrane-based separation process for subsea gas dehydration was investigated in previous projects. The process includes a membrane contactor unit for gas dehydration and a thermopervaporation unit for TEG regeneration (Figure 1). This project aims to provide experimental data on alternative configurations of membrane contactors to improve separation performance and investigate TEG loss.

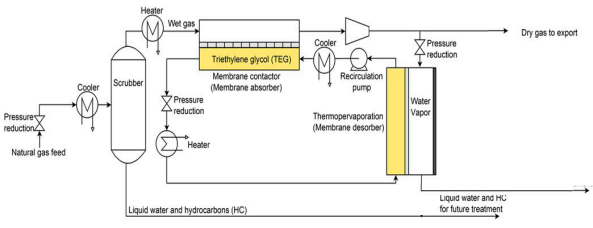


Figure 1: Proposed subsea natural gas dehydration process diagram

2. MEMBRANE PERFORMANCE AND EXPERIMENTAL DURABILITY TESTS

A tubular in-house membrane contactor module was made and tested under operating conditions. The results showed outstanding performance in reducing the dew-point and long-term operations. Polypropylene fibers were coated from inside to form a composite membrane with a dense layer of Teflon AF2400 and a thickness of around 2.77±0.05 µm was obtained (Figure 2). Moreover, the performance of the membrane was tested at different pressures and liquid and gas flow rates. Increasing gas flow rate resulted in higher water flux through the membrane due to higher driving force. Liquid flow rate enhancement did not significantly affect the membrane performance, while the increased pressure enhanced water flux through the membrane by increasing the absorption rate in the liquid phase (Figure 3).

The durability of the membrane was investigated experimentally to ensure stability and long-term performance. A long-term operation was performed for 30 days at determined operating conditions. Three tests with randomly picked pressures and gas flow rates (at determined temperature and liquid flow rate) were carried out before the long-term operation. The performance of the membrane was re-examined after the long-term operation for comparison. The results showed a maximum 10% deviation in water flux under similar operating conditions (Figure 4).

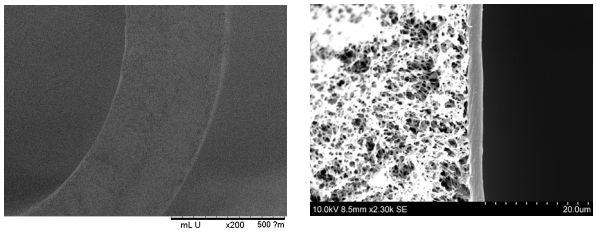


Figure 2: SEM image of the composite membrane

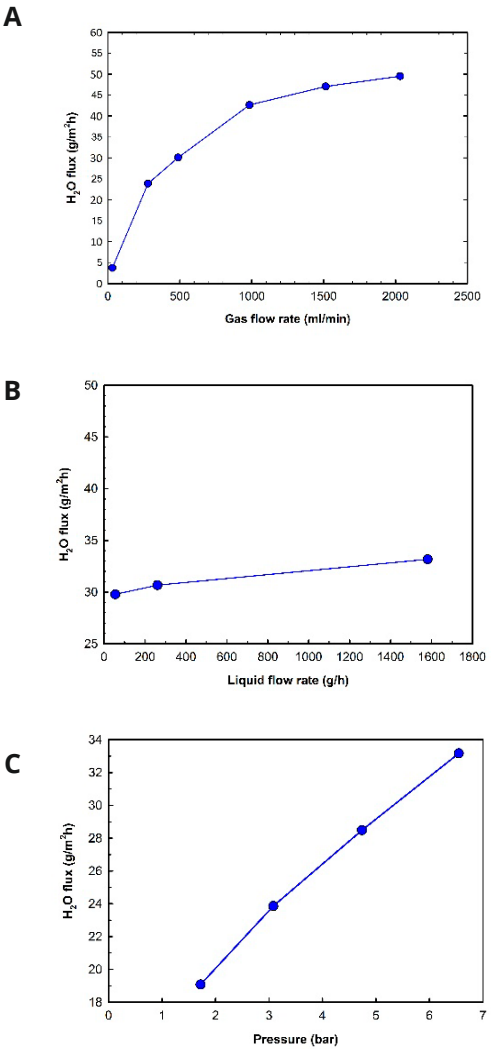


Figure 3: Effect of process conditions on the performance of membrane contactor. (a) gas flow rate, at 35°C, 3.5 bar, and 1600 g/h of liquid flow rate, (b) liquid flow rate, at 35°C, 7 bar, and 300 ml/min of gas flow rate, (c) pressure, at 35°C, 1600 g/h of liquid flow rate, and 300 ml/min of gas flow rate.

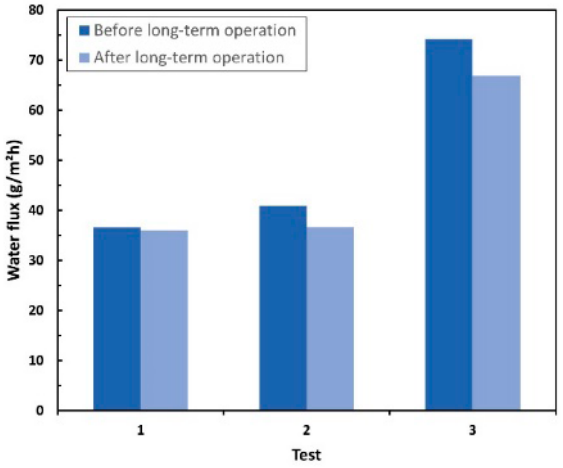


Figure 4: Performance of membrane contactor before and after the long-term. Test 1: at 3 bar and a gas flow rate of 800 ml/min, Test 2: at 5 bar and gas flow rate of 1600 ml/min, and Test 3: at 5 bar and gas flow rate of 400 ml/min. (all tests were performed at a temperature of 35°C and liquid flow rate of 1600 g/h)

3. POTENTIAL APPLICATION IN THE INDUSTRY

The subsea membrane dehydration process designed at NTNU provides industries with a stable and efficient operation in both onshore and offshore fields. Our industry partners, including Equinor and TechnipFMC, have shown keen interest in this project and contributed significantly to its design.

4. FURTHER WORK

The TEG loss rate has been one of the biggest concerns in the industry. One of the most important aspects of making this procedure financially viable is preventing TEG loss in the treated gas. A pervaporation setup will be used to investigate TEG flux through the membrane. The sample will be further analyzed using FTIR. The experiments are still ongoing.

Feasibility study of blue H_2

"Preliminary study on heat integration, carbon intensity and efficiency identifying opportunities and challenges to produce low-carbon H2 offshore".

Green Shift Impact: Decarbonized H2 will be necessary for achieving the climate targets. Either as an energy source or a feedstock to produce other fuels/chemicals. Producing decarbonized H2 with readily CO2 storage can contribute to achieve faster carbon neutrality.

Researchers: **Diego Di Domenico Pinto**
and **Juliette Limpach**
Start date: 01.06.2022
Planned end date: 30.08.2023 and 31.10.2023
Project manager and supervisor: Prof. Hanna K. Knuutila
Department of Chemical Engineering
Project nr: 3.3.c

1. THE PROJECT:

H2 is acknowledged to play a vital role in the energy transition and contribute to meeting climate targets. Nevertheless, H2 production is rather carbon intensive. Low-carbon H2 (e.g., from electrolysis using renewable energy) production is not yet mature (or cost-competitive). Steam-methane reforming (SMR) is the state-of-the-art technology for H2 production where methane (natural gas) is reacted with steam at high temperature and pressure. This project aims to study the opportunities to implement low carbon hydrogen production offshore. Producing low-carbon H2 offshore shows some potential opportunities to reduce the costs. The first opportunity is that CO2 and water do not need to be removed before entering the reformer as those are intrinsic components of the process. Also, since the production is offshore, CO2 transporting costs can be avoided/minimized which will decrease the overall CCS costs.

A thorough literature review is performed to identify literature gaps and improvement opportunities. Simulation of the process will identify sensitive operating parameters, namely CO2 concentration in the feed gas, reformer temperature, pressure, and steam/CH4 ratio, and its impacts on the production and overall costs. A key factor is heat integration. The heat demands (cooling and heating) were identified, and a study on heat integration is performed. Typically, SMR is a steam exporting process. However, if production is intended offshore, steam could be redirected to the needs of the carbon capture plant. Preliminary analysis shows that excess heat from the SMR is able to provide heat to the carbon capture plant. There are mainly 3 places where a CO2 capture can be placed in a SMR process. In this project, we will investigate the optimal configuration (and position) of the CO2 capture plant. The simulation of the integrated concept will serve to calculate cost estimation which will consider different configurations of absorption (e.g., single absorption, multiple absorption points, etc.).

2. DELIVERABLES:

2 Peer Reviewed Journal publications

2 conference presentations

Final project report

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 graduate: **Mahdi Ahmadi**
Start date: 01.08.2020
End date: 31.10.2022
Project manager and main supervisor: Professor Magne Hillestad
Co-supervisors: Professor Liyuan Deng, Dr. Eivind Johannessen (Equinor)
Department of Chemical Engineering
Project nr: 2.4.c

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 □ at 70 bara) and TEG content in the gas pipelines (TEG emission < 0.8 liter/MSm3 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.

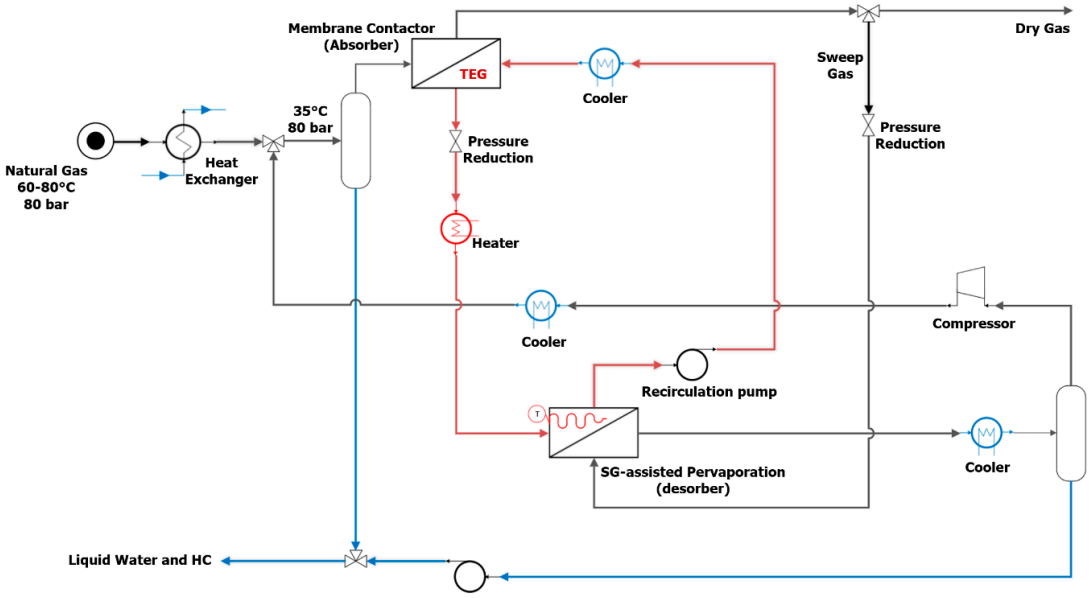


Figure 1: Process flow diagram of subsea membrane-based natural gas dehydration process.

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.

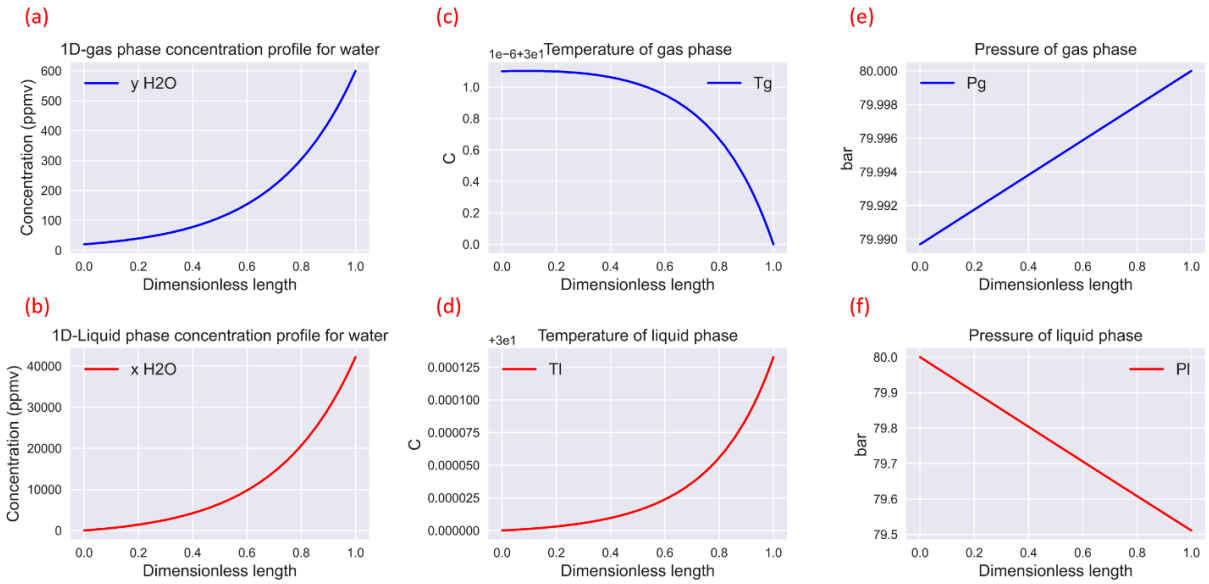


Figure 2: Concentration (a,b), temperature(c,d), and pressure (e,f) profiles in membrane contactor (absorber) for gas (1D) and liquid phases (1D). The process is a counter-current process and water content in inlet gas (~600ppmv) is captured by pure TEG and reduced to below 50 ppmv (pipeline specification). 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.

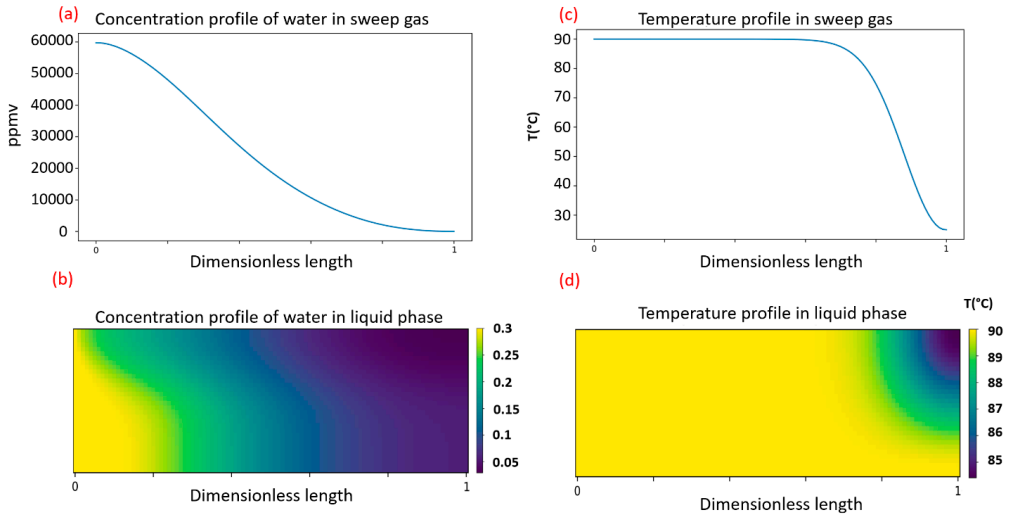


Figure 3: Concentration (a,b) and temperature profiles (c,d) in sweep gas (1D) and liquid side (2D) in membrane pervaporation unit with sweep gas flowing counter-current towards liquid phase. Inlet liquid temperature and water mole fraction of 90°C and 30% were used for simulation. An internal electrical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

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.

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. COMPLETE LIST OF PUBLICATIONS

Ahmadi, Mahdi; Ansaloni, Luca; Hillestad, Magne; Deng, Liyuan.
"Solvent Regeneration by Thermopervaporation in Subsea Natural Gas Dehydration: An Experimental and Simulation Study".
Industrial Engineering Chemistry Research (2021); Volume 60 (17); Page 6262-6276; 2021.

Ahmadi, Mahdi; Ansaloni, Luca; Hillestad, Magne; Deng, Liyuan.
"Membrane-based thermopervaporation to improve the glycol recovery in subsea natural gas dehydration system".
ICOM-2020 - 12th International Congress on Membranes and Membrane Processes; (2020-12-06 - 2020-12-12).

Ahmadi, Mahdi; Lindbråthen, Arne; Hillestad, Magne; Deng, Liyuan.
"Subsea natural gas dehydration in a membrane contactor with turbulence promoter: An experimental and modeling study".
Chemical Engineering Journal (2020); Volume 404; 15 June 2021.

Ahmadi, Mahdi; Arne, Lindbråthen; Liyuan, Deng; Magne, Hillestad
"Subsea Membrane Dehydration Process with Zero Methane Loss".
The 28th Underwater Technology Conference; Bergen, Norway; 14-16 June 2022.

RESEARCH AREA

System Control

In this research area, we develop methods for achieving optimal operation of subsea production and processing systems. This includes design of control systems, digital twins and methods to handle uncertainty in the process, that work together to realize intelligent autonomous production systems that operate in a safe and optimal way, and thus enable us to reduce emissions to air and water.

Professor Johannes Jäschke
Research Area Manager
Department of Chemical Engineering

In the Research Area System Control we study the development of new methods, models and tools related to autonomous, safe and optimal operation of subsea processes.

Subsea production and processing installations can improve field economics by increasing recovery and reducing operation costs. They can also enable producing from marginal fields.

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.

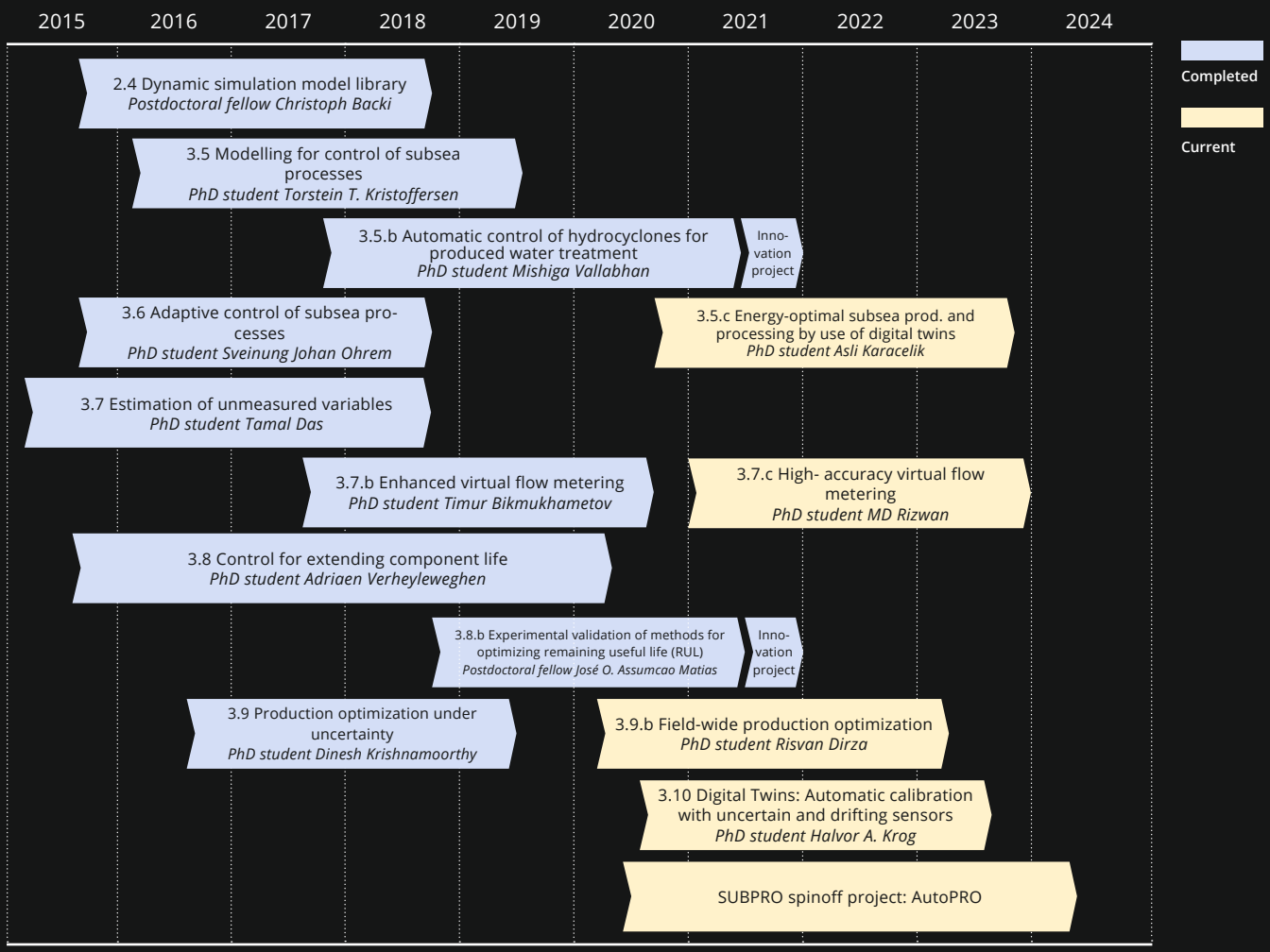
Our current research focuses on:

- Short and medium-term production optimization of large-scale installations
- Production optimization taking equipment degradation into account
- Control algorithms for energy-efficient production and processing
- Methods for calibrating 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), as well as optimization of systems of gas-lifted wells.

In the last year, no new projects were started. 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.

Adjunct Professor Gunleiv Skofteland (Equinor)and Associate Professor Milan Stanko were not present when the picture was taken.

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

Increasing Net Present Value by Reducing Energy Consumption in Subsea Processing Plant.

Green Shift Impact: Energy consumed per unit of production will be decreased.

PhD student: **Asli Karacelik**
Start date: 14.09.2020
Planned end date: 13.09.2023
Project manager and main supervisor: Associate Professor Christian Holden
Co-supervisors: Adjunct Professor Gunleiv Skofteland (Equinor) and Professor Sigurd Skogestad
Department of Mechanical and Industrial Engineering
Project nr: 3.5.c

1. BACKGROUND OF THE PROJECT

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 advanced process control models based on model predictive control (MPC) and nonlinear model predictive control (NMPC) using the Bayesian Neural Network. We did not prefer to combine first principles and machine learning because first principles are not always feasible in nonlinear model predictive control due to the complexity that comes with the mathematical model. Furthermore, machine learning accuracy depends on proper data size and validation methods for a particular system. Unfortunately, there are no standard validation methods for machine learning models; therefore, comparing results is difficult.

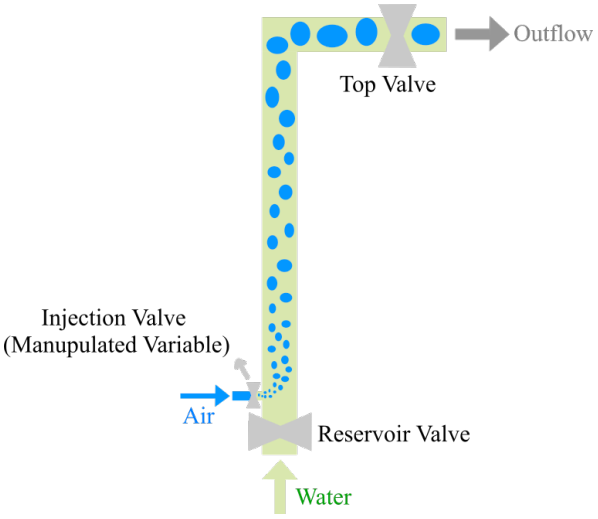


Figure 1: Gas-lift system.

2. RESEARCH ACTIVITIES

First, we investigated the physical behavior of the gas lift (Fig. 1) by analyzing feasible and infeasible areas with MPC and NMPC. The 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 liquid outflow rate is the control variable in the second case. Now, we study the slugging (Fig. 2) problem. The aim is to find a critical production rate to prevent slugging without controlling the choke valve. We model slugging via a Bayesian neural network.

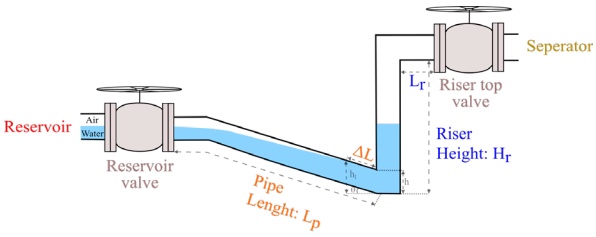
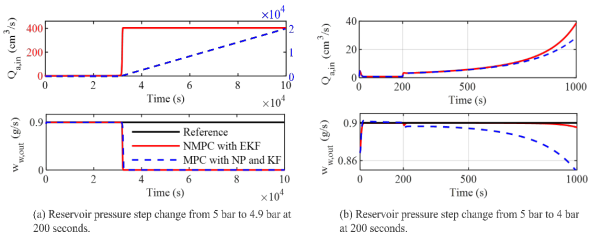


Figure 2: Slugging

3. RESULTS

1. When we changed the reservoir pressure from 5 bar to 4.9 bar and from 5 bar to 4 bar at 200 seconds, both controllers failed to control the system (Fig.3). At 0.1 bar pressure change, the manipulated variable nearly stabilized. However, the system was running around the maximum fluid outflow rate (Fig. 4), so we knew the controller would fail at some point. Consequently,| the minimal change in reservoir pressure caused the controllers to fail.



(a) Reservoir pressure step change from 5 bar to 4.9 bar at 200 seconds.

(b) Reservoir pressure step change from 5 bar to 4 bar at 200 seconds.

Figure 3: Effect of reservoir pressure change on controllers' performance. Here Qa,in is the gas inflow rate, and ww,out is the liquid outflow rate.

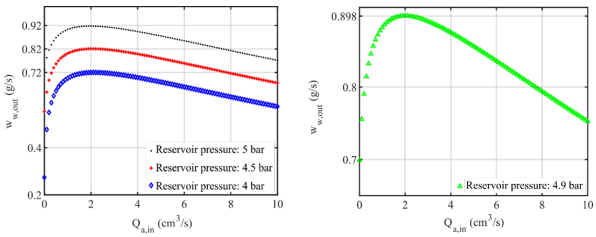


Figure 4: The liquid outflow rate versus the gas inflow rate for different reservoir pressures. Here Qa,in is the gas inflow rate, and ww,out is the liquid outflow rate.

2. We changed the prediction horizon to prevent the controllers from failing. Although the liquid outflow rate did not go to zero for the 1 bar reservoir pressure change, it did not stabilize during the simulation.

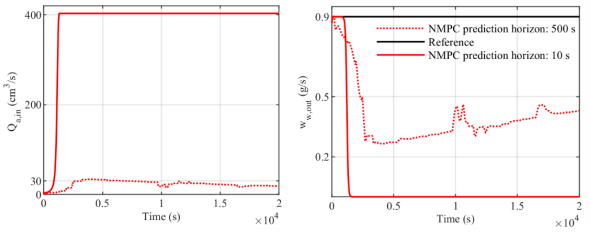


Figure 5: Effect of prediction horizon on controllers' performance at 1 bar reservoir pressure change. Here Qa,in is the gas inflow rate, and ww,out is the liquid outflow rate.

3. We provided a simple way to find the optimal input using the fsolve (MATLAB® solver) and applied it to the mathematical model in Simulink®. When we applied the optimal input, we found the same result with NMPC (Fig. 6).

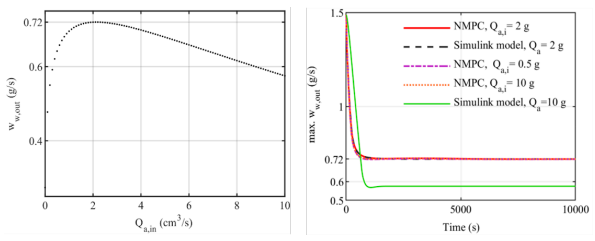


Figure 6: Maximum liquid outflow rate. Here Qa,i is the initial gas inflow rate, Qa,in is the gas inflow rate, and ww,out is the liquid outflow rate.

4. We changed two equations drastically in the predictive model. The results showed that the NMPC is highly robust against model inaccuracies compared to MPC with the linear and nonlinear plant models (Fig. 7).

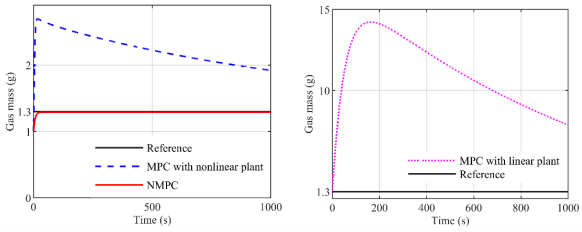


Figure 7: Plant-model mismatch.

4. MAIN RESULTS

This project aims to provide a new control structure for the slugging problem. We think that the root cause of the slugging problem is pressure change inside the system. Therefore, we need to manipulate pressure such that the slugging effect mitigates. One way to control the system pressure is to change the reservoir pressure. If we can recirculate unwanted gases in the system to increase the reservoir pressure, we can raise the production rate, mitigate slugging and have zero emissions.

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**
Start date: 01.02.2020
Planned end date: 30.11.2023
Project manager and main supervisor: Professor Sigurd Skogestad
Co-supervisor: Assistant professor Dinesh Krishnamoorthy (TU/e)
Department of Chemical Engineering
Project nr: 3.7.c

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, building the models for the entire field is impractical (and maybe less accurate) and numerical optimization solver can be computationally extensive. These issues, in the end, may lead to a sub-optimal operation. Therefore, it is necessary to decompose the optimization problem into several subproblems and coordinate them to achieve the optimal operation for the entire field. Moreover, to avoid the use of complicated solver, it is possible to use simple and well-known tools such as PID controllers to drive the production system to the optimal operation.

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

In this project, we have 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 partially (subsystem model). By doing so, it is practically easier to construct a good enough 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 one 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], and we have validated the method in an experimental lab rig [2]. However, this method has two issues; first, extensive pairing tasks for highly interactive systems, and secondly, a slow timescale constraint controller that may lead to significant back-off. For highly interactive systems, we combined the method with a simple solver [8]. To minimize the back-off, we have modified the method by introducing direct/override constraint control [3]. The next research question of introducing direct/override constraint control is how to select the right input to directly control the constraint. We address this issue in [4]. Introducing direct/override 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 [5]. Alternatively, one can reformulate the problem into a primal decomposition framework [6]. This framework can also be formulated in graph-based theory [7]. 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 (if 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 this project to address open problems we discussed in the previous sections. The following deliverables have been published.

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).
2. "Experimental Validation of Distributed Feedback-based Real-Time Optimization in a Gas-lifted Oil Well Rig." Control Engineering Practice, 2022.
3. "Primal-dual Feedback-optimizing Control with Direct Constraint Control for Oil Production." The 14th International Symposium on Process System Engineering, 2022.
4. "Systematic Pairing Selection for Economic-oriented Constraint Control." The 32nd European Symposium on Computer-Aided Process Engineering, 2022.

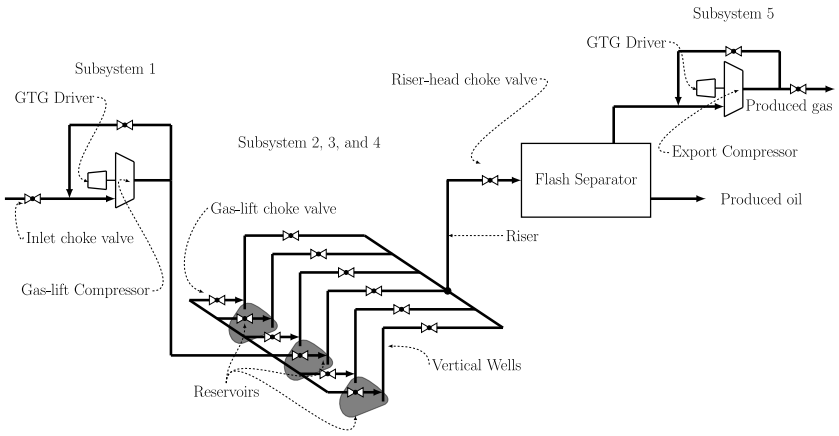


Figure 1. Illustrated "synthetic" case system for the project, comprising production and processing system for an oil and gas field with gas lift, control valves, separator, and two compressors in deliverables.

5. "Online Feedback-based Optimization with Multi-input Direct Constraint Control." International Federation of Automatic Control Symposium on Dynamics and Control of Process Systems, 2022.
6. "Real-time Optimal Resource Allocation using Online Primal Decomposition" International Federation of Automatic Control Symposium on Control, Optimization, and Automation in Mining, Mineral and Metal Processing, 2022.
7. "Real-Time Optimal Resource Allocation and Constraint Negotiation Applied to A Subsea Oil Production Network". Society of Petroleum Engineers Annual T echnical Conference and Exhibition 2021.
8. "Handling Interactive Systems in Primal-Dual Feedback-optimizing Control". Foundations of Computer Aided Process Operations / Chemical Process Control 2023 (Accepted).

THESE WORKS HAVE ALSO BEEN PRESENTED IN VARIOUS EVENTS AS FOLLOWS

1. Computer-aided Process Engineering Forum 2020.
2. The American Institute of Chemical Engineers Annual Meeting 2021.
3. Nordic Process Control Workshop 2022.
4. Brazil Norway November Workshop 2022.
5. The American Institute of Chemical Engineers Annual Meeting 2022.

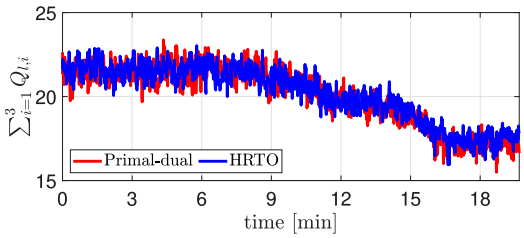


Figure 2: Experimental validation results in deliverables [2]: Our proposed approach applied and extended in [1] (indicated by the solid red line) has comparable performance, i.e., the same oil production rate, as the previous method Hybrid Real-time Optimization (HRTO) that still requires numerical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

4. FINAL GOAL FOR POTENTIAL INDUSTRIAL APPLICATIONS

As the 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.

5. INNOVATION GRANT

Several discussions have been conducted with AkerBP to proceed the proposed and available optimizing-control method closer to industrial practice. We agreed to test the methods on more realistic case that exists in their production fields. AkerBP has granted access to analyze operation data in one of them. These resources are essential to construct case studies that demonstrate important aspects of the project. At this moment, we agreed to have three subprojects, illustrated in Fig. 3, for this innovation project.

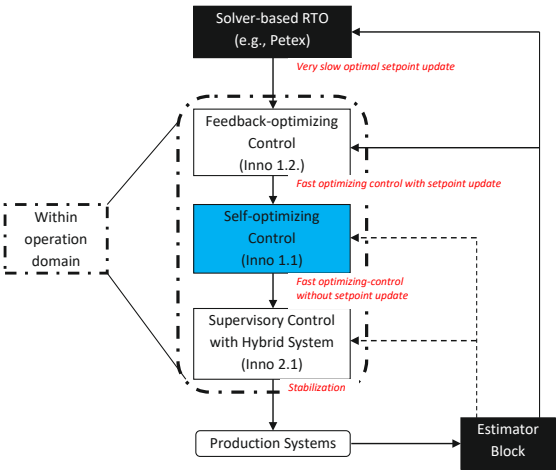


Figure 3: Illustration of Innovation Project Scope of Work

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 relies on matching the model with the physical asset to the greatest possible extent.

PhD student: **Halvor Arnes Krog**
Start date: 17.08.2020
Planned end date: 01.01.2024
Project manager and supervisor: Professor Johannes Jäschke
Department of Chemical Engineering
Project nr: 3.10

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, although 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. On subsea facilities, sensors cannot be simply recalibrated, and the drift must instead be estimated from the sensor measurements and process model. This is a suitable task for a state estimator.

Incorporating information about the sensor drift into the modelling phase is one of the aims of this project. The overall project goals are therefore to:

1. Develop robust and trustworthy state estimators to minimize the real plant-model mismatch, resulting in operation closer to the truly optimal point.
2. Detect if we have sensor drift in our plant and try to pinpoint the faulty sensor out of potentially many healthy sensors. Based on this information, we aim to estimate the drift. This is combining fault detection and identification techniques with state estimation.

2. RESULTS THIS YEAR

State estimation is all about estimating quantities which are not directly measured, or to refine low quality measurements to reliable estimates. This is done by combining information from a process model and available (uncertain) measurements. A state estimator is implemented on a computer. All computers have a limited memory to store decimal numbers, and this limitation may lead to round-off errors in computation. When the round-off error accumulates over time, we may experience that the state estimator diverges (crashes). To remedy this, we have developed a method which significantly reduces numerical issues compared to the standard implementation, as shown by Figure 1. This work is submitted to the IFAC World Congress.

3. INNOVATION GRANT AND POTENTIAL INDUSTRIAL APPLICATIONS

One bottleneck for implementing state estimators in the industry is that the process models must be accurate and simple to implement. Luckily, dynamic simulation platforms such as K-spice simplifies the process modelling step significantly. Funded by an innovation grant from SUBPRO, we worked together with Kongsberg Digital to make a Python-based state estimator which used K-spice for the process model, and the remaining parts were handled by Python. We tested the state estimator on real data from the Åsgard field, where the objective was to estimate the liquid density through a subsea booster pump in order to improve the liquid flow-metering. The results indicated that using state estimation to merge information from high-fidelity simulators as K-spice and plant data is indeed a fruitful approach. The innovation project was done in collaboration with Equinor, Aker Solutions and Kongsberg Digital.

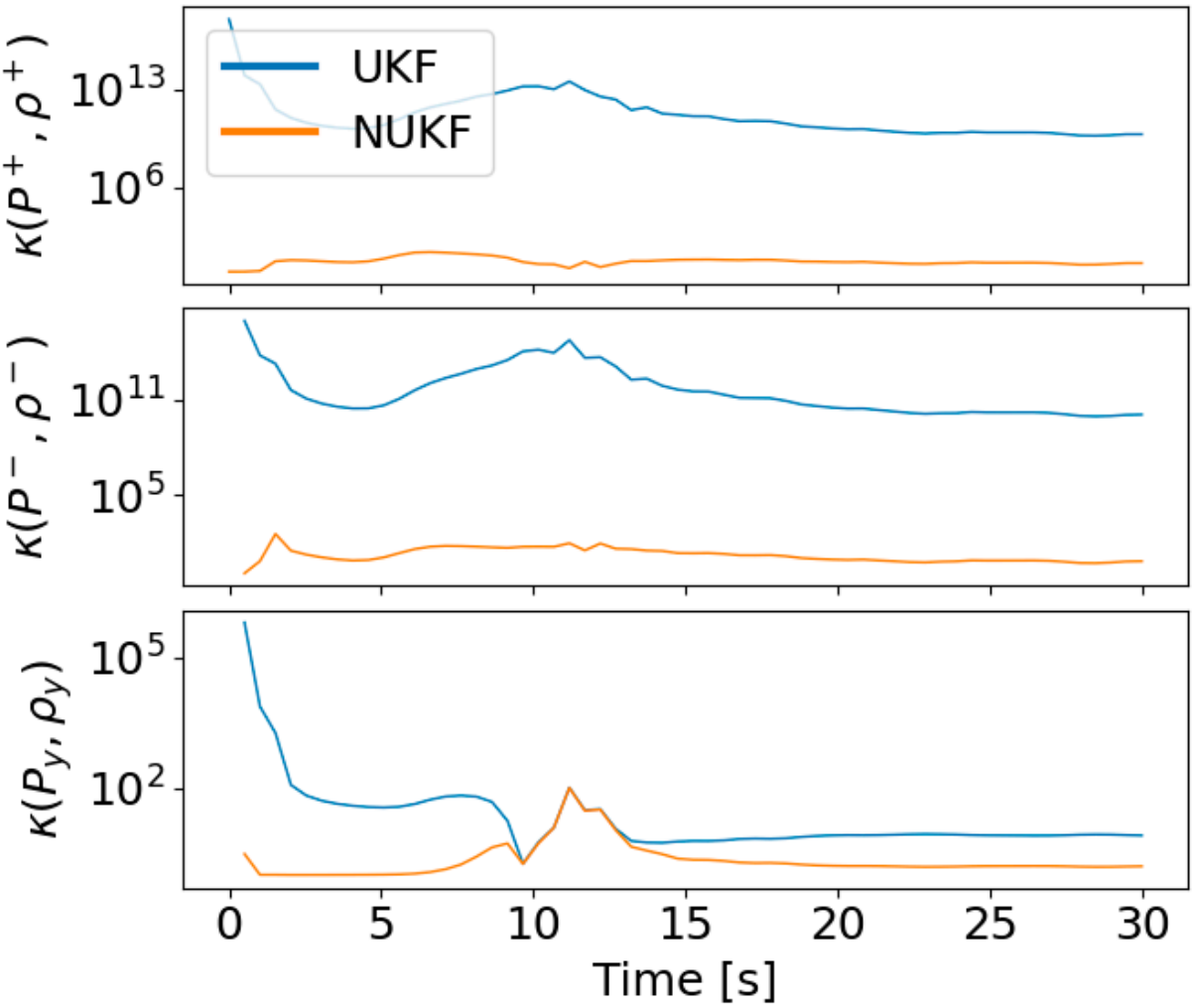
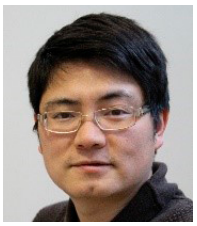


Figure 1. The condition number of a matrix tells you how sensitive the matrix is for numerical issues (the smaller number, the better). For the case study in the IFAC World Congress paper, we calculated the condition number for every time step for three relevant matrices. The standard implementation of the relevant state estimator (UKF) has always a significantly higher condition number than our proposed implementation (NUKF).

AutoPRO: Digitalization for autonomous prognosis and production optimization in offshore production systems

A SUBPRO SFI spin-off project


Professor **Johannes Jäschke**, NTNU Systems Control, Project leader and PhD supervisor

Professor **Yiliu Liu**, RAMS Systems Control NTNU, PhD supervisor

Edmary Altamiranda, Aker BP, Industrial PhD supervisor

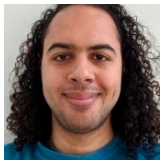
The collaboration between SUBPRO and the industry partners resulted in the spin-off project AutoPRO, funded by the Norwegian Research Council and Aker BP. The project involves the Department of Chemical Engineering and the RAMS group from Department of Mechanical and Industrial Engineering at NTNU, and is a collaboration project between NTNU, Aker BP and 3 Chinese Universities: China Univ. of Petroleum (East 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 AutoPRO project develops new technologies to facilitate the digital transformation in the oil and gas industry. More specifically, we use methods from big data, artificial intelligence and machine learning, combined with in-depth domain knowledge, to develop new approaches for optimal decision-making in operations, control and maintenance.

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



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

2. Condition-based maintenance decision-making with digital twins for subsea systems
(PhD project Emefon Dan - RAMS)

3. Autonomous production optimization with degrading equipment
(Postdoc project Rafael David de Oliveira)

The collaboration between Norway and China has taken place in form of common online seminars. A face-to-face Workshop is planned in June 2023.

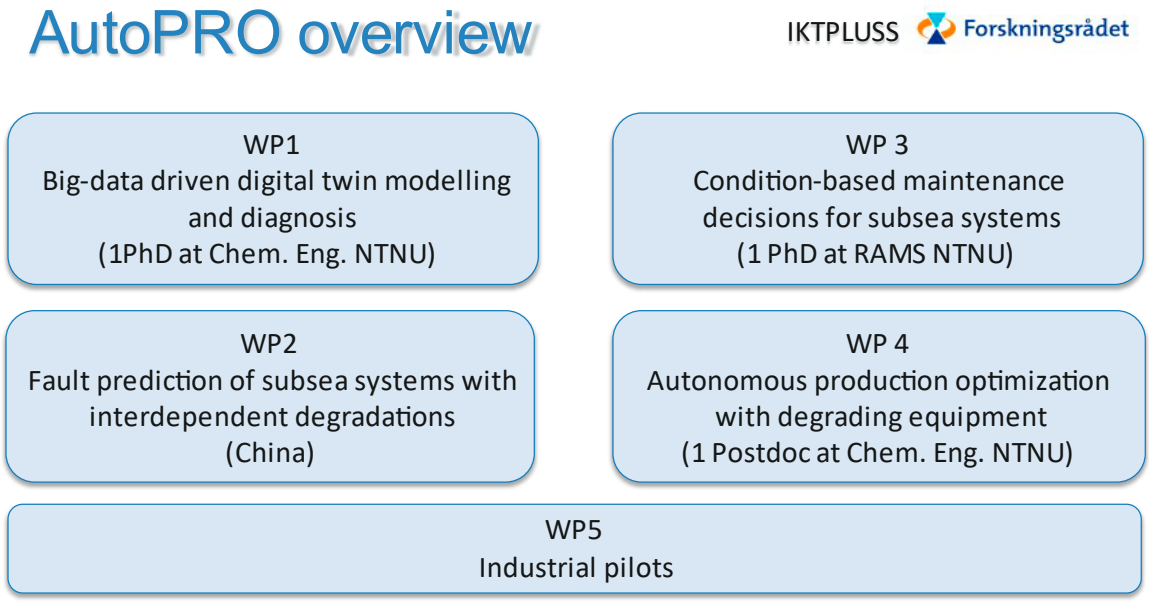


Figure 1. AutoPRO Project organization.

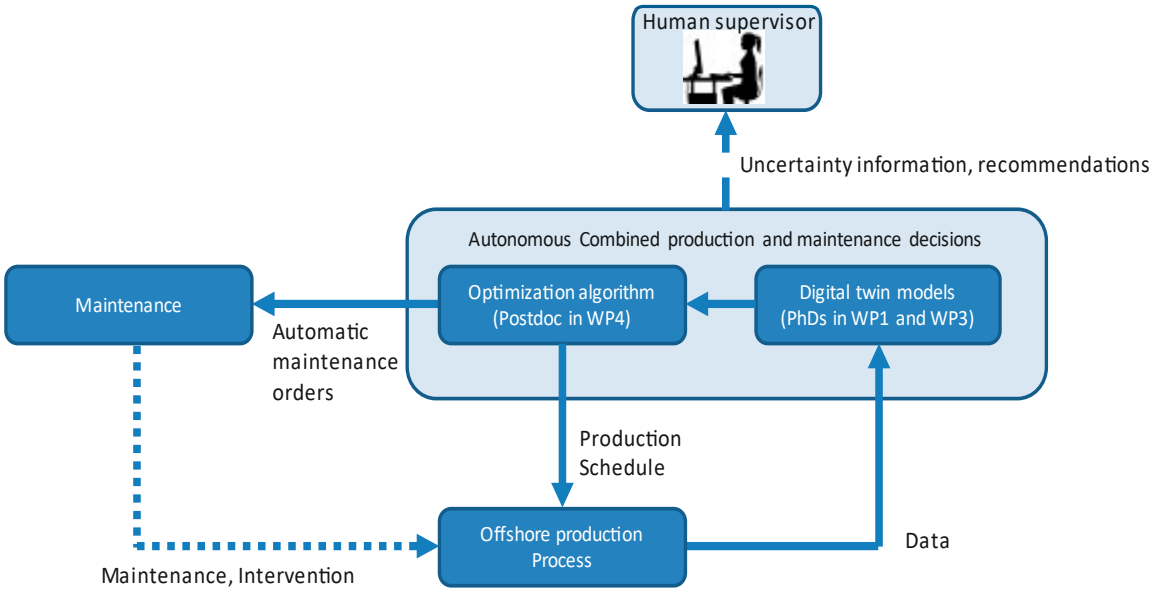


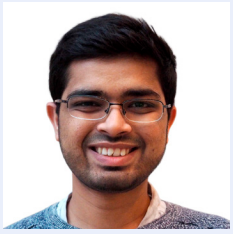
Figure 2. AutoPRO concept for realizing autonomous production, including automatic maintenance planning. Only high-level information is passed to the human supervisor.

Final project Report

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.



Researcher: **Md Rizwan**
Start date: 03.01.2021
End date: 04.09.2022 (PhD work discontinued)
Project manager and main supervisor: Associate professor Christian Holden
Co-supervisors: Professor Johannes Jäschke and Associate Professor Milan Stanko
Department of Mechanical and Industrial Engineering
Project nr: 3.9.b

1. BACKGROUND FOR THE PROJECT

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

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

The goal of this project was to develop tools that combine machine learning methods with knowledge-based first principles models to optimize overall production systems. The plan is to bring virtual flow metering to its full potential; that is, accurate and inexpensive flow measurements based in reliable sensors in lieu of using inaccurate and expensive physical flow meters.

2. WHAT I HAVE DONE

- **Comprehensive literature review** on the topic of Virtual Flow Metering using first principles and machine learning models. Based on this review, we identified main directions for future research and development.
- **Proposal on a potential method** of combining machine learning models with multiphase flow physics to construct accurate and more explainable Virtual Flow Metering solutions using sparse data. The proposed concept can potentially be extended to modeling of other engineering systems.

3. MAIN RESULTS

In my work, I reached the following conclusions.

1. The literature review showed that currently first principles-based approaches for multiphase flowrate estimation take the leading role. The more recent works on using machine learning methods for the virtual flow metering have concluded that the performance of purely data driven virtual flow metering models is limited to the characteristics of the training data. The general trend of the multiphase flowrate estimation methods development is positive, and approaches that can combine physics-based knowledge with the real plant data can replace physical multiphase flow meters in the future.

2. A hybrid modeling approach was explored wherein the parts of the differential equations that represent an approximate physics-based model for riser slugging were replaced by a neural network. This approach is described in the research literature as neural ordinary differential equations. The key technical detail for training such models is the backpropagation of the gradient of loss term with respect to the model parameters which is especially difficult for the studied slugging model because of the oscillating behavior of key process variables. This could be addressed by using multiple shooting for neural differential equations. This method is currently under implementation and is planned to be tested for the riser slugging case.

Based on the obtained results on combining first principles and machine learning models for multiphase flow estimation purposes even simple physical models introduced to machine learning models might enhance the accuracy and explainability of the resulting data-driven solutions.

4. INNOVATION AND INDUSTRY COLLABORATION

The developed proposal of method for multiphase flow estimation using hybrid approaches utilizing machine learning with multiphase flow physics formulate a great basis for further improvements of accuracy and robustness of multiphase flow estimation solutions that are currently not well-developed in the industry but have a rising trend in the research and development. We believe the proposed methods will show how to fully uncover the potential of machine learning algorithms and available production data to form reliable multiphase flow metering solutions at an affordable cost.

The proposed work is focused on industrial applicability. After development, the industry partners can potentially exploit this approach for improving their soft-sensing solutions not only for multiphase flow estimation problems, but also for other process engineering systems of interest.

5. FURTHER WORK

Based on the conducted research work during the stay at NTNU the following research directions are planned to extend the work:

Extending the work on neural ODEs to model the slugging behavior in a pipeline riser using data from OLGA simulations and multiphase flow physics and investigate how these models can be used under limited data criteria. The findings from this work are planned to be published in academic journal/conference.

6. MY NEW JOB

Company: DNV AS

Position: Researcher, Energy Systems

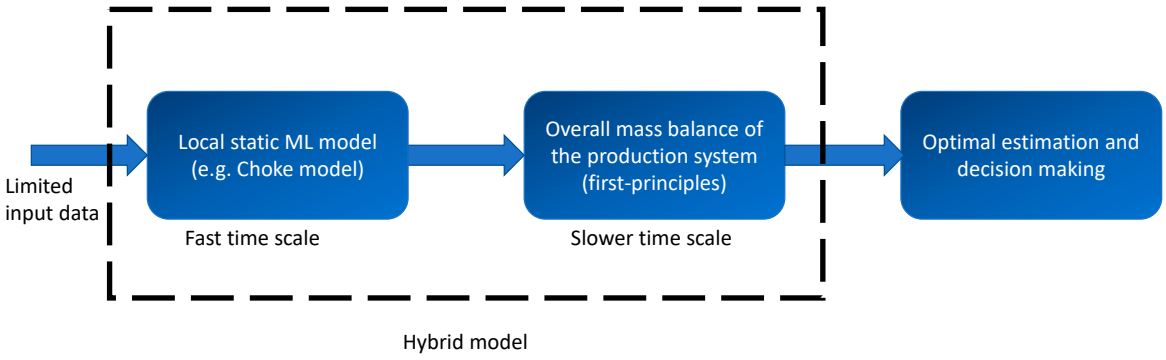


Figure 1. Hybrid model

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.

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

PhD student Muhammad Gibran Alfarizi testing "The Equinor Simulator Support Center" during the SUBPRO visit to the Equinor office in Stjørdal - March 2023

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

SUBPRO members attending the BN Subsea Operations 3rd workshop in Brazil – November 2022

Master student projects and summer internships at SUBPRO

Student-industry partner information meeting at NTNU in March 2022.
This picture was taken during the presentation held by Odd-Ivar Haugen from DNV.

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 the 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. the last industry meeting was held in April 2023.

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

In 2022, 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 2022 and the Master thesis during the spring of 2023, was offered to the students.

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

- Modeling of CO2 flow in pipes.
- Modelling of Offshore Blue Hydrogen Production.
- Subsea separation and compression laboratory upgrades.
- Verification of the Lagrangian model equations.
- Gas flotation for subsea produced water treatment.

SUBPRO encourages its summer students to extend their assignments after the master's degree, by applying for a PhD education at NTNU and SUBPRO/SUBPRO Zero.

Serving of pizza; optimal time for open discussions between the master students and the SUBPRO representers on site.

SUBPRO Centre Director Sigurd Skogestad, interacting with the master students at the end of the industry meeting.

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 excursions have been combined with meeting fellows from the BRU21 project.

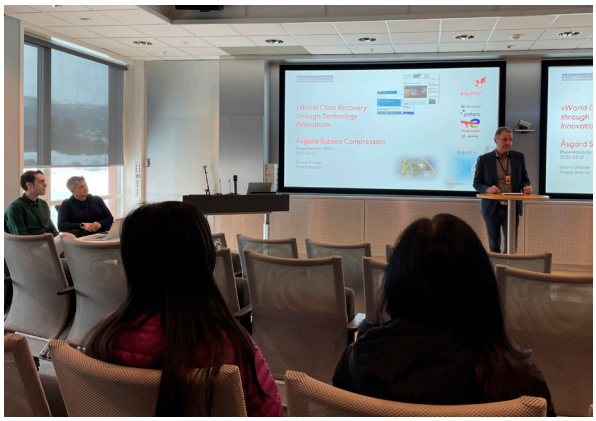
BRU21 is a parallel NTNU Research and Innovation Program that kicked off in 2018, with focus on Digital and Automation Solutions for the Oil and Gas Industry.

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 with fellow students from BRU21. And since then, the tradition kept being honored yearly -expect in 2021 due to Covid19 restrictions. The casual atmosphere of the trips has been very favorable for the students of both projects to get to know each other further and to discuss their projects together in a very casual atmosphere.

This year's trip from the 17th-18th March 2023, the two projects arranged a common trip to Åre. The trip contained a program that combined both technical content and a lot of fun!

SUBPRO PHD FORUM:
PHD students and postdocs at SUBPRO were able to meet on regular intervals during 2022; in an informal context combining social interaction and multi- discipline collaboration possibilities through knowledge sharing.

A technical presentation is included in each event – students from all research areas get the opportunity to present their projects to their SUBPRO fellows.



Presentation about the Åsgard Subsea Compression field held by Snorre Grande, followed by a presentation about employment opportunities for graduates of SUBRO and BRU21– held by SUBPRO PhD graduate Ilgar Azizov currently employed by Equinor.

Photo taken at The Equinor office in Stjørdal during the SUBPRO/ BRU21 excursion – March, the 17th 2023.

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 2022 we arranged a very nice and cosy Christmas party (julebord) for our staff, at Gløshaugen Campus.

Members of SUBPRO and BRU21 in front of Buustamons Fjällgård restaurant in Åre. Heading for dinner right after the SUBPRO/ BRU21 Technical session – March, the 17th 2023.

International collaboration

International collaborations at SUBPRO have picked up again after the lift of Covid 19 restrictions. Participation in conferences and international events have been taking place both on a physical and digital bases.

Here are some of the international collaboration activities held in 2022:

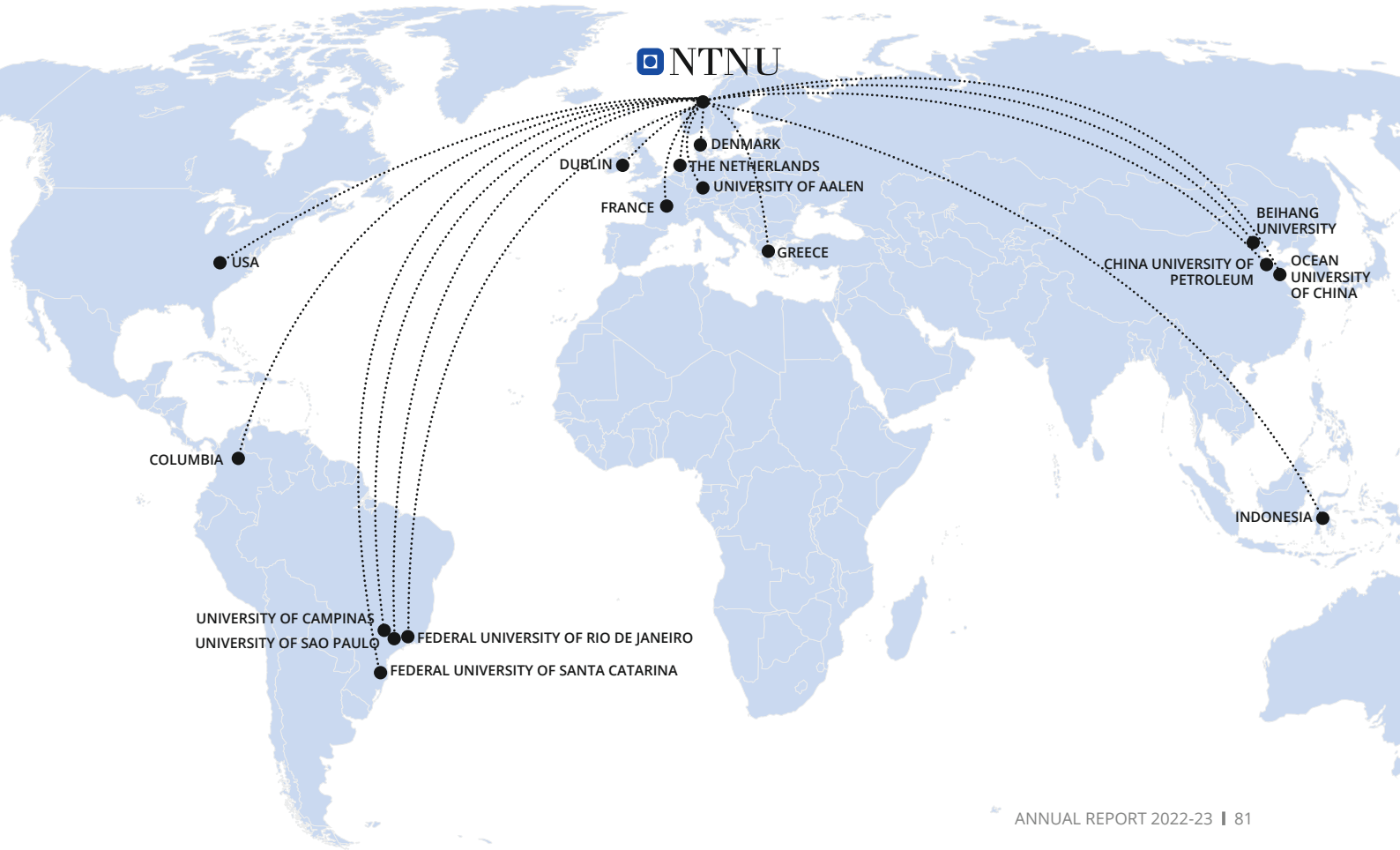
- IAESTE exchange student: Dionysia Kouranou (Greece)
- PhD student Ludvig Björklund has been on a research stay in University of Aalen, (Germany).
- Four researchers from Aalen University (Germany) visited SUBPRO, each for one week, in collaboration with the SUBPRO RAMS team.
- PhD student George Claudiu Savulescu has been on a research stay in Eindhoven University of Technology (TU Eindhoven) in The Netherlands.
- PhD student George Claudiu Savulescu and Phd student Martina Piccioli attended Petrophase conference 2022, the 22nd International Conference on Petroleum Phase Behavior and Fouling (Bucaramanga, Colombia).
- Researcher Diego Di Domenico Pinto is performing his research for SUBPRO as a Managing Director in Hovyu (the Netherlands).
- Members from the RAMS group held a physical presentation ESREL, i.e., Home | ESREL European Safety and Reliability Conference, (Dublin).
- Cooperation with Chinese universities through Auto-PRO -ref. page 74.
  - China University of Petroleum.
  - 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:

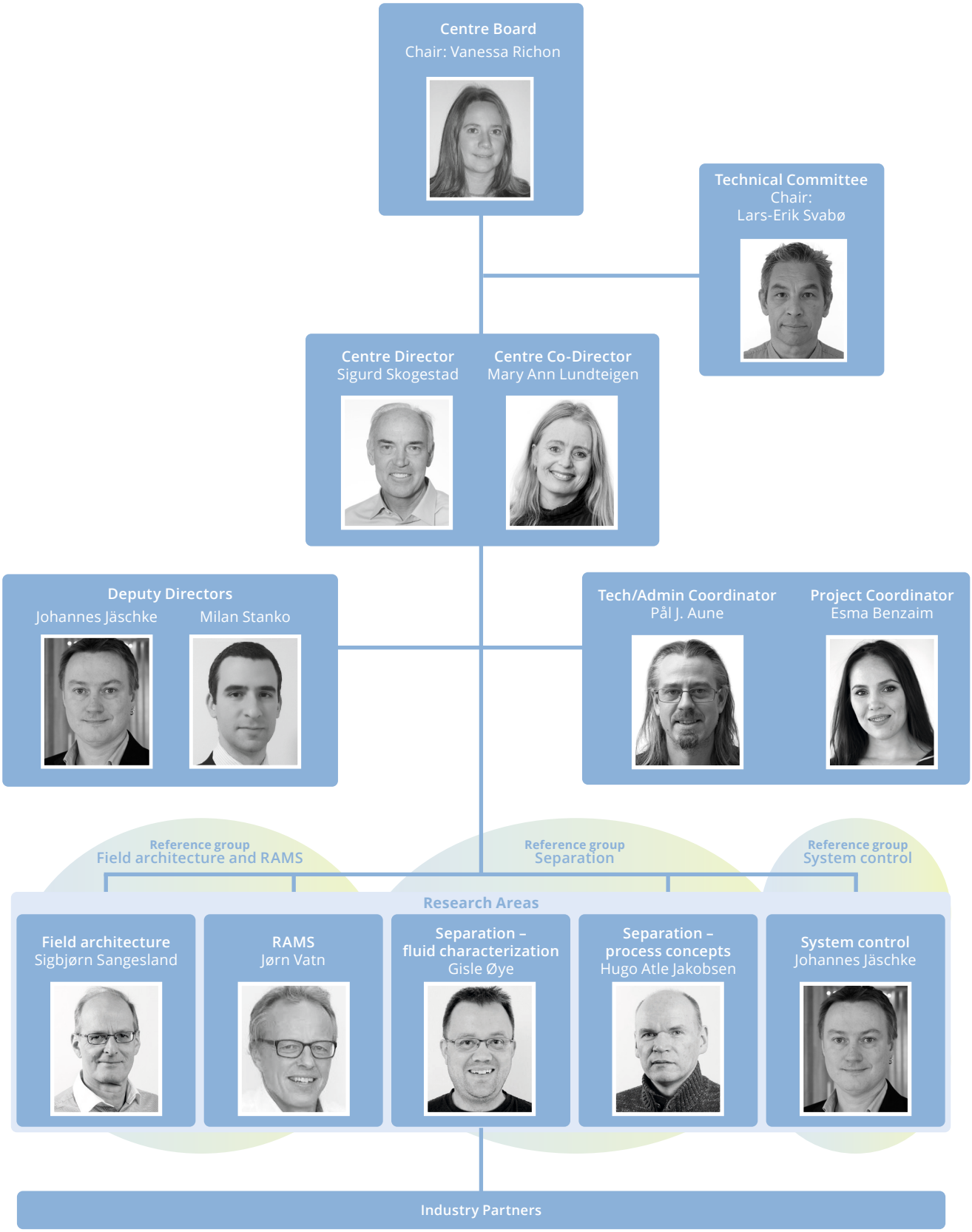
- Federal University of Rio de Janeiro/COPPE Federal
- University of Santa Catarina
- University of Sao Paulo
- University of Campinas

- Brazil-Norway Subsea Operations Consortium2 (BN-SOC2); SUBPRO members attended this INTPART event as well as the Annual November Conference (November 2022).
- In addition to Greece, Germany, The Netherlands, Columbia, Dublin, China and Brazil, SUBPRO has co-operated with researchers from Indonesia, Denmark, France and USA.



Organization of the Centre

GOVERNANCE STRUCTURE (2023)



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 transfer of knowledge; providing advice, co-supervision of PhD students, co-authoring of scientific papers and industrial cases using field data for testing models and software.

In addition, there are three adjunct professors assigned to enhance the collaboration between the Centre and the industry. Two of them are from Equinor; Professor Audun Faanes and Professor Gunleiv Skofteland, and a third Professor Shen Yin from DNV for the RAMS research group.

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 2022 several of our PhD's and Postdoc's started a 3-6 month innovation projects:

- Researcher Haoge Liu & Equinor (See page 14-15).
- PhD student Tae Hwan Lee & Equinor, Kongsberg Digital, DNV (See page 26-27).
- PhD student Martina Piccioli & Equinor, Aker Solutions (See page 42- 43).
- PhD student Hamidreaza Asaadian & Equinor, TotalEnergies (See page 56-57).
- PhD student Risvan Dirza & Aker BP, Equinor, TotalEnergies (See page 70-71).
- PhD student Halvor Arnes Krog & Aker Solutions, Equinor, Kongsberg Digital (See page 72-73).

CENTRE BOARD 2022-2023

Trine Boyer
TotalEnergies, Chair
Until 31.08.2022

Vanessa Richon
TotalEnergies, Chair
from 01.09.2022

Kristin Moe Elgsaas
Aker BP

Audun Faanes
Equinor

Jostein Kolbu
Aker Solutions

Lars-Erik Svabø
Kongsberg Digital

Olav Dolonen
Neptune Energy Norge

Espen Gjørv
Lundin Energy Norway
Until 01.09.2022

Ola Jemtland
TechnipFMC
Until 31.12.2022

Kimberly C. Mayes
Research Council of Norway, observer

Øyvind Weiby Gregersen
NTNU

Sigurd Skogestad
NTNU, Centre Director and Secretary of the board

Health Security and Environment

Reported events during 2022

There has been no reported HSE incidents connected to SUBPRO staff and laboratories during 2022.

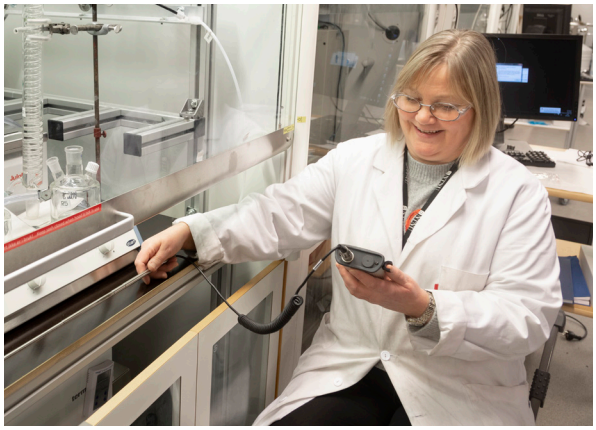
All SUBPRO personnel is required to report HSE incidents that have occurred in their projects. This brings learnings from the events and from general HSE work at the for departments at NTNU which are involved in SUBPRO:

- Department of Chemical Engineering.
- Department of Geoscience and Petroleum.
- Department of Mechanical and Industrial Engineering.
- Department of Engineering Cybernetics.

In case of a reported incident both the HSE engineer and the Campus service office have the responsibility to follow up on the incident and to mitigate adequate measurements and solutions.

NTNU is currently working on a new HSE-system which is to be implemented during 2023.

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.



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

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.

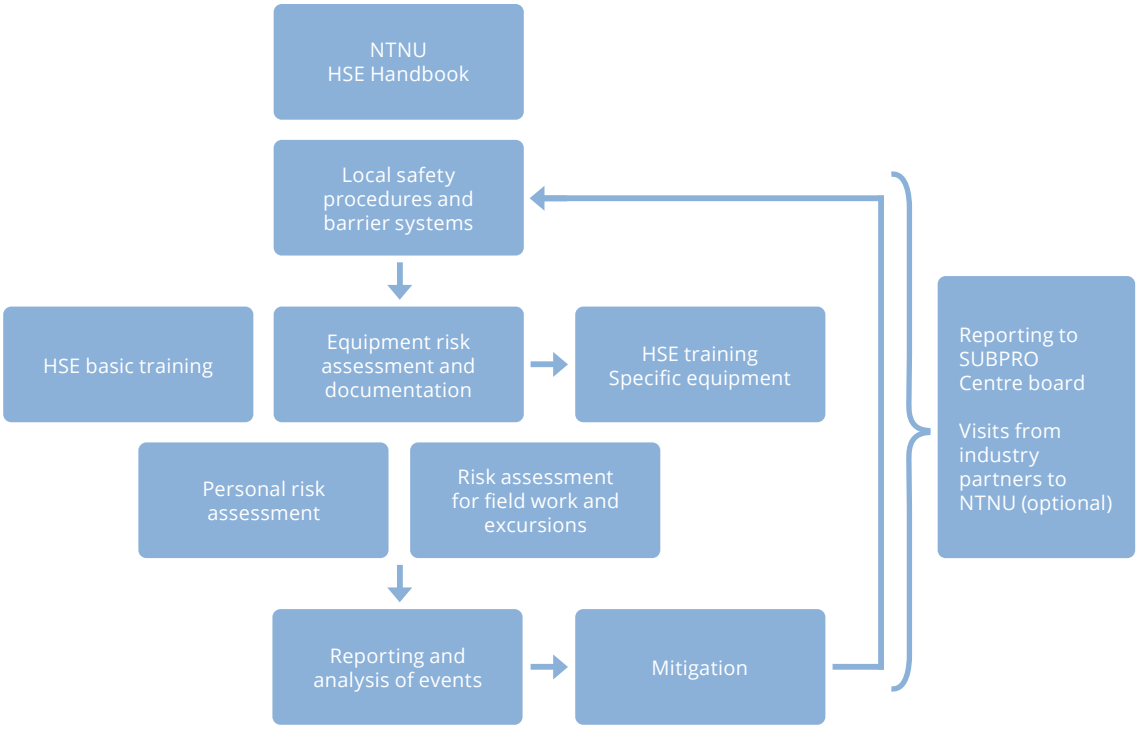


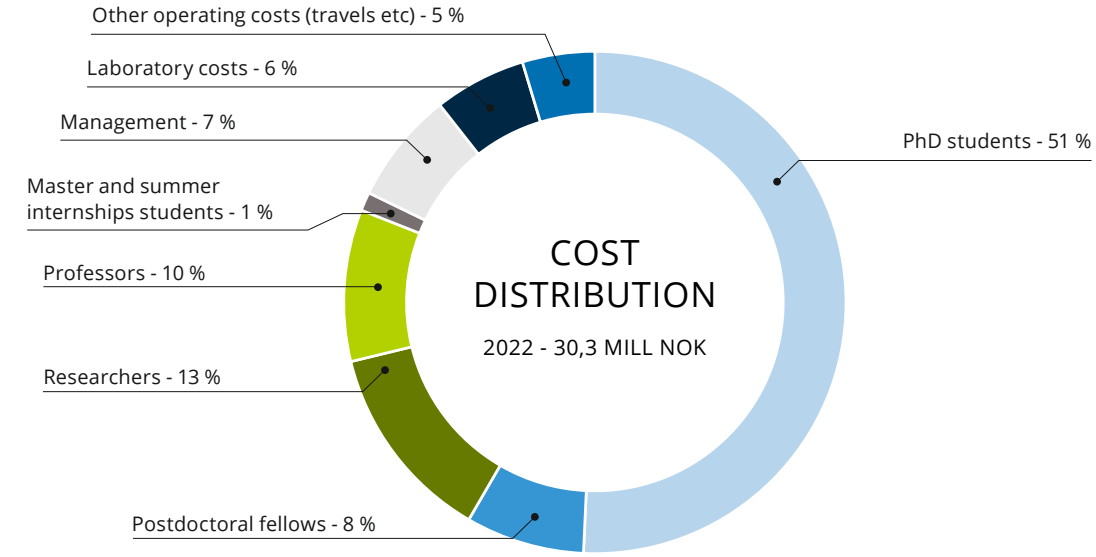
Figure 1. NTNU/SUBPRO HSE system

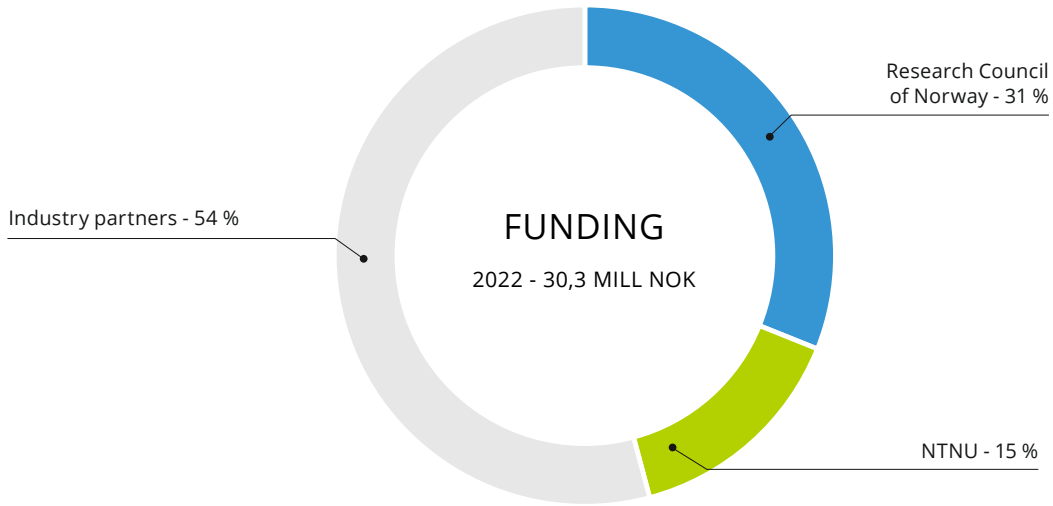
Key figures 2022

PROJECT DURATION	AUGUST 2015 – DECEMBER 2023		
Total annual budget (Annual average, 2015-2023)	32 mill. NOK		
Personnel	Expected 2015-2023	Engaged in 2022	Female percentage 2022
PhD students	35[1]	14	21 %
Postdoctoral fellows	11[1]	2	0 %
Researchers (full or part time)	7[1]	9	33 %
Professors	25[1]	22	14 %
Master students educated (per year)	20	15	47 %

[1] *Accumulated over 8 years*

PUBLICATIONS 2022	
Journal and conference papers	34





Publications

Journal papers and conference papers published in 2022.

FIELD ARCHITECTURE

Leonardo, Sales; Johannes, Jäschke; Milan, Stanko.
"Designing Subsea Processing Systems Using a Hybrid Genetic Algorithm".
41st International Conference on Ocean, Offshore and Arctic Engineering (OMAE2022); 2022-06-05 - 2022-06-10.

Leonardo, Sales; Milan, Stanko; Johannes, Jäschke.
"Superstructure optimization of subsea processing layouts".
Journal of Petroleum Exploration and Production Technology; 2023.

Leonardo, Sales; Thomas, Stolpnes; Milan, Stanko; Audun, Faanes.
"Subsea Processing Optimization Considering Reliability and Maintenance".
42nd International Conference on Ocean, Offshore and Arctic Engineering (OMAE2023); 2023-06-11 - 2023-06-16.

Sevillano, Lucas Cantinelli; Sangesland, Sigbjørn.
"Assessment of power requirements for alternative vertical transportation system for deepsea mining".
41st International Conference on Ocean, Offshore, and Arctic Engineering (OMAE2022); 2022-06-05 - 2022-06-10.

Sevillano, Lucas Cantinelli; Sangesland, Sigbjørn; Gjersvik, Tor Berge; Faanes, Audun.
"A more accurate approach for the design of subsea chemical storage systems regarding volue requirements of valve leakage tests".
41st International Conference on Ocean, Offshore and Arctic Engineering (OMAE2022); 2022-06-05 - 2022-06-10.

RELIABILITY, AVAILABILITY, MAINTENANCE AND SAFETY (RAMS)

Björklund, Ludvig; Lundteigen, Mary Ann; Imle, Sebastian; Glaser, Markus.
"Design of a digital twin of gate valves for partial stroke testing".
ESREL 2022; 2022-08-28 - 2022-09-01.

Liu, Jie; Vatn, Jørn; Pedersen, Viggo Gabriel Borg; Yin, Shen; Tajiani, Bahareh.
"A comparison study for bearing remaining useful life prediction by using standard stochastic approach and digital twin".
International Journal of Reliability and Safety; 2023.

Xingheng, Liu; José, Matias; Johannes, Jäschke; Jørn, Vatn.
"Gibbs sampler for noisy Transformed Gamma process: inference and remaining useful life estimation".
Reliability Engineering & System Safety; Volume 217; Page 084-108; 2022.

Xingheng, Liu; Jørn, Vatn.
"Erosion state estimation for subsea choke valves considering valve openings".
The 32nd European Safety and Reliability Conference; 2022.

SEPARATION – FLUID CHARACTERIZATION

Assar, Moein; Grimes, Brian Arthur.
"A new approach to analyze the equilibrium and transient behaviors of particulate systems and the subsequent application to multiphase fluid systems".
Journal of Chemical Engineering Research and Design; Volume 188; Page 1083-1096; 2022.

Assar, Moein; Simon, Sebastien Charles Roger; Sørland, Geir; Grimes, Brian Arthur.
"A theoretical and experimental investigation of batch oil-water gravity separation".
Chemical engineering research & design; Volume 194; Page 136-150; 2023.

Azizov, Ilgar; Dudek, Marcin; Øye, Gisle.
"Studying droplet retention in porous media by novel microfluidic methods".
Chemical Engineering Science (CES); Volume 248; 2022.

Piccioli, Martina; Gjelsten Larsen, Robert André; Dudek, Marcin Jan; Aanesen, Svein Viggo; Øye, Gisle.
"Combined Influence of High Pressure and High Temperature on the Removal of Crude Oil from Water during Laboratory-Scale Gas Flotation".
Energy & Fuels; Volume 37; Page 5644-5651; 2023.

Rutkowski, Gregory Philip; Azizov, Ilgar; Unmann, Evan; Dudek, Marcin; Grimes, Brian Arthur.
"Microfluidic droplet detection via region-based and single-pass convolutional neural networks with comparison to conventional image analysis methodologies".
Machine Learning with Applications (MLWA); 2022.

Savulescu, George Claudiu; Simon, Sebastien Charles; Sørland, Geir Humborstad; Øye, Gisle.
"Novel NMR techniques to assess the wax precipitation evolution in crude oil systems".
The 22nd International Conference on Petroleum Phase Behavior and Fouling; 2022-06-12 - 2022-06-17.

Savulescu, George Claudiu; Simon, Sebastien Charles; Sørland, Geir Humborstad; Øye, Gisle.
"Novel Nuclear Magnetic Resonance Techniques To Assess the Wax Precipitation Evolution in Crude Oil Systems".
Energy & Fuels; Volume 37; Page 291-300; 2022.

Vazquez, Oscar; Dudek, Marcin; Beteta, Alan; Øye, Gisle.
"Microfluidic Method to Investigate the Precipitation of Calcium/Magnesium Phosphonate Scale Inhibitor Complexes".
SPE International Oilfield Scale Conference and Exhibition; 2022-05-25 - 2022-05-26.

SEPARATION – PROCESS CONCEPTS

Ahmadi, Mahdi; Arne, Lindbråthen; Liyuan, Deng; Magne, Hillestad
"Subsea Membrane Dehydration Process with Zero Methane Loss".
The 28th Underwater Technology Conference; Bergen, Norway; 14-16 June 2022.

Asaadian, Hamidreza; Harstad, Sigurd; Stanko Wolf, Milan Edvard.
"Drainage Potential Curves of Single Tapping Point for Bulk Oil–Water Separation in Pipe".
Energies; Volume 15; Page 19; 2022.

Asaadian, Hamidreza; Stanko Wolf, Milan Edvard.
"An Experimental Study on the Effect of Gas on the Performance of a Multi-parallel Pipe Oil-Water Separator (MPPS). Gas & Oil Technology".
Showcase and Conference; 2023-03-13 - 2023-03-15.

SYSTEM CONTROL

Assumpcao Matias, Jose Otavio; Jäschke, Johannes.
"From-scratch development and improvement of a problem-based learning course: Nonlinear Model Predictive Control for Chemical and Biochemical Processes".
IFAC-Papers Online ; Volume 55; Page 174-179; 2022.

Assumpcao Matias, Jose Otavio; Myrvang, Frida Bakken; Jäschke, Johannes.
"Implementation of Extremum Seeking Control in an Experimental Lab-Rig".
IFAC-PapersOnLine; Page 137-142; 2022.

Assumpcao Matias, Jose Otavio; Oliveira, Julio 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; Volume 115; Page 181-196; 2022.

Assumpcao Matias, Jose Otavio; Yemane Ghebredngl, Salmon; Jäschke, Johannes.
"Health-aware control using hybrid models applied to a gas-lifted oil well network".
Computer-aided chemical engineering; Page 1135-1140; 2022.

Dirza, Risvan; Krishnamoorthy, Dinesh; Skogestad, Sigurd.
"Primal-dual Feedback-optimizing Control with Direct Constraint Control".
Computer-aided chemical engineering; Volume 49; Page 1153-1158; 2022.

Dirza, Risvan; Rizwan, Md; Skogestad, Sigurd; Krishnamoorthy, Dinesh.
"Real-time Optimal Resource Allocation using Online Primal Decomposition".
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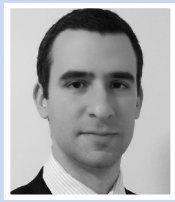

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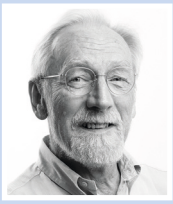
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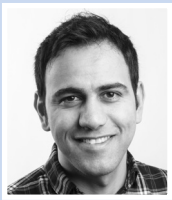
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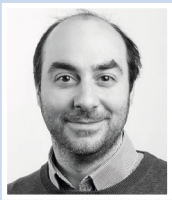
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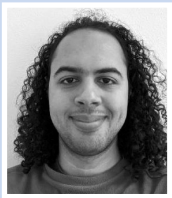
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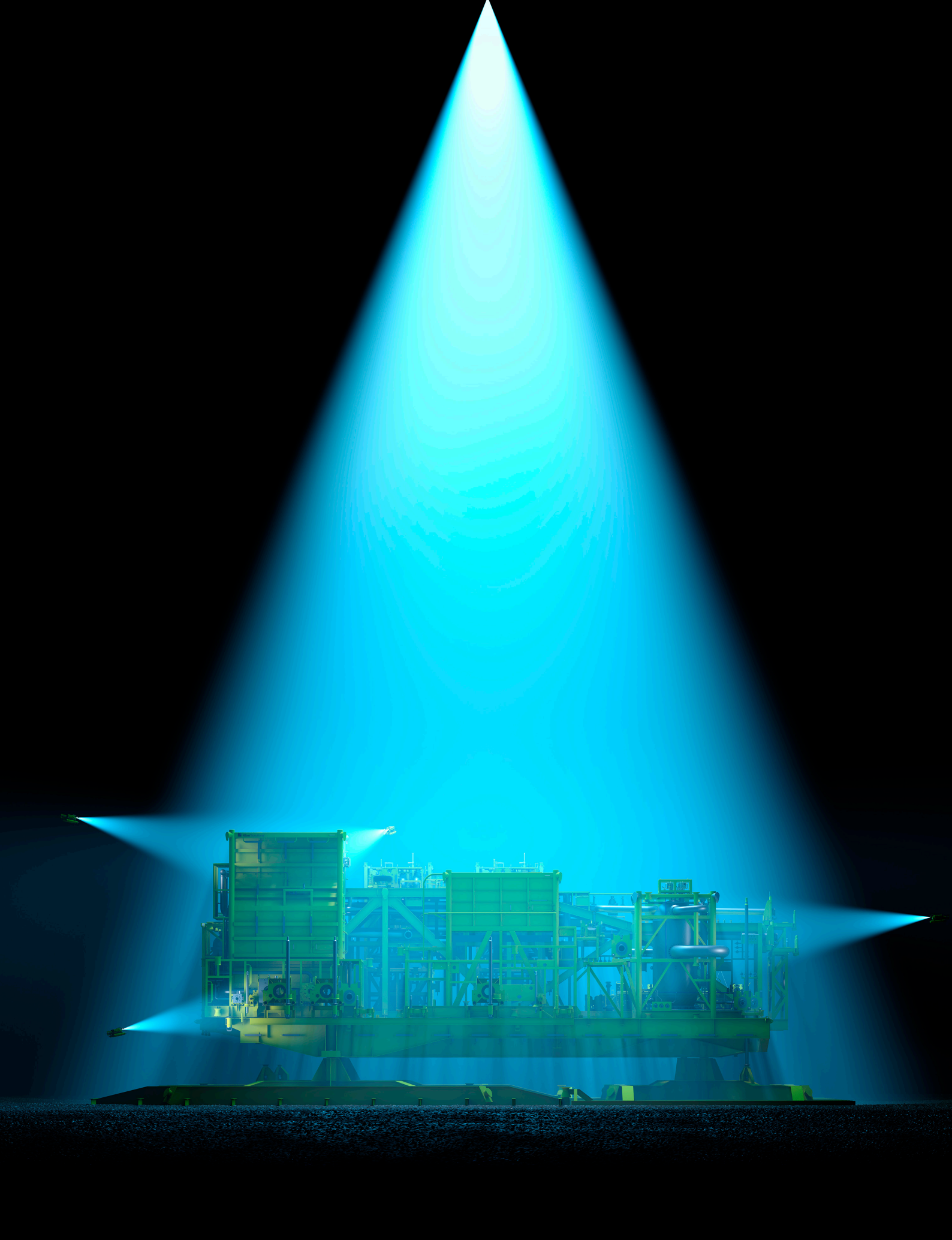

Subsea gas compression station. Courtesy of Aker Solutions.

SUBPRO

SUBSEA PRODUCTION AND PROCESSING

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

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