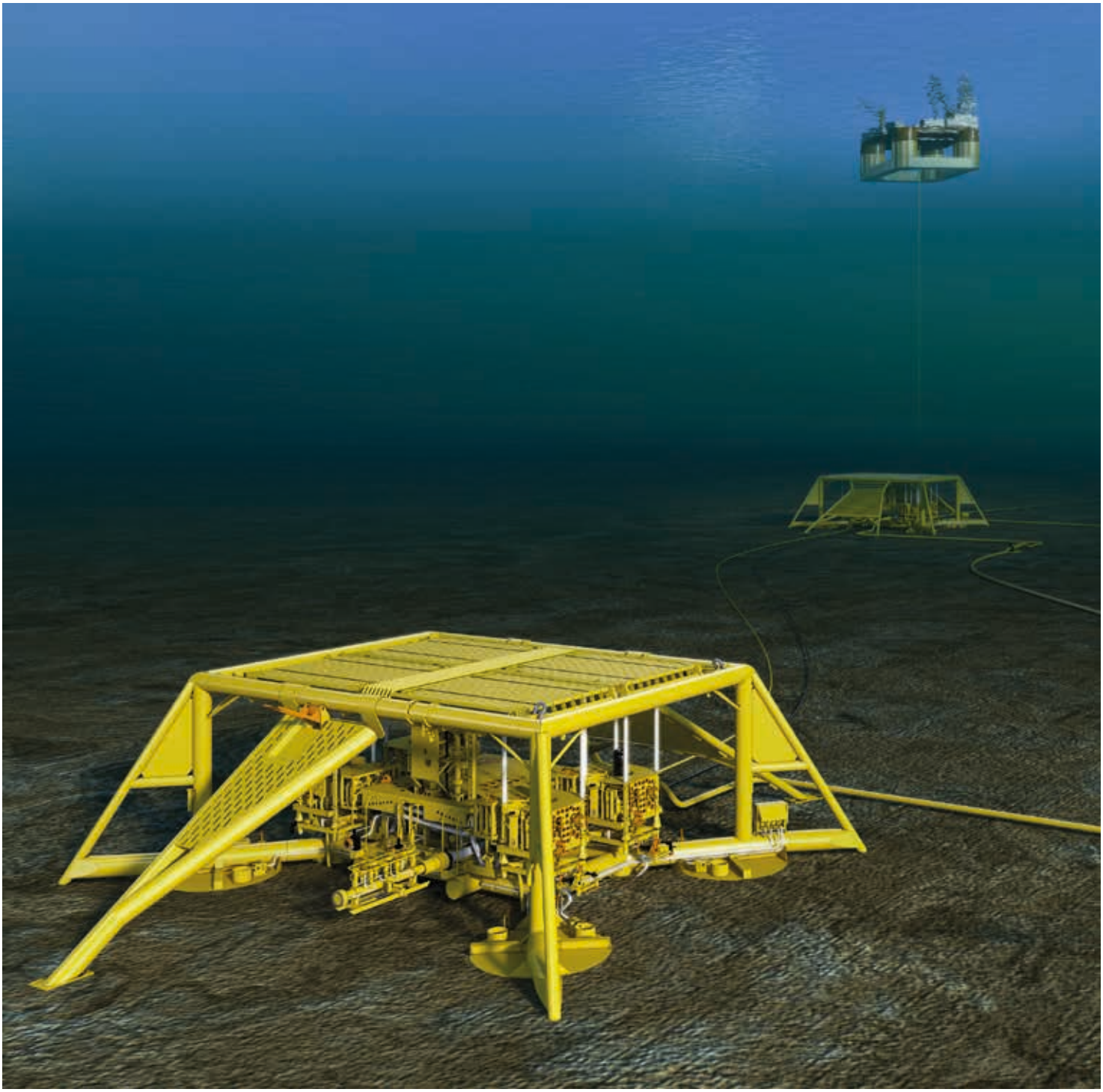
SUBPRO

SUBSEA PRODUCTION AND PROCESSING

Annual Report
2019
2020



sfi Centre for Research-based Innovation
Established by the Research Council of Norway

NTNU
Norwegian University of Science and Technology

What is SUBPRO?

SUBPRO is a centre for research based-innovation (SFI) funded by the Research Council of Norway and 8 industrial partners. Norwegian companies have been in the forefront of developing and implementing subsea technology for many years, and the purpose of starting up SUBPRO was to bring the academic community in Norway to a similar top international level in selected areas of subsea technology, and use this as a basis for further innovation in the industry. Subsea technology covers many areas, and in SUBPRO we focus on five main areas:

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

SUBPRO started up in August 2015, and we are now four and a half year into the planned eight years duration of the Centre. Almost all the research work is done at the Norwegian University of Science and Technology (NTNU) where SUBPRO has funded 25 full time PhD students and Postdoctoral fellows in 2019. In addition, 20 professors and 10 researchers contribute to the projects on a part time basis.

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

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

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

Why SUBPRO?

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

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

FUTURE CHALLENGES REQUIRE

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

Front page picture: Vega field. Courtesy of Equinor.

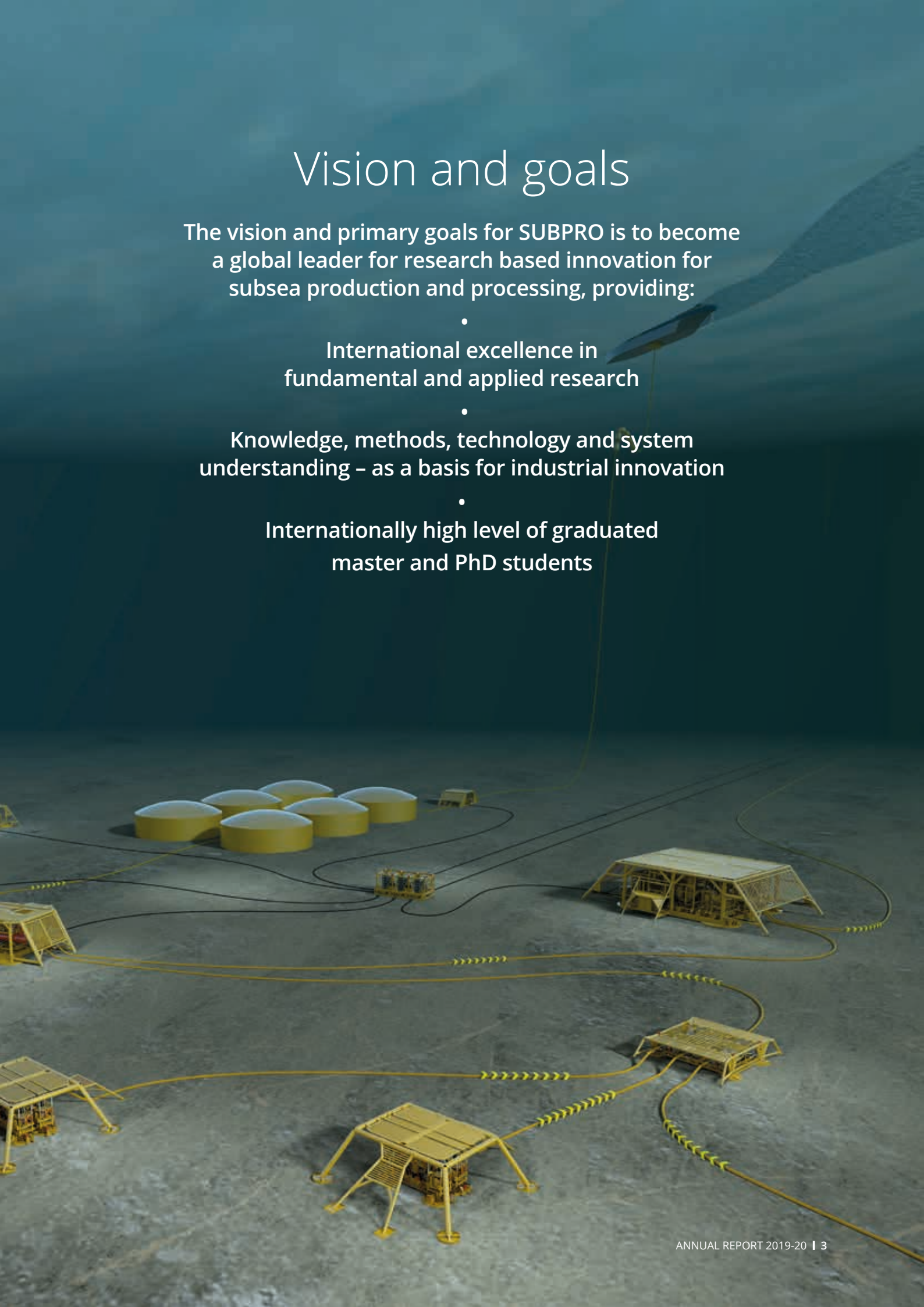
CONTENT

Subsea factory – Courtesy of Equinor

Vision and goals

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

- **International excellence in fundamental and applied research**
- **Knowledge, methods, technology and system understanding – as a basis for industrial innovation**
- **Internationally high level of graduated master and PhD students**



Chairman of the board

Norway has always been at the forefront of oil & gas technology developments and has today a leading global position within subsea technologies. Collaborations, innovation, boldness and early adoptions have been key to success. SUBPRO plays an important role in extending this past success into the future.

FRANK BØRRE PEDERSEN
VICE PRESIDENT AND PROGRAMME DIRECTOR DNV GL

CHAIRMAN OF THE SUBPRO CENTRE BOARD

The oil and gas history of Norway is one to be proud of. Based on engineering and operational competence from the maritime industry and a willingness to take risk, the Norwegian oil & gas industry was built up in the 1970s through collaborations, innovations, boldness and early adoptions of new technology. Today, around half of the production on the Norwegian Continental Shelf comes from subsea wells and the Norwegian subsea industry has achieved a leading global position. In the current situation with increased focus on reducing the environmental footprint and the need for reducing costs, subsea technology is more important than ever. Developing and qualifying new technologies for subsea production and processing will be an enabler for new developments and cater for more tie-ins to existing infrastructure. Such developments are attractive from both emissions and cost perspectives. And in the bigger picture this may also open for simpler topsides solutions that in some cases may even be normally unmanned.

Collaboration and innovation have been key in achieving this position within subsea. Through the Center for Research-based Innovation on Subsea Production and Processing (SUBPRO) the academia, operators, contractors and others have the opportunity to jointly address and solve research challenges and develop new innovations. Through such a collaborative approach the academia is guided by real industrial problems, and the industry is enabled to address fundamental problems holding back new business. Furthermore, this model involves partners from different parts of the value chain and thus cater for early adoptions by the participants and the industry in general.

SUBPRO is progressing well and 2019 was another good year. Important research has been carried out and new innovations have been developed. This is corroborated by the midway evaluation carried out by the Norwegian Research Council in 2019. SUBPRO received very positive feedback and I want to thank everyone in SUBPRO for their contributions to this achievement.

Another positive milestone for SUBPRO this year was the onboarding of new members. This year Total, Kongsberg, Aker Solutions and TechnipFMC joined as members and I wish them all very welcome onboard! Their expertise and contributions will be very valuable to SUBPRO.

A total of 15 new research projects have been approved in 2019, where 6 of them have already started by fall 2019. Going forward, the 9 remaining new projects will be important. They range from fundamental chemistry, flow improvements, remaining useful life estimations, low cost developments to applications of digital twins. They are scheduled to start during 2020, and they will all address the needs of the industry for both cost reductions and climate change improvements. I am very confident that these projects will be important in maintaining our strong position within subsea in Norway.

Centre director

We are now four and a half year into the planned eight-year duration of the SUBPRO project, and the progress is very good.

PROFESSOR
SIGURD SKOGESTAD

SUBPRO
CENTRE DIRECTOR

The midway evaluation from the Research took place in 2019 and SUBPRO got very positive feedback and all accounts. We have developed a close collaboration between industry partners and academia and are delivering scientific results with a high potential for industrial innovation.

As a Centre for research-based innovation (SFI), SUBPRO has two major goals; academic excellence and industrial innovation. There has some been changes in our industrial partners over the years, and we are happy that Total joined from July 2019 and Technip FMC from January 2020.

5 PhD candidates have graduated during 2019 and most of them are recruited by the oil and gas industry. During 2019 the work has resulted in 37 journal and conference papers. NTNU/SUBPRO educated 21 Master students in 2019, who specialised in various fields of subsea technology. We are happy to report that we are close to reaching the goal of 30% females among PhD students, Postdoctoral fellows and Master candidates. We are now in the last phase of the SUBPRO center and about 9 new PhD and postdoc projects are starting up in 2020.

SUBPRO takes part in an extensive international research collaboration. Our close cooperation with several leading universities in Brazil continues, partly through the INTPART program. We also have close cooperation with several other renowned universities throughout the world. We are also working closely with BRU21, a new oil and gas research program at NTNU, which presently has about 30 industrially funded PhD projects. The BRU21 model may be the basis for a possible extension of SUBPRO after 2023.

Just as this report goes to printing, the Corona virus has hit the world with full power and at the same time oil prices have dropped from 60 USD per barrel to less than 30 USD. The future is uncertain, but this is nothing new. The SUBPRO projects continue as planned, although from home offices at the moment, and we hope and expect that our partners will get through this and stay with us.

Partners

STATEMENTS FROM TWO OF OUR INDUSTRY PARTNERS

TRINE BOYER

RESEARCH & DEVELOPMENT SUB-SEAEXPLORATION & PRODUCTION

TOTAL E&P NORGE

What is the main motivation for Total to join SUBPRO?

- TOTAL continues to see Deep Water, Subsea oil and gas production as important in the future energy mix – together with renewable, sustainable and low carbon intensive energy supply. The competitiveness of subsea developments will depend on the industry's ability to implement efficient solutions. TOTAL see that Subsea technology and Subsea Processing will potentially be important contributors to achieve this. SUBPRO's focus on Subsea technologies is therefore of interest for TOTAL and is well aligned with the group's strategies. It is important to cooperate with academia and to support the basic research in a subsea context to gain deeper knowledge. SUBPRO will contribute to this and will as well educate and provide PHDs and Master students that will ensure the future for this business.

Total joined SUBPRO in 2019.

JOSTEIN KOLBU

SENIOR MANAGER SUBSEA PROCESS

AKER SOLUTIONS

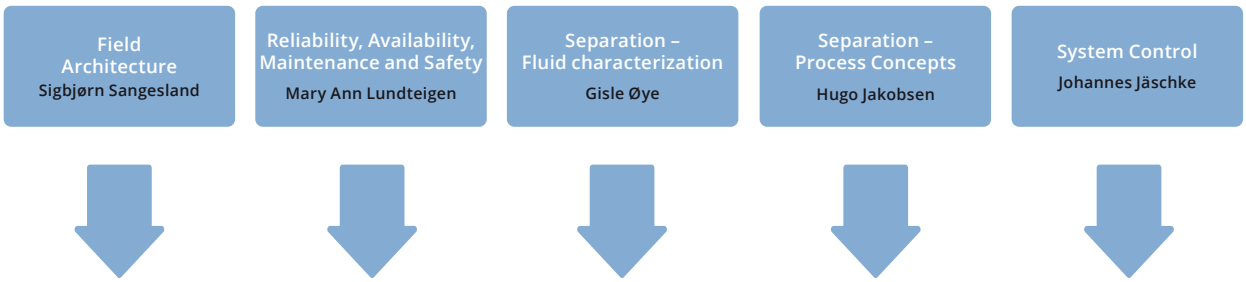
What is the main motivation for Aker Solutions to join SUBPRO?

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

Aker Solutions re-joined SUBPRO from 2019.

Project structure

RESEARCH AREAS



CURRENT PROJECTS

The subsea gate box	Performance management of safety-critical systems at unmanned facilities	Influence of production and EOR chemicals on produced water quality	Membranes for gas dehydration	Automatic control of subsea separation
Optimization of subsea systems with processing equipment	Optimizing condition monitoring	Re-injection of produced water - dispersion in porous media	Mechanistic modeling of fluid particle breakage	Enhanced virtual flow metering
Field development concepts	Associated project: Safety 4.0 Demonstrating safety of novel subsea technologies	Gas flotation for subsea produced water treatment	Experiments on fluid particle breakage	Control for extending component life
Methods for minimizing cost and risk in subsea field development		A digital twin library for oil/water emulsion separation and transport processes	H_2S and hydrate control	Validation of methods for optimizing remaining useful life
			Compact separation	Field-wide production optimization
				Associated project: IKTPLUSS Production optimization under uncertainty
				Novel approaches to online process optimization under uncertainty
				Modelling and multivariable control of subsea systems
				Adaptive control of subsea processes

PROFESSOR
SIGBJØRN SANGESLAND

RESEARCH AREA MANAGER

RESEARCH AREA

Field Architecture

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

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

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

Specific industrial and research challenges and goals:

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

Three business cases with relevant data and information are formulated to guide and narrow the scope of the R&D work. They represent reference oil and gas fields with current gaps and challenges to subsea production and processing:

Case 1: Gas field with low Gas Oil Ratio (GOR)

Case 2: Remote, low energy oil field (typical example: Barents Sea)

Case 3: Oil field with future tie-ins

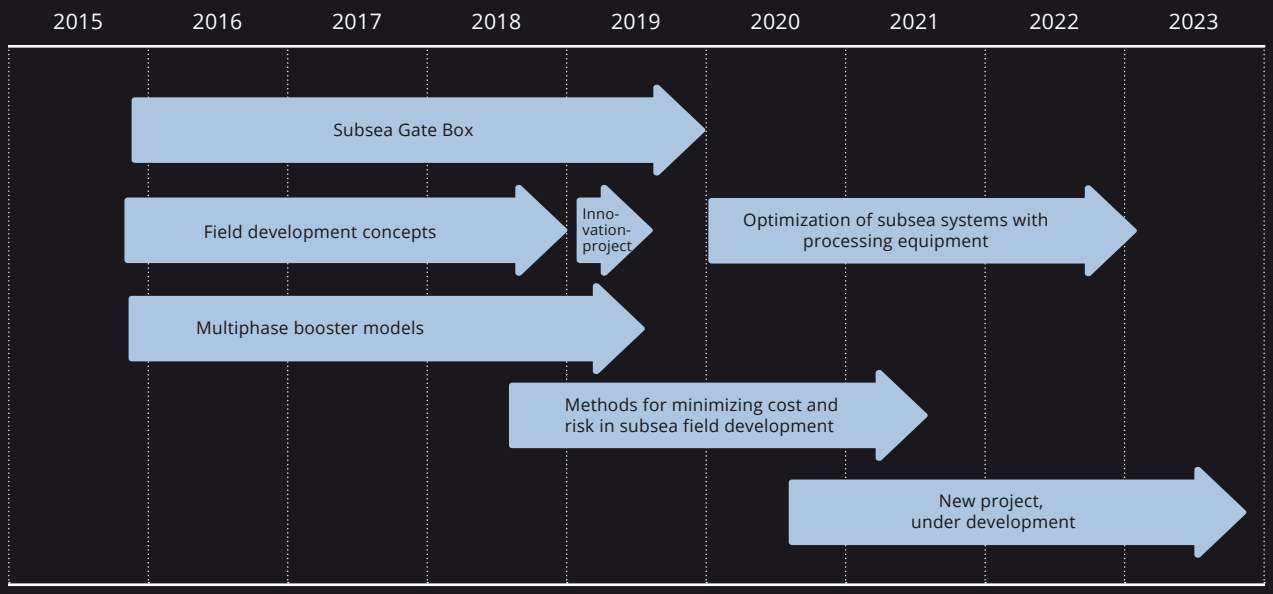
PROJECTS OF FIELD ARCHITECTURE
During 2019, two PhD projects have been completed:
- Field development concepts
- Multiphase booster model

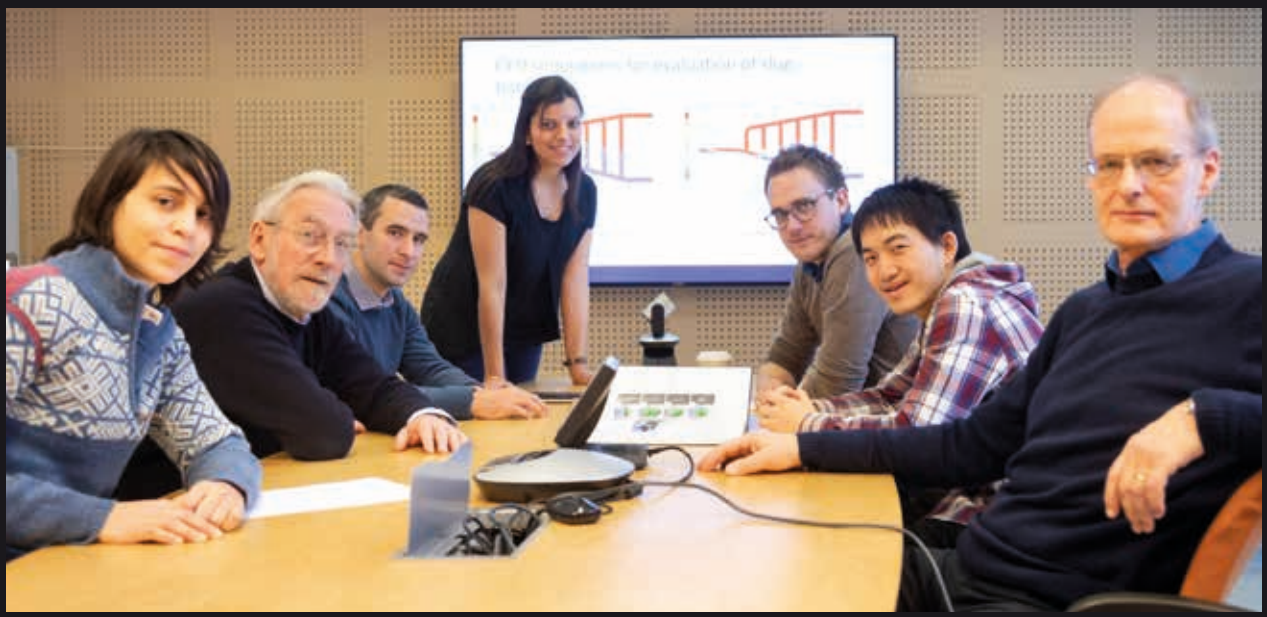
One new project has started up
- Methods for minimizing cost and risk in subsea field development

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

Consult page 60, for new projects with kick off planned in 2020.

Completed, current and planned projects





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

The Subsea gate box

A possible way to enhanced production.

Green shift impact: The Subsea Gate Box (SGB) could contribute to energy efficiency by improving the individual performance of the subsea processes and equipment.

Postdoc: **Mariana Diaz**

Project manager:
Professor
Sigbjørn Sangesland

Co-supervisor:
Professor
Sigbjørn Sangesland and
Associated Professor
Milan Stanko

MOTIVATION

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

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

THE SUBSEA GATE BOX: A NEW WAY TO ENHANCE PRODUCTION MANAGEMENT FLEXIBILITY

The subsea gate box (SGB) in Figure 1, is a novel concept that opens the opportunity for increasing the production management capability along the subsea facilities network and over the lifetime of the field. The project aims to evaluate the SGB concept in terms of its applicability and contributions within subsea field developments. Our partners and specially Equinor, AkerBP, Aker Solution, and Lundin haven been a key element to outline the scope of the project and identify the necessities of the industry in this area.

The project execution has been divided into four main stages: feasibility analysis, technology evaluation, concept definition and design methodology.

1 During the feasibility analysis, a performance evaluation of the SGB was carried out using an integrated production model for a synthetic case. The study demonstrated the possibility to increase the overall production by around 10% when comparing the SGB to a typical central boosting station.
2 As part of the technology evaluation, a Computational Flow Dynamics model was developed for a pipe-type gas-liquid separator that can be used in the SGB. The model offers an interesting tool to explore the performance maps and separation efficiencies for such separators. The publication of this study has contributed to expand understanding of this type of separator and make it available for the public domain.
3 For the concept definition stage, part of the analysis contemplated the cost evaluation of installing different SGB assemblies in different field layouts. The study has shown that by using the SGB it may be possible to increase the oil production such that the life cycle costs per barrel could be comparable or lower than with the centralized solutions, with the advantage of improving the system flexibility.
4 The final stage of the project is addressed to develop a methodology framework for screening process functionalities on the SGB and its location along the field layout within a given subsea field development. There is an ongoing work to develop an evolutionary algorithm to support automatic case screening and optimization. The algorithm may open the opportunity to enhance designs and decision-making process when it comes to evaluating subsea processing for new developments or for future modifications of brownfields

HOW THE PROJECT RESULTS COULD BE USED

The subsea gate box might be an alternative solution for field developments that include large heterogeneity among different producing regions. The project results include a compendium of master theses, technical reports and scientific papers that outline the principle of the concept as well as their advantage and limitations. Such compendium could be used as reference material for defining new strategies within the field development. Furthermore, the design methodology under development could be used to generate future computational tools to use through the asset development phase.

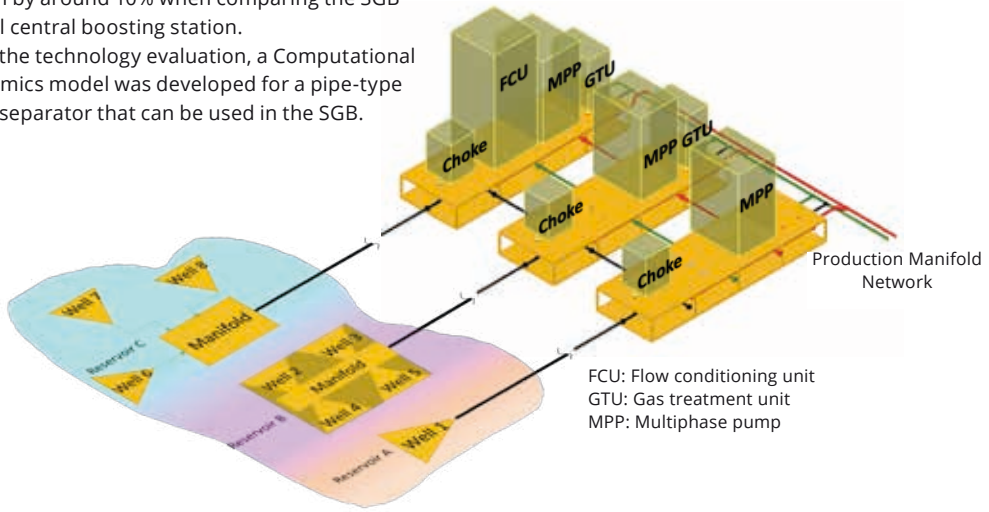


Figure 1. Subsea gate box concept targets different well configurations (satellite, clusters or template). Each module of the SGB will offer the opportunity of handling the different streams according to their own specific operating conditions by means of customized processing trains over the lifetime of the field.

Optimization of subsea systems with processing equipment

Developing better methods for early planning of subsea systems with subsea processing.

GREEN SHIFT IMPACT: Increasing production and reducing environmental footprint for a more sustainable industry.

PhD student
Leonardo Sales

Project manager:
Prof. Milan Stanko
Supervisors:
Associate Prof. Milan Stanko and Associate Prof. Johannes Jäschke

1. BACKGROUND FOR THE PROJECT/ WHY ARE WE DOING THIS RESEARCH?

Worldwide, the oil and gas industry has the ambition to expand the use of subsea processing in existing and future fields, as it has found that in order to reduce environmental footprint and increase profits, surface facilities must be kept to a minimum or eliminated. This ambition impacts offshore field development decisions, which are complex, based on uncertain data, and involve multibillion-dollar investments and human resources, especially when employing relatively new technologies such as subsea processing. A crucial task in field development is to design the subsea field layout, which is directly linked to well productivity, ultimate recovery, flow assurance, and capital and operating costs. To improve field layout while considering uncertainties, we propose to develop robust stochastic methods for field layout optimization with subsea processing.

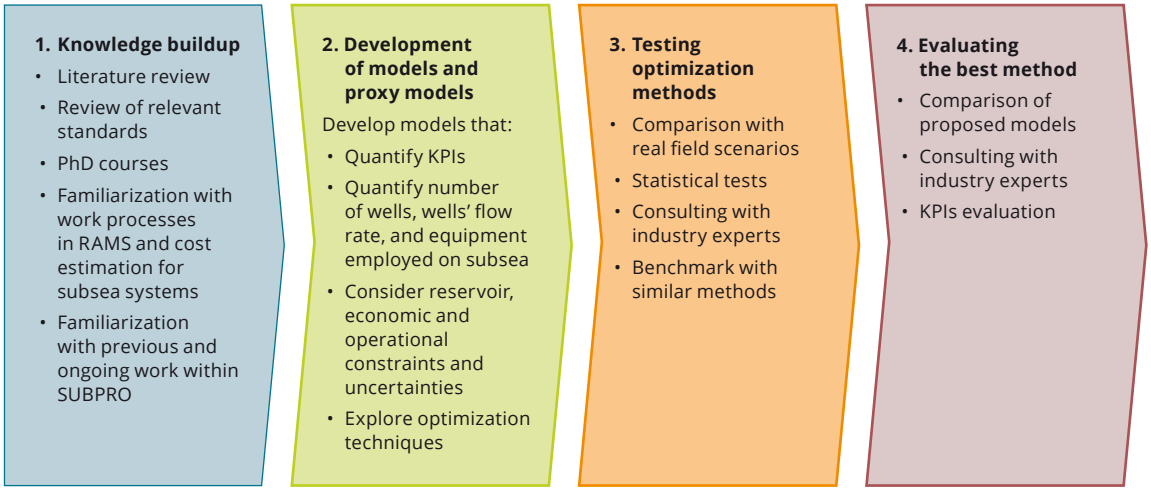
2. WHAT I HAVE DONE

To achieve this goal, a thorough literature review will be conducted, along consulting with our industry partners to determine an effective and practical approach to the problem. Methods and results of previous research within SUBPRO will also be taken into account. More details of the proposed research activities can be found in Figure 1. Extensive work will be performed to:

- Develop a methodology to early plan the use of subsea processing equipment and its deployment schedule in order to maximize system performance and reduce cost.
- Define the number of wells and their flow rate in an optimum manner considering economic, operational and reservoir uncertainties and constraints.
- Study, analyze and consider key performance indicators (KPIs) used in subsea systems, such as availability, reliability, hydrocarbon production, and environment-related indicators.

3. MAIN RESULTS AND HOW CAN THEY POSSIBLY BE USED BY THE INDUSTRY

We expect to obtain a subsea layout optimization model that enables an objective comparison of alternatives and provides a more scientific, quantitative and probabilistic approach for the subsea layout problem. This manner, the industry can benefit from a more standardized and streamlined approach for subsea layout, while redirecting thousands of working hours saved due to the automation of subsea layout procedure to more engineer-intensive tasks. Besides, the optimization of the subsea layout may obtain solutions with a higher NPV and reduced environmental footprint, otherwise overlooked by other methods. As the proposed model will be a series of objective procedures, it can easily be modified in the future to accommodate new challenges, improve the understanding and modelling of specific issues, or serve as a baseline for analogous problems.



Field development concepts

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

PhD student:
Diana Gonzáles

Project manager
and
main supervisor:
Associate professor
Milan Stanko

BACKGROUND

The purpose of field development planning is to identify the most efficient strategy in exploiting an asset by finding concepts that are technically feasible and provide the best economic performance. The need to refine the methodologies to provide decision support to field development has increased in the current era of the petroleum industry. Newly discovered reservoirs and the associated development schemes are becoming more challenging. Therefore, providing simple, structured, and transparent decision methodologies is strongly required.

METHODOLOGY FOR DECISION SUPPORT DURING EARLY FIELD DEVELOPMENT

The objective of this project is to create better methods for decision support in feasibility studies and concept planning phases of oil and gas field development.
The method employs proxy models to represent the production performance of the integrated production system, which allow estimating production profiles without having to run the coupled model each time target rates are varied. Cost figures are estimated using models obtained from linear regression of cost data points. Mathematical optimization is used to find production and drilling schedule that maximize NPV for a specific field development strategy. Finally, the effect of uncertainty and several design alternatives is quantified using probability trees. The workflow of the methodology is presented in Figure 1.

AUTOMATED METHODOLOGY FOR CONCEPT PLANNING/ENGINEERING DESIGN

The method was evaluated on field-scale data from the Barents Sea Wisting field, which is currently under predevelopment study phase. This methodology allows to obtain optimum early field design features in an automated fashion within practical running times. At the same time, it ensures global optimality and takes uncertainty into account. The results at the end of the study and the testing of the results provide a template and an input for developing a commercial software package for performing structured feasibility studies and concept planning during the engineering design of oil and gas fields.

INNOVATION AND COLLABORATION WITH INDUSTRY PARTNERS

The PhD project has been followed up by a 6-months innovation project, which consisted of creating a server-based tool with a user-friendly interface that allows engineers and field planners to use the method for their cases. This allows for SUBPRO partners and other companies to test the methodology with their data and to validate and improve the methodology generated in the PhD project. The tool has been completed successfully and it is available for partners to download.

In addition, a 2-months collaboration with Aker Solutions has followed up the innovation project with the objective to implement parts of the server-based tool in their field planner cloud application. The current task is to develop a production profile generator based on well's production type curves. Aker Solutions has shown great interest on this project and has indicated that it brings new working processes that are not currently used during early field planning that could create significant value.

MY NEW JOB

Diana is currently looking for new opportunities and eager to work for and make significant contributions to the industry.

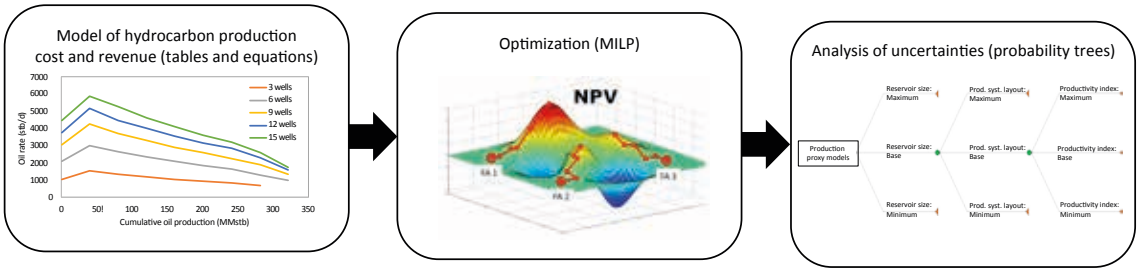


Figure 1. Workflow of methodology to use optimization in field design

Methods for minimizing cost and risk in subsea field development

The location-allocation problem of manifolds and well positions – from MINLP to BLP.

PhD student:
Haoge Liu

Project manager and main supervisor:
Professor
Tor Berge Gjersvik

Co-supervisors:
Prof. Audun Fannes (Equinor)
Prof. Sigbjørn Sangesland

BACKGROUND FOR THE PROJECT/ WHY ARE WE DOING THIS RESEARCH?

Field development work processes are iterative and dependent on manual input of data and compilation of total cost of a given layout. Besides, layout optimization is one of the hardest engineering problems if we want to achieve the exact global optimal. Therefore, a scope has been raised aiming to improve these work processes and to save time on the engineering in early abstract phases. The project will develop an efficient method to achieve the global optimal layout with the flexible input of user-defined cost.

NEW METHOD TO GUARANTEE THE GLOBAL OPTIMAL IN LESS COMPUTATIONAL TIME

- We found that the "size-constrained clustering problem" defined in data science and the "location-allocation problem" defined in operations research are relevant basis for our subsea field layout optimization problem.
- We tried various existing methods and model our layout optimization problem as a mixed integer nonlinear programming (MINLP) formulation or a mixed integer linear programming (MILP) formulation, but found that none of the existing methods can guarantee the global optimal at a low or even an affordable computational time cost for the layout optimization for a subsea field of a moderate size.
- We successfully developed a new method converting the original MINLP formulation into a simpler binary linear programming (BLP) formulation which is much easier to solve. Our new method can guarantee the global optimal of the problem while consuming less computational time. The comparison with commercial solvers proves the unparalleled advantage of our method.
- Two master students have started to build practical cost functions of the well construction and subsea facilities. These cost functions will be fed into our method for more realistic case studies.

A GENERIC SOLVER FOR LOCATION-ALLOCATION PROBLEMS

An example shows the results of a simple case where there are 40 wellheads randomly distributed on the sea-bed. In the example case, we use 10 off 4-slots manifolds to connect them while ensuring the total tie-back cost to be minimum. The cost function, i.e. the tie-back cost of each segment is here assumed to be square of the distance between the wellhead and the manifold. The table shows the comparison between our method and the commercial solver (LINGO), including both its local optimal solver and its global optimal solver.

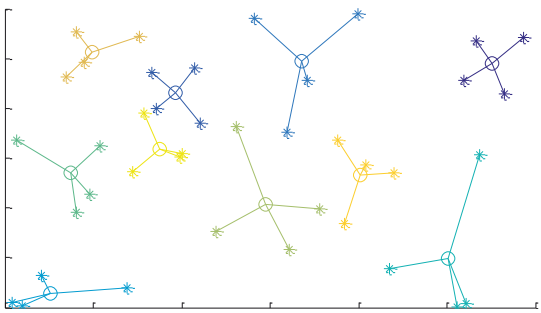
It should be noted that practically the cost function is much more complicated. The advantage of our method is that its high efficiency is completely irrelevant with the cost function. When we are dealing with a real case, we can just input any reasonable user-defined cost function.

The new method can drastically shorten the field layout designing phase in subsea development, meanwhile it can provide the best solution which any empirical method can never provide.

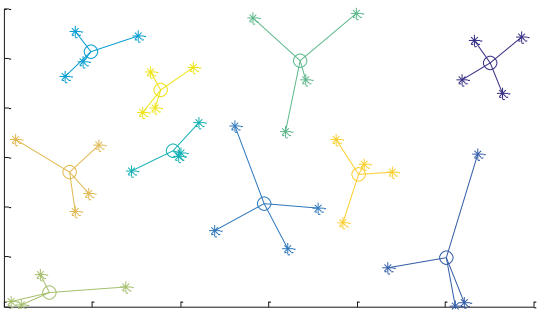
Additionally, our new method is actually a generic solver for the location-allocation problem. It is thus expected that the method can be utilized in a variety of industries facing similar resource allocation challenges.

Equinor participates actively in the research through technical advice and co-supervision.

	LINGO/local	LINGO/global	Our Method
Optimal Cost	1020.51	Infeasible	1010.96
Global Optimal (Y/N)	N	Infeasible	Y
Computational Time	751s~850s	>8h	0.32s~0.36s



(a) Result by LINGO



(b) Result by Our Method
Subsea field layout with ten 4-slot manifolds

PROFESSOR
MARY ANN LUNDTEIGEN

RESEARCH AREA MANAGER

RESEARCH AREA

Reliability, Availability, Maintenance and Safety (RAMS)

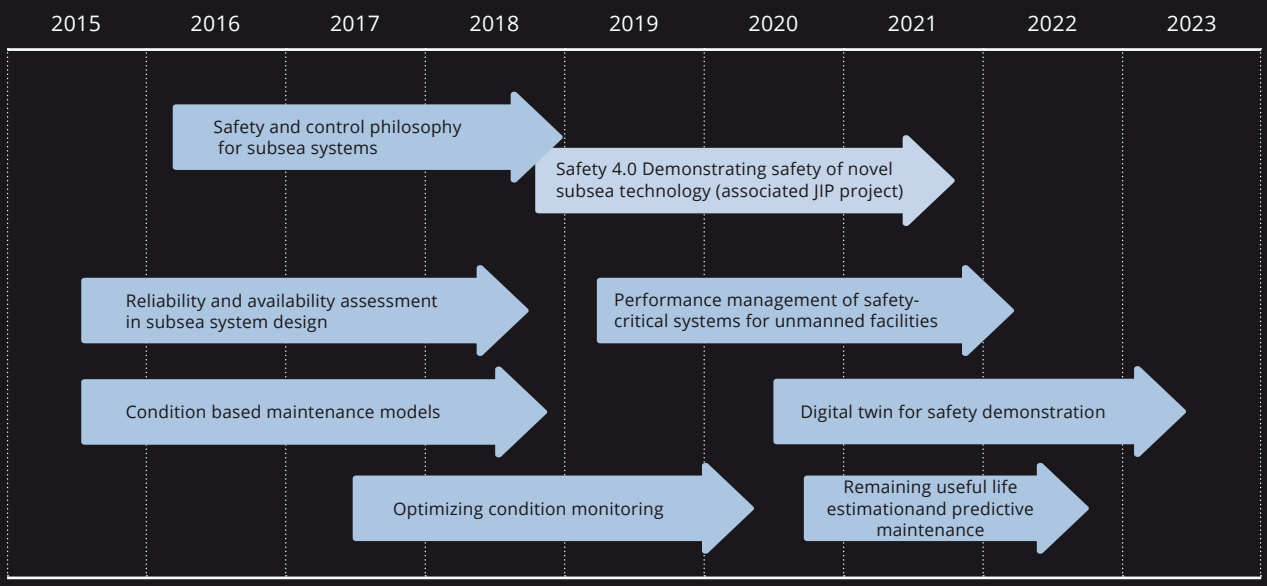
Cost efficient solutions without compromising safety and environment.

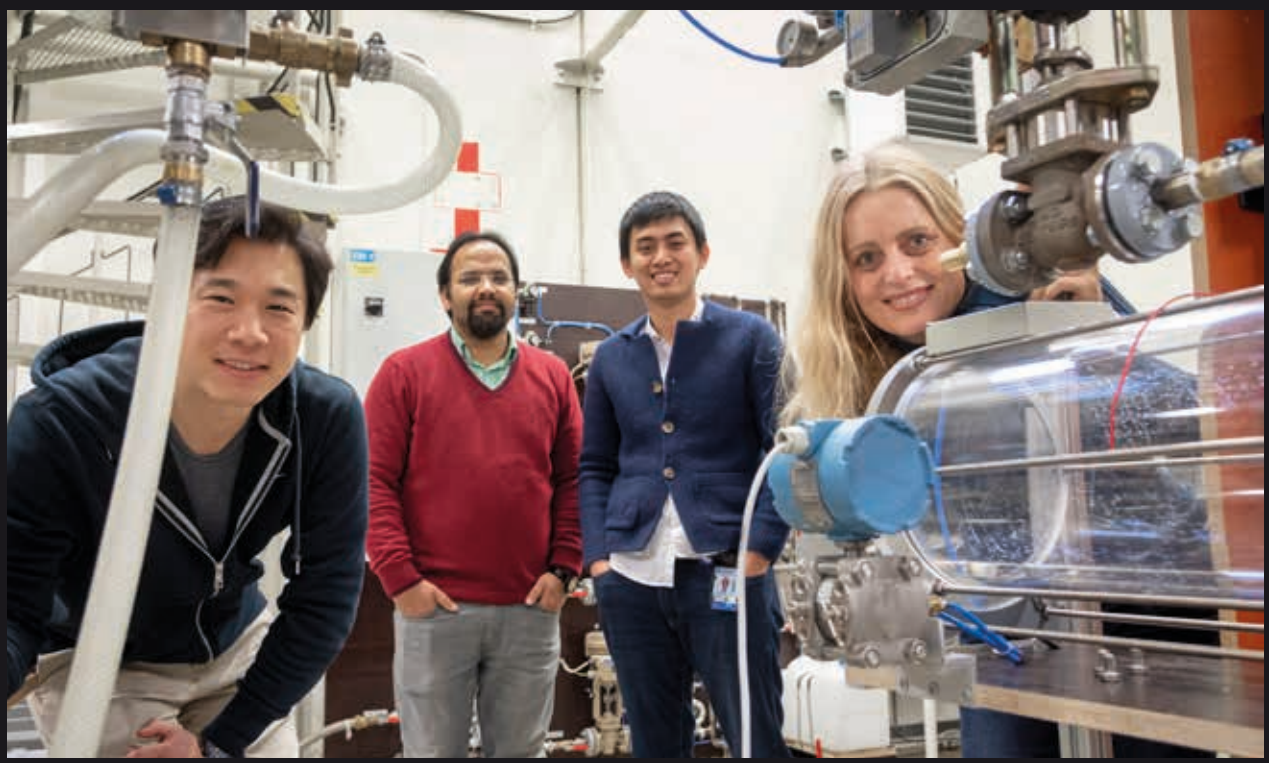
2019 was a year for the continuation of ongoing research and initiation of new research within the established topics of the RAMS research area. In the spring, we received a guest researcher, Professor Markus Glaser from the Aalen University in Germany, whose collaboration resulted in a new joint project on digital twin for safety demonstration, with industry use case all-electric subsea control system. Professor Glaser has headed several projects in the area of subsea all-electric systems in Germany. The RAMS area also developed an innovation project proposal on estimation and optimization of remaining useful lifetime, a project with the aim to deploy and further develop results from a finalized project on condition-based maintenance planning. Both proposals were approved in the end of 2019 and will start up in 2020. This means that the collaboration with Aalen university will continue.

The ongoing project on optimizing condition monitoring with PhD candidate Himanshu entered the last stage at the end of 2019, with planned submission of PhD thesis in mid 2020. At the end of the year, a new project started up on performance management of safety-instrumented systems for unmanned facilities with restricted access started up, with PhD candidate Tae Hwan from South Korea. As a kick-off to this project, DNV-GL, Equinor, Aker Solutions and NTNU arranged a workshop on 29th of October to gather the most recent industry status and view on challenges. It included invited presentations from OG21, Petroleum Safety Authority, and invited partners as well as groupwork, and partners from SUBPRO as well as the SUBPRO associated project Safety 4.0 (headed by DNV-GL) were invited. In total, around 50 participants joined the workshop which took place in DNV-GL offices at Høvik, Oslo. This is a good evidence of the strong collaboration established between Safety 4.0 and SUBPRO RAMS area.

I would conclude the summary of this year by expressing our appreciation to Professor Anne Barros for her significant contributions to SUBPRO since the start of the Centre period. Professor Barros received a new full professorship at Centrale-Superlec in Paris from 2020, as a chair and team head of safety and risk research group. SUBPRO RAMS area will continue to seek opportunities for collaboration with her and her strong team. We also hope to welcome a new professor funded by DNV-GL in the RAMS area in 2020 and use this opportunity to strengthen the momentum of research and industry collaboration.

Completed, current and planned projects





The Reliability, Availability, Maintenance and Safety team.
From left : PhD student TaeHwan Lee, PhD student Himanshu Srivastav, PhD student Nanda Anugrah Zrikullah and professor Mary Ann Lundteigen.

Performance management of safety-critical systems at unmanned facilities with restricted access:

"To formalize decision-making processes and needs related to safety-critical systems for unmanned facilities, and to propose suitable methods for data analysis to support performance management of safety-critical systems."

Green shift impact: Unmanned facility has a great potential of oil and gas production with low cost/carbon, and development of SIS performance management system that satisfies new requirements for an unmanned facility will greatly support in early adaptation and stabilization of such technology.

PhD student:
TaeHwan Lee

Project manager:
Prof. Mary Ann Lundteigen

Supervisors:
Prof. Mary Ann Lundteigen,
Prof. Gunleiv Skofteland (Equinor)

BACKGROUND

Performance management of safety instrumented systems (SIS) 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, manually carried out, and dependent on local presence of humans at the facilities. For some of the future oil and gas facilities in offshore that are to be completely unmanned, 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 and event data from multiple monitoring systems.

RESEARCH ACTIVITIES AND DELIVERABLES

Key purpose of this research is to research and develop how data analytics and other techniques can be utilized to improve SIS performance management system for unmanned facilities to reduce resource demand while maintaining or enhancing safety level.

Gap analysis will be performed by surveying literatures on currently available or existing system and by doing research on desired system. Literature survey will be done on various applications in both areas of academy and industry such as company standards, regional regulations, new products, review articles on journal or conference proceedings, and so on.

An industry joint seminar was held on 29/Oct/2019, titled "Safety-instrumented systems for unmanned facilities with restricted access", to share concerns and understandings, which will be a good input from industry.

Main research questions would be on:

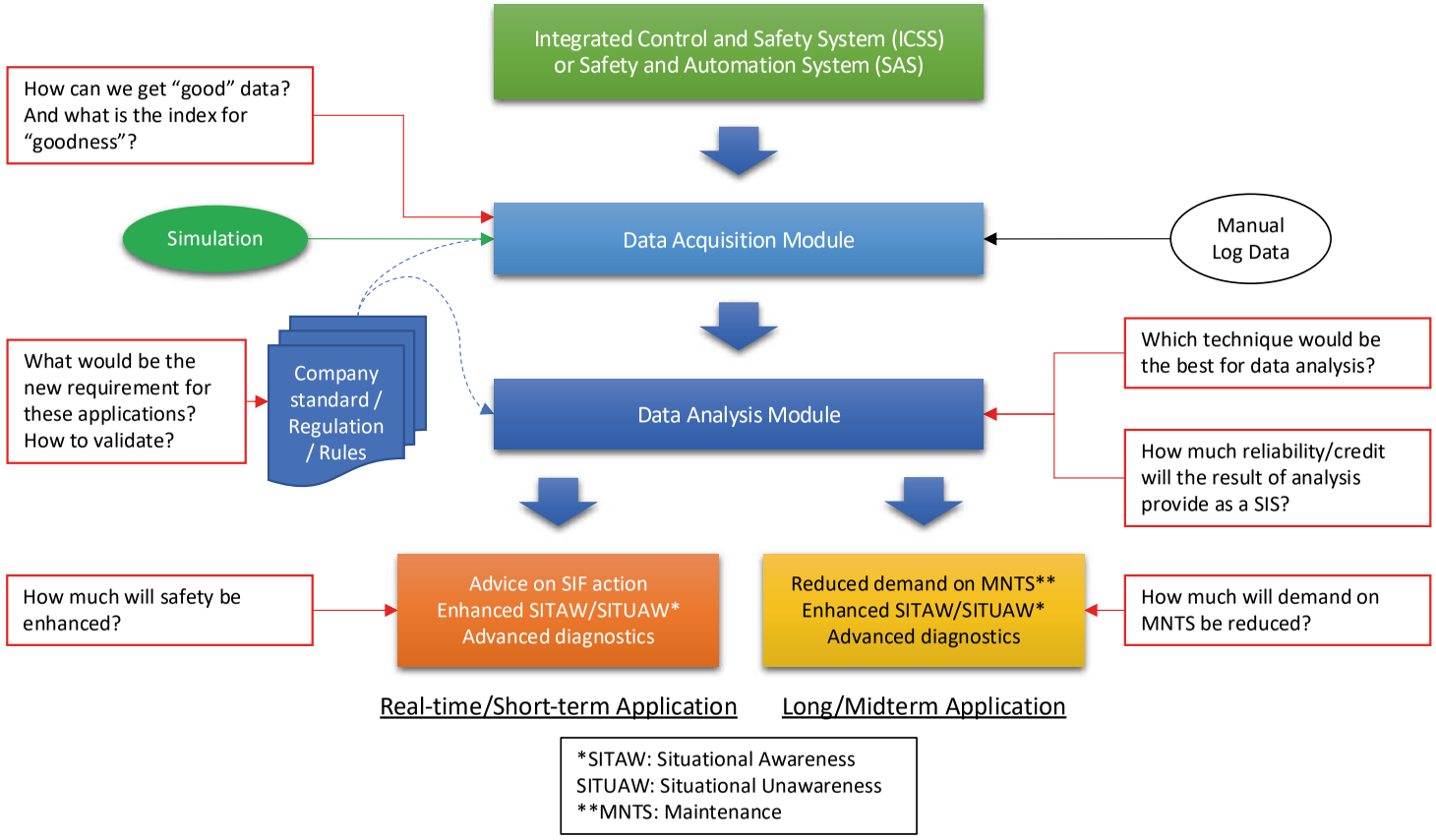
- Data analytics as a solution
  - o Why data analytics?
  - o Best data analytics techniques?
  - o How will the solution provide "enhanced safety with reduced efforts?"
- How to define system requirement from functional necessity and to validate it in an application of
  - o Long/mid-term duration (e.g. maintenance demand analysis and prediction system)
  - o Short-term duration or real-time (e.g. supporting tool in SIS decision making)
- Key performance index in decision making and demand analysis
  - o How to ensure reliability of data analytics?
  - o What is "good" data?
  - o How much maintenance demand or cost can be reduced via this solution?

It is also planned to seek collaboration within SUBPRO Center, starting from RAMS group, to create synergy.

INDUSTRY PARTICIPATION

Currently, Equinor and DNV GL are participating actively into this project, and more potential collaboration with other industry partners are under exploration within SUBPRO.

Result of this research can be used in pilot plant to boost up early adaptation and stabilization of unmanned oil and gas platform technology which has great potential in low cost/carbon oil and gas production.



Proposal of SIS Performance mangement system

Optimizing condition monitoring

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

PhD student:
Himanshu Srivastav

Project manager and main supervisor:
Professor Anne Barros

WHY THIS PROJECT

Condition based maintenance is very promising strategy for management of subsea facilities from a cost and safety perspective. The implementation of condition-based maintenance relies on several interacting steps including data collection, data processing, prognostics and decision-making for optimization.

The aim of the project is to focus on the first steps dedicated to data collection and data processing, on inspection and condition monitoring. Currently, there is a lack of knowledge and methods for optimizing monitoring schedules and efficient use of available condition data in subsea systems.

WHAT WE ARE DOING

The research questions we propose to address are:

1. For a given a for condition monitoring and inspection programme, what is the value of added condition information for future decision making?
2. What are the most efficient ways to build models that utilize existing (even poor) data collected from subsea equipment?
3. How can data intentionally not collected for condition monitoring be utilised in such models?

PROGRESS SO FAR:

In this project year 2019 was dedicated to successful collaborations with internal and external partners of subpro. Following is achieved from these collaborations:

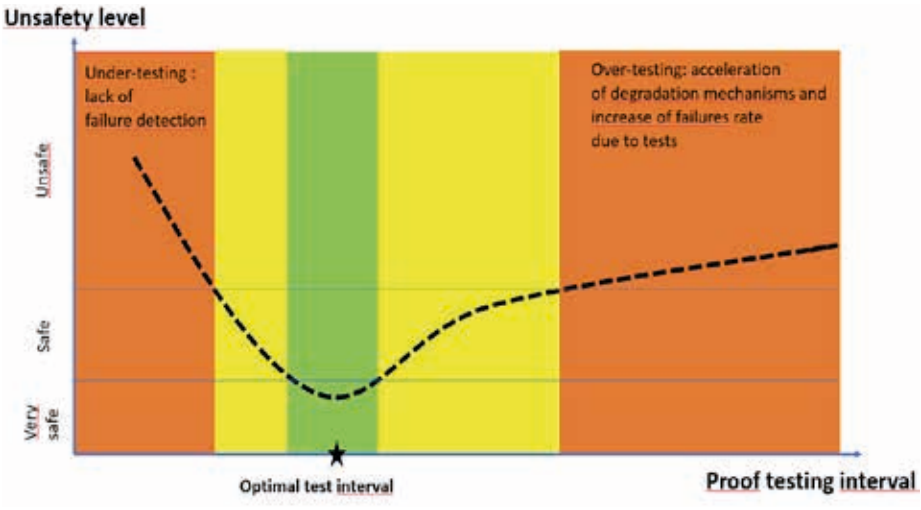
a. The research work carried out in collaboration with DNV-GL on shut-down valves in low demand mode successfully published. Such systems are submitted to periodic tests that, as a side effect can degrade the condition of system components. The goal for the case study was to find the optimum testing frequency, which balances the added value of frequent testing versus the negative (see illustration)

b. Master thesis from two master students under co-supervision from Equinor were delivered. One of them was on the topic of condition monitoring and prognosis of remaining life for a heat exchanger, the other one was related management of sensors batteries for condition monitoring.

c. Collaboration with another SUBPRO project "Control for extending component life" from System Control group resulted in developing a framework for integrating deterministic control laws and stochastic degradation models in the presence of various maintenance strategies. Based the proposed framework case studies were performed on subsea oil and gas production and processing system.

FUTURE PLANS

The main plan for the year 2020 is to extend the research studies performed on safety instrumented system operating in low-demand mode operation to high demand mode of operation. The main challenge envisaged here is to quantify the degradation caused by experiencing the random demand.



Trade-off between added condition information and increased wear.

Demonstrating safety of novel subsea technologies

An associated Safety 4.0 project.

PhD student:
Nanda Anugrah Zikrullah

Main Supervisor:
Professor Mary Ann Lundteigen
Co-Supervisor:
Associate Professor Hyungju Kim (Usn)
Meine J.p. Van Der Meulen (Dnv Gl)

Project manager
Tore Myhrvold DNV GL

INCREASED DIGITALIZATION OF EQUIPMENT – A MAJOR CHALLENGE FOR SAFETY DEMONSTRATION

The collaboration between industry partners and NTNU in SUBPRO on reliability and safety has led to the development of a new independent R&D project outside the Centre, which is closely related to the topics of SUBPRO. The project is named "Safety 4.0 – Demonstrating safety of novel subsea technologies" (visit: https://www.dnvgl.com/research/oil-gas/safety40/). The new joint-industry research project is headed by DNV GL and involves NTNU, University of Stavanger, and eight industry partners, of which five are current members of SUBPRO. The project is funded by the Petromaks 2 program and the partners. The R&D project was awarded by the Research Council of Norway and started up in the second quarter of 2018.

THE PETROLEUM SAFETY AUTHORITY TAKES AN IMPORTANT ROLE AS AN OBSERVER THROUGHOUT THE WHOLE PROJECT.

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

The objective of the Safety 4.0 project is to enable and accelerate uptake of novel subsea solutions by developing a framework for standardized demonstration of safety. This is done by developing a new safety demonstration framework, which is: modular, facilitating reuse of safety arguments, risk-based, and addressing safety from a systemic and life cycle perspective. The framework is developed based on relevant use cases together with industry partners: i) all-electric safety systems, ii) integration of process control and safety, and iii) safety demonstration based on API RP 17 V. The intermediate results are expected to be of direct support to the partners decision-making and concept selection.

PHD PROJECT – ENSURING FUNCTIONAL SAFETY OF NOVEL TECHNOLOGIES

The project has been dedicated to develop a method for safety demonstration of a novel subsea processing system considering integration between process control and safety.

The research focuses on:
(1) Identification of safe design principle
(2) Investigation of qualitative safety assessment approach
(3) Investigation of quantitative safety assessment approach
(4) Development of method for safety assessment of system considering dependency

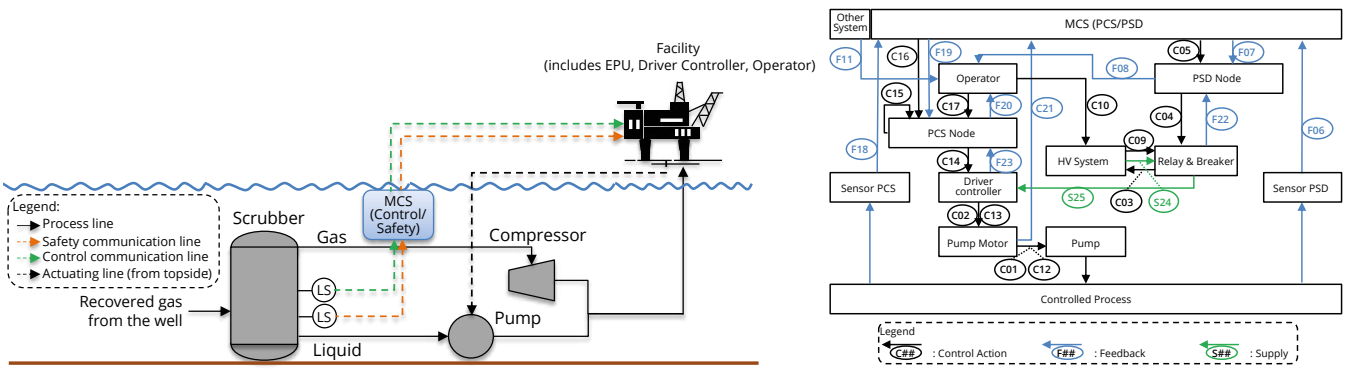
A BETTER UNDERSTANDING OF QUALITATIVE ANALYSIS OF COMPLEX SYSTEM

Preliminary results indicate that the model used in a qualitative safety assessment approach helps greatly for the identification of problems (including, failures and interactions) that may cause hazards at a system level. However, the heavy focus on qualitative assessment still hinders the application of the method for actual industrial practice. The utilization of the quantitative method is expected to solve some of the remaining problems.

DNV GL and partners from the Safety 4.0 project have contributed a lot to the development of the research by providing inputs and platforms for discussion of the results with experienced practitioners.

POTENTIAL FOR INDUSTRIAL APPLICATIONS

More focus on the complexity aspects during the safety demonstration process is required with the increased digitalization of equipment. The method has shown its potential to be used for the safety analysis during design and operation of complex systems.



A hierarchical control structure model of process control and safety system (right) from a typical subsea processing system (left). The model is used to analyze qualitatively the implications of unsafe control action that may cause a hazard in the system.

PROFESSOR
GISLE ØYE

RESEARCH AREA
MANAGER

RESEARCH AREA

Separation – Fluid characterization

Enhancement of separation efficiency and flow assurance.

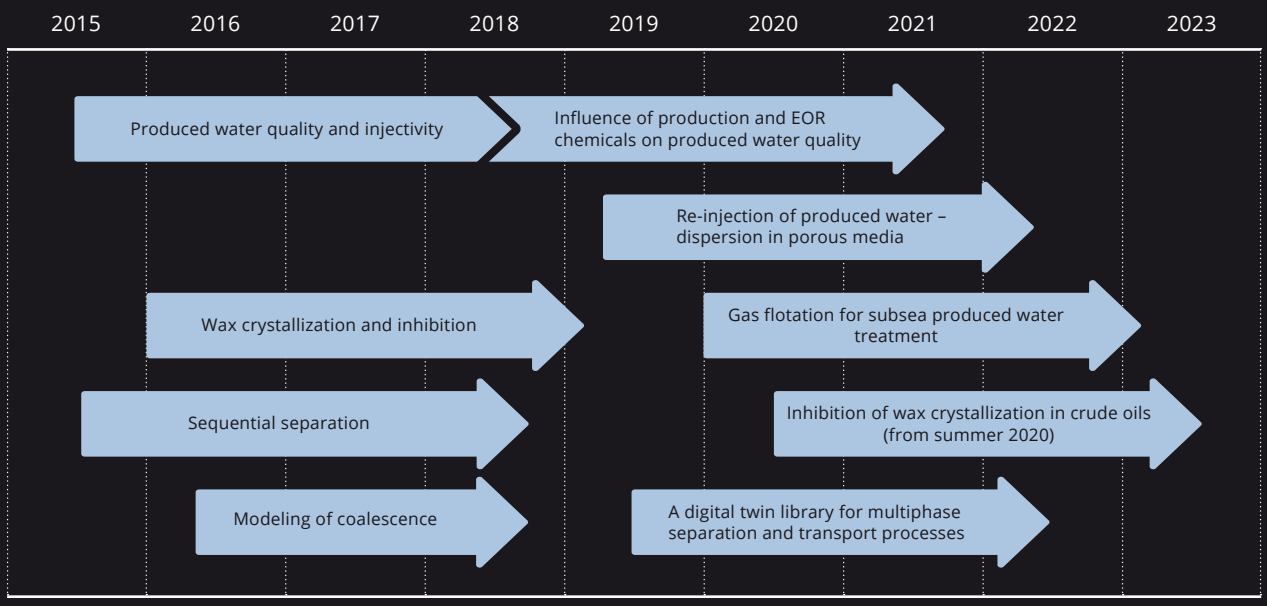
Successful subsea installations require high efficiency and minimal maintenance need of the processing equipment. This means that the behavior of the fluids must be well understood. Efficient separation of gas, oil and water and reliable transport of the hydrocarbons are central for optimization of subsea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

During 2019 two new projects have been started, while two new projects will start during 2020. The figure to the right shows an overview of all projects within the research area.

For description of individual projects: See input from Marcin, Ilgar, Martina and Moein.

Consult page 60, for new projects with kick off planned in 2020.

Completed, current and planned projects



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

Influence of production and EOR chemicals on produced water quality

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

Postdoc
Marcin Dudek

Project manager:
Prof. Gisle Øye

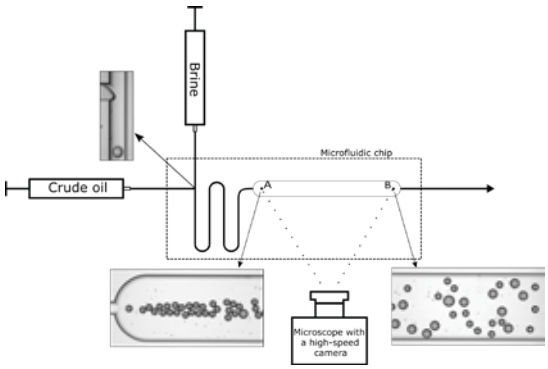
Green shift impact: Reduced amount of fluid samples and waste necessary for performing experiments.

1. BACKGROUND FOR THE PROJECT/ WHY ARE WE DOING THIS RESEARCH?

In order to mitigate or prevent undesirable fluid state changes, and to ensure predictable and continuous flow, production chemicals are added to the fluid stream during crude oil processing. In general, these chemicals can help avoid fouling problems (scale or wax inhibitors), decrease the stability of formed dispersions (de-emulsifiers, flocculants), lower the environmental footprint of the production and guarantee the integrity of the installation (corrosion inhibitor). With the increasing volumes of produced water, the unknown effect of these chemicals on the water treatment processes can become problematic and requires better fundamental understanding.

2. WHAT I HAVE DONE

Building on the methodologies developed during the completed project "Produced water quality and injectivity", this project seeks to utilize microfluidics for studying the effect of production chemicals on the fundamental phenomena during produced water treatment. Microfluidics is a technique that allows observation and manipulation of fluids in microchannels. Emulsion droplets are generated in a controlled manner and their behavior in various conditions is visualized and recorded by high-speed imaging (see Figure). In 2019 the focus was on flocculants, scale inhibitors and de-emulsifiers. Flocculants were studied in comparison with other, more established techniques. Samples of crude oils and flocculants were supplied by SUBPRO partners and chemical vendors, while the results were discussed during internal meetings. Scale inhibition was investigated during a 3-month research stay at ETH Zurich in Switzerland. The host research group had the necessary expertise and facilities to manufacture and tests several microfluidic devices for studying inhibition of scaling. While the initial results were promising, they require more follow-up, possibly as a future student project. Additionally, a method for studying the effect of de-emulsifiers on coalescence of water droplets in crude oil was developed and will be tested against standard bottle tests.



Microfluidic setup for studying the effect of flocculant on coalescence of crude oil droplets. Monodispersed drops are generated at the T-junction where brine and crude oil meet and later enter the coalescence chamber, where they can collide and undergo coalescence. Additional inlet allows the injection of flocculant at specific concentration. The effect of the flocculant (larger, coalesced droplets) is recorded at the outlet.

3. MAIN RESULTS AND HOW CAN THEY POSSIBLY BE USED BY THE INDUSTRY

The coalescence of crude oil droplets in microfluidic devices upon addition of several types and various concentrations of flocculants was compared with three other techniques. Simple bottle tests allowed to estimate time needed for water clarification. Turbidity measurements, performed in similar conditions, gave a quantitative answer on the kinetics of the gravity separation. Experiments performed with light scattering method were conducted in dynamic conditions, allowing droplets to continuously coalesce and break, and follow their size distribution.

The results obtained from all techniques were generally in agreement. Some differences could be attributed to different conditions (static vs dynamic) or type of data obtained during experiments. Overall, it was concluded that microfluidics can successfully be used for studying the efficiency of flocculants. More importantly, it offers several advantages over traditional techniques, such as low sample consumption and quicker measurements (see Table below).

	Bottle test	Turbidity	Light scattering	Microfluidics
Total volume of sample	50 ml	40 ml	400 ml	1-2 ml
Duration per measurement	30-60 min	30-40 min	60-90 min	20-30 min
Flow conditions	No flow	No flow	Flow	Flow
Type of data	Gravity separation (fast)	Gravity separation (slow)	Coalescence/ breakage (fast)	Coalescence (fast)
Limitation	-	Lower limit of OiW	Upper limit of OiW	Oil type

Re-injection of produced water – dispersions in porous media

New methodology for understanding of transport and retention phenomena.

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

PhD student:
Ilgar Azizov

Project manager & main supervisor:
Prof. Gisle Øye

Co-supervisor:
Postdoctoral fellow Marcin Dudek

1. BACKGROUND FOR THE PROJECT

Produced water re-injection (PWRI) back into the reservoir is economically and environmentally attractive option as it limits the need for processing and discharge into the sea of large amounts of water produced along with oil and gas. PWRI is often considered to be the base case for new fields as there are strict regulations regarding discharge of produced water (PW). It is potentially the preferred way of PW management in subsea production and processing.

The main limitation for implementation of PWRI is often the risk of uncontrolled permeability decline of a formation due to retention of dispersed oil and particles in porous media. However, retention phenomenon is not understood for complex fluids such as PW because experimental methods (usually core flooding) utilized in previous studies showed only overall "behavior" of the system. All in all, there are gaps in the knowledge and research challenges that must be addressed.

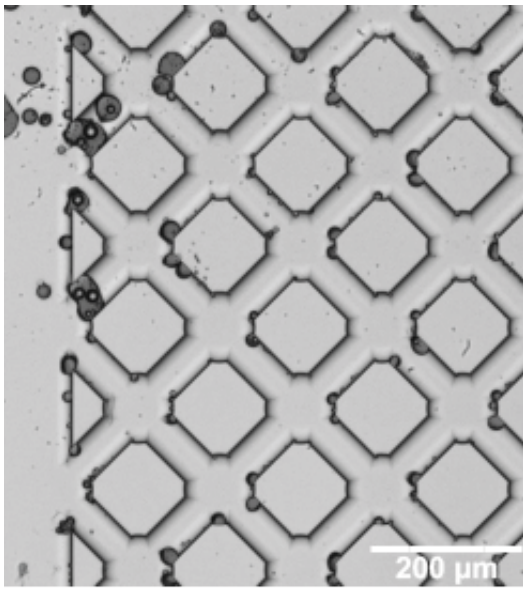
2. OBJECTIVE OF THE PROJECT AND PLANNED ACTIVITIES

The principle objective of the project is to acquire better fundamental understanding about transport and retention of dispersions in porous networks. For this purpose, a microfluidic methodology to follow transport of dispersions in porous network is under development. A microfluidic system is a lab-on-a-chip device where the behaviour of fluids in micro-channels or networks of micro-channels can be followed and visualised. This will allow us to study dynamics of droplets and particles at capillary level using digital microscope equipped with a high-speed camera.

Complexity of PW arises from, amongst other things, crude oil and water composition and the presence of production chemicals (inhibitors, flocculants, EOR chemicals etc.). Hence, understanding the effect of these chemicals on permeability reduction is essential and will be studied extensively. Crude oil provided by industry partners will be used in the most of experiments.

3. EXPECTED OUTCOME

Understanding the behaviour of the water injected into porous reservoirs is essential to obtain predictive models for simulating and optimising water injection. A major shortcoming in the current models is the lack of detailed understanding of transport and deposition mechanisms. Hence, it is expected that knowledge obtained from this study will improve existing models and increase their effectiveness. New microfluidic methodology will extend our existing toolbox and provide foundation for future studies.



Crude oil droplets attached to the surface of porous matrix by interception mechanism. Microfluidic chip represents uniform network of channels.

Gas flotation for subsea produced water treatment

Better understanding of the impact of fluid properties at high pressure and temperature on the removal of oil and solids is essential for optimal subsea gas flotation efficiency.

Green shift impact: An improvement in gas flotation efficiency can reduce the environmental footprint and optimize the production.

PhD student:
Martina Piccioli

Project manager and main supervisor:
Professor Gisle Øye

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

BACKGROUND

Gas flotation is a common and efficient technique used in upstream petroleum processing to reduce oil concentration in produced water. This method is based on the dispersion or nucleation of gas bubbles in the water phase and their attachment to oil droplets or solid to the bubbles, which makes them rise faster. This should reduce the oil and solids content into the water to below the discharge limit or reach the quality required for re-injection of the water in a reservoir. Compared to topside separation, subsea gas flotation is performed under considerably higher pressure and at higher temperatures. These conditions can cause significant, unknown differences to the fundamental, microscopic phenomena associated with this water treatment process.

OBJECTIVES OF THE PROJECTS

The main objective in this project is to study and understand how the removal of oil and solids is influenced by the different fluid properties at high temperatures and high pressures. Gas flotation experiments will be carried out in a high-pressure gas flotation cell, while parallel experiments will be carried out in a microfluidic setup (see Figure).

ACTIVITIES AND DELIVERABLES

Four main research activities will be carried out in the project:

i Systematic studies of how parameters such as pressure, temperature, oil and water composition, oil concentration, gas phase composition and size distribution (drops and bubbles) influence the oil removal efficiency by gas flotation;

ii Systematic studies of how solids affect the removal of oil and solids;

iii Systematics studies of the effect of the production of chemicals and EOR chemicals on gas flotation process;

iv Parallel studies in the gas flotation rig and microfluidic setup, using similar parameters and conditions.

The crude oil samples that will be used for the experiments will be provided by the SUBPRO industry partners.

This project will give a better knowledge about fundamental mechanisms, the influence of solids and the influence of chemicals in HP gas flotation. It can also assess the scalability of microfluidic data and its potential to provide information about larger scale process.

Figure: High pressure gas flotation cell: flotation cell inside the temperature-controlled cabinet (left) and the flotation cell (right). Attachement of an oil droplet to a gas bubble from a microfluidic experiments is shown below.

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 / water processes.

Green shift impact:
- **Reduction of oil content in oily water effluents can be achieved by applying the models to optimize the oily water treatment processes.**
- **Digitalization can reduce the necessity to perform experiments.**

Phd student:
Moein Assar

Project manager and main supervisor:
Associate professor
Brian Arthur Grimes

Co-supervisor:
Professor
Magne Hillestad,
Adjunct professor
Audun Faanes

THE NEED FOR ADVANCED MODELS

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

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

POPULATION BALANCE MODELS

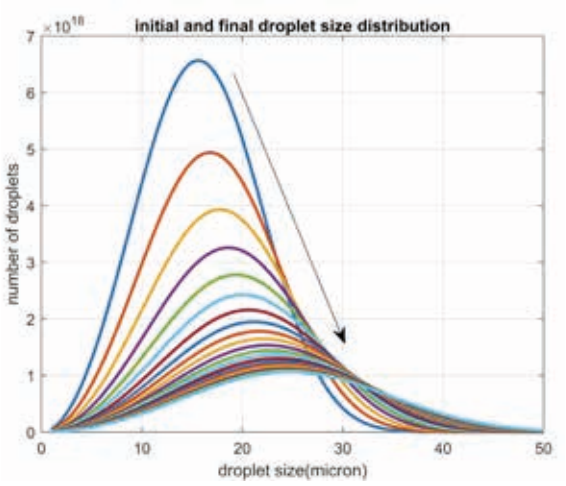
Population balance models (PB) can provide a theoretical framework to model processes involving Interaction between droplets as well as settlement/skimming and mass transfer which eventually leads to evolution of droplet distribution size over time. The knowledge of droplet size distribution can play an important role in predicting physical properties like viscosity as well as determining efficiency of separation equipment.

DEVELOPMENT OF THE MODEL LIBRARY

The core activity of the proposed project is to employ the fundamental advances to coalescence and breakage modeling in a population balance model framework to construct a class-library in C++ for dynamic drop size evolution in 0, 1, and 2 spatial dimensions. The class inheritance structure of the C++ language will facilitate a modular approach for development and future expansion of transport and separation models with varying complexity suited to their task while the memory handling of C++ and existing numerical libraries for the solution of the highly non-linear differential equations will ensure fast calculation speeds on modern computational platforms. The portability of C++ class libraries will allow the PB models to be readily incorporated into common general purpose simulation software packages (e.g. MATLAB), process modeling packages (e.g. ASPEN PLUS, HYSYS), or multi-phase flow simulation packages (e.g. OLGA).

The class-library will have different subroutines including 0, 1 and 2 spatial dimensions each enabling us to model different applications ranging from pipe flow to batch settlers and also continuous oil/water separators. However, further features like coupling to available CFD software will also be envisaged in order to simulate more realistic industrial processes.

Moreover, in conjunction with other SUBPRO projects, experimental results and findings of other teams will be used to estimate coalescence and breakage model parameters.



PBE can predict the dynamics of droplet size distribution which evolves over time and reaches steady-state condition.

PROFESSOR
HUGO ATLE JAKOBSEN

RESEARCH AREA MANAGER

RESEARCH AREA

Separation process concepts

Enabling new solutions for subsea separation.

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

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

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

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

The ongoing project "Experimental investigation and visual characterization of single particle breakup under turbulent flow conditions" will be followed up by a new project from 2020; "Particle breakup, turbulence and image analysis"

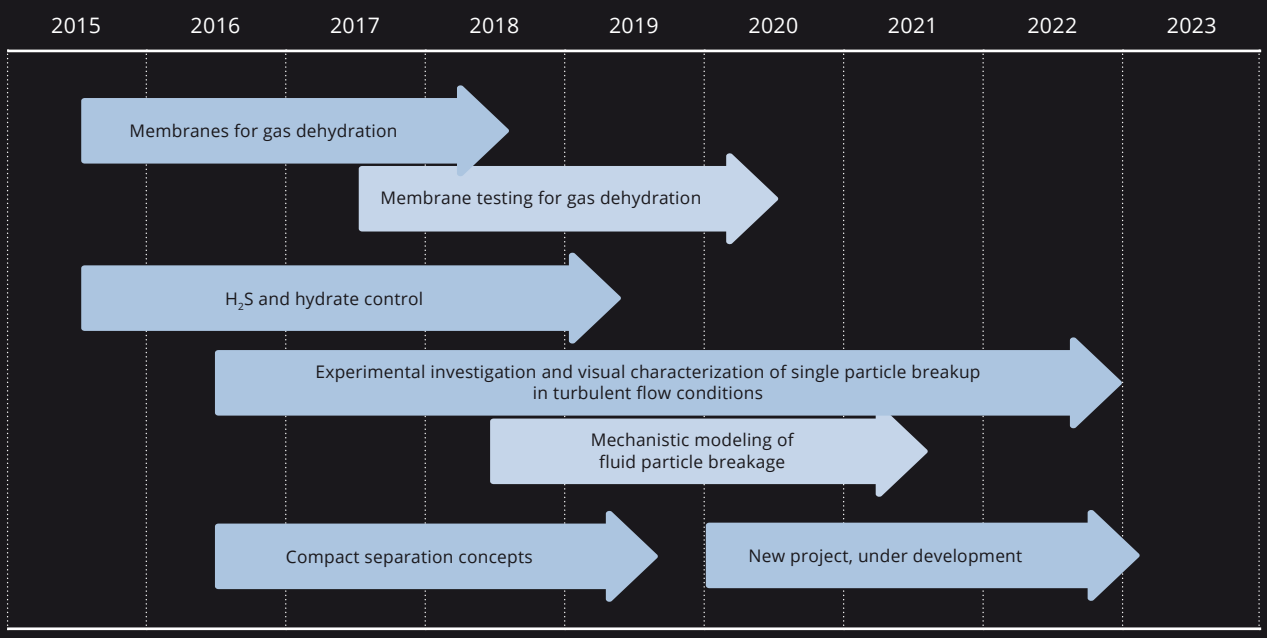
Nicolas La Forgia is now employed as a researcher at the Department of Chemical Engineering.

During 2019, the PhD project; "Compact separation concepts" was completed and the PhD candidate, Håvard Skjefstad, defended successfully his thesis. The project is followed up by a new PhD project "Subsea bulk oil-water separation". The PhD candidate has been selected and the project will start during the spring semester 2020.

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

Consult page 60, for new projects with kick off planned in 2020.

Completed, current and planned projects



The Separation- Process concepts team,
From the left: PhD student Mahdi Ahmadi, Postdoctoral fellow Hanieh Karbas, PhD student Eirini Skylogianni, Associate professor. Liyuan Deng, Professor. Hanna Knuutila, Professor. Hugo Atle Jakobsen, PhD student Eirik Helno Herø and researcher Nicolas La Forgia. (PhD student Håvard S. Skjefstad was not present when the picture was taken).

Membrane testing for natural gas dehydration

Subsea membrane gas dehydration technology offers an energy saving and green process supplying a purified dehydrated gas stream directly exported to pipelines.

PhD student:
Mahdi Ahmadi

Project manager:
Prof. Liyuan Deng

Co-supervisor:
Prof. Magne Hillestad

A FEASIBLE MEMBRANE PROCESS FOR SUBSEA DE-HYDRATION AIMS AT REDUCING THE WATER CONTENT IN GAS STREAM TO MEET THE PIPELINE SPECIFICATION

Natural gas usually saturated with water and it is the chief culprit of hydrate formation and pipeline corrosion. The high-pressure gas stream needs to be dehydrated before transportation. Compared to conventional dehydration processes, the novel membrane gas dehydration process offers a larger contact area, less methane loss, high modularity and compact design. The objective of this project is to test membrane materials and process to experimentally evaluate the feasibility of the new membrane system for high pressure subsea gas dehydration. This project is a follow up of modelling work in the project "membranes for gas dehydration". A closed-loop process was designed to dehydrate natural gas using glycol as solvent, including membrane absorption unit to absorb water from gas stream and a thermopervaporation unit for glycol regeneration.

MEMBRANE ABSORPTION (CONTACTOR) PROCESS SHOWS DEW-POINT DROP TO LOWER THAN -20°C

A flat sheet membrane contactor setup was designed and built in house. A new hydrophobic composite membrane (Figure 1) was fabricated and tested at different pressure, temperature, liquid and gas flow rate, and inlet dew-point of gas stream. Membrane material selection was performed based on the compatibility with glycol and durability for long-term operation. High membrane selectivity ensures the application of the membrane contactor in subsea remote area. The novel system allows the operator to tune the operating condition in order to keep the outlet water content to a specified value. The preliminary results show outstanding performance capturing effectively the water and reducing the dewpoint (Figure 2). The obtained experimental data will be then used to develop and validate a model to be employed in process design and optimization by our industry partners.

MEMBRANE THERMOPERVAPORATION PURIFIES THE GLYCOL-WATER STREAM AND PRODUCES 99.99% PURIFIED WATER, WHICH CAN BE DISCHARGED DIRECTLY TO THE SEA.

Membrane thermopervaporation setup and module was designed and constructed. The performance of the thermopervaporation process depends on operating parameters including temperature and composition of the feed, temperature of the cooling water, and flow rates of the feed and cooling water. Moreover, design parameters including thermal resistance of the condensation plate and membrane, air gap thickness, and the geometry of the membrane module are also affecting the performance of the process. The diagram in figure 3 shows separation factor of glycol-water solution through a hydrophobic membrane compared to VLE equilibrium as a function of feed temperature and concentration. The separation performance shows the separation factor in all cases is better than VLE lines. The impressing results confirmed by Equinor as the industrial partner can be further evaluated and be used for model development and validation in process performance prediction.

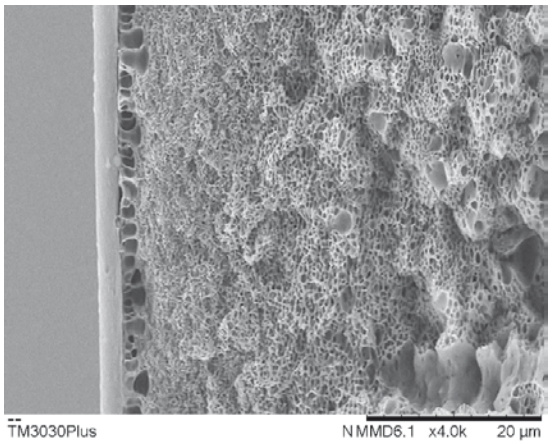


Figure 1 SEM image of the composite membrane for membrane absorption (contactor)

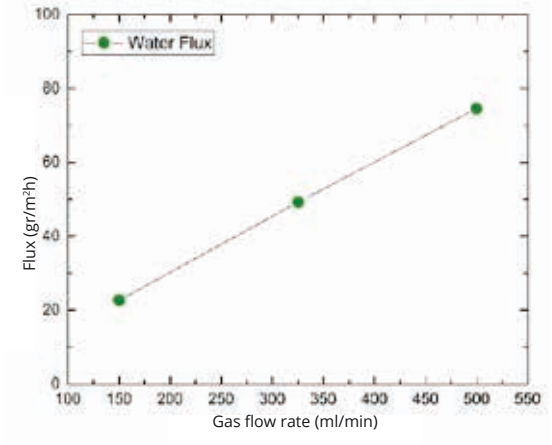


Figure 2 Performance of membrane absorption, water flux through a hydrophobic membrane as a function of gas flow rate at 35°C, 6 bar, and 1600 g/h of liquid flow rate.

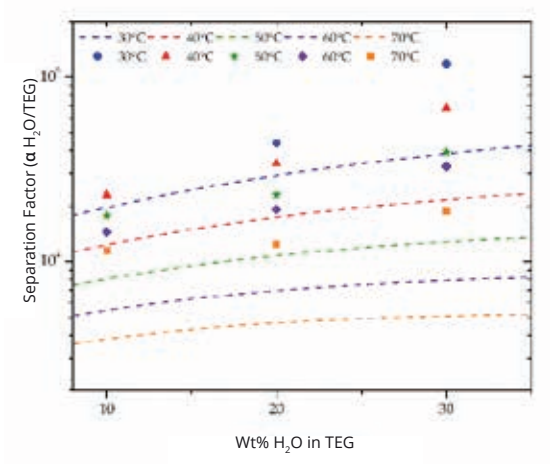


Figure 3 Separation Factor of water-Glycol using a hydrophobic membrane as a function of feed temperature and concentration (The dash line is VLE equilibrium obtained from Hysys Aspen).

Mechanistic Modeling of Fluid Particle Breakage

Subsea membrane gas dehydration technology offers an energy saving and green A complementary methodology for the prediction of fluid particle interface instability and its breakage.

Postdoctoral fellow:
Hanieh Karbas Foroushan

Supervisor:
Prof. Hugo Atle Jakobsen

UNDERSTANDING PARTICLE BREAKAGE MECHANISMS IS ESSENTIAL FOR DESIGNING EFFICIENT SEPARATORS

Having subsea processing as one of the most effective ways for enhancement of oil and gas production, multiphase separators are recognized as the primary aid to separate the fluid components of wellbore multiphase flows for further processing. Insufficient separation can hinder the effective performance of downstream processing equipment, whereas a proper design of separator can greatly assist to prevent adverse operational events with costly and hardly-feasible remedial actions. There is a wide range of methods used to design multiphase separators. The design of separators, however, does not appear to be trivial, as it essentially requires careful considerations of underlying physical phenomena, one being accurate quantification of fluid particle breakage and coalescence mechanisms. Separation efficiency is not only affected by separator vessel configuration and operational conditions, but also by the particle break-up and coalescence processes within the internal sectors. Thus, proper characterization of particle breakage is essential for enhancement of separator designs and, consequently, effective control of separation efficiency.

IMPROVEMENT OF CONVENTIONAL PARTICLE BREAKAGE MODELS THROUGH ANALYSIS OF FLUID-PARTICLE INTERFACE INSTABILITY

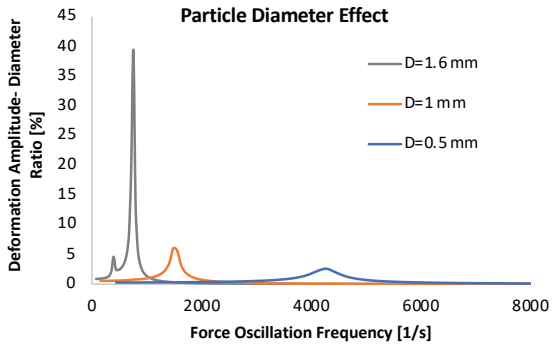
Acquiring a knowledge on the dynamics of dispersed phase fluid particles and continuous fluid interaction and interface instability enables better understanding of fluid particle breakage and helps to identify the possible factors affecting the instability of the interface, leading to a breakage. Considering the random nature of the turbulent flow, a fluid particle in a turbulent field can be subjected to various-size deformations over a certain period of time. These deformations are normally caused by successive or simultaneous interactions of turbulent structures with the fluid particle. An instability analysis for the fluid particle interface, experiencing oscillations by a dynamic force, can provide better predictions of the ultimate state of the fluid particle, as denying the effect of interaction history might lead to over-simplifications.

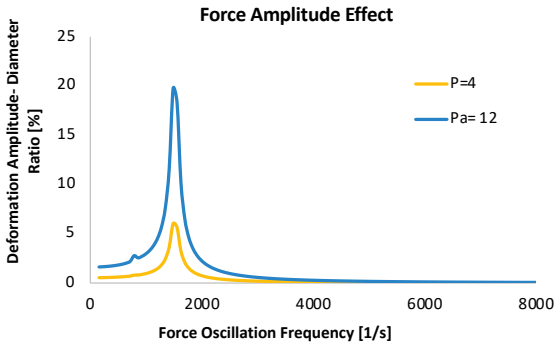
The aim of this work is to evaluate the possibility of instability analysis implementation in fluid particle breakage modelling to possibly redefine or improve the determination of major parameters required for breakage predictions.

RESEARCH ACTIVITIES AND DELIVERABLES

The current study comprises several stages:

- Develop a model to study the forced oscillations of a fluid particle interface, providing qualitative judgements on the deformation/instability of a fluid particle subjected to a pre-defined force. Figures below illustrate examples of effect of particle diameter and force amplitude on interface deformations.
- Extend the model to the case of fluid particle deformation in turbulent field, investigating forced oscillations of a fluid particle due to its random interactions with turbulent structures.
- Implement the instability analysis into conventional particle breakage models and evaluate its influence on predictions
- Experimental study on gas bubble breakage
- Possibly propose improvements on conventional breakage models for the enhancement of as-liquid separators design, hence elevating the separators efficiency





Experiments on fluid particle breakage

Experimental data from oil droplet breakage investigations can help design models for complex phase separation equipment.

Green shift impact: A better understanding of the dispersed phase physics can provide the tools for designing and optimizing the separation processes. In turn, this may lead to increasingly energy efficient systems with less emissions.

PhD student:
Eirik Helno Herø

Researcher:
Nicolas La Forgia

Project manager
& supervisor:
Prof. Hugo A. Jakobsen

IMPROVED UNDERSTANDING OF THE DISPERSED PHASE

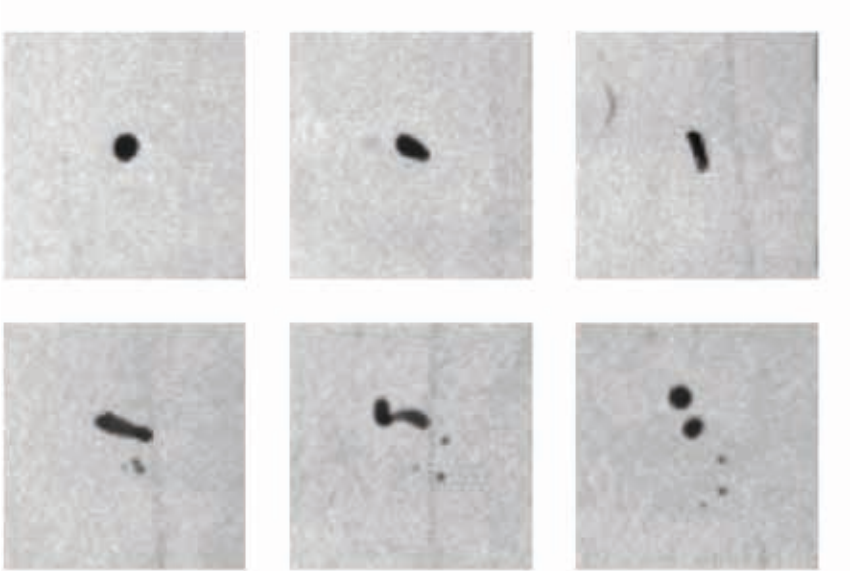
Understanding the mechanism of phase separation is key for many industrial processes, especially for subsea processing. In particular, the separation of oil and water plays a major role in the design of separators. However, a big challenge for the design of oil-water separators is accurate modelling that predict the droplet size distribution of the dispersed phase. Especially accounting for the effects of droplet breakage and coalescence (or merging) under turbulent flow conditions. These processes are in turn dependent on the, dispersed phase properties, system properties, such as surface tension and continuous flow conditions. While many models have been proposed, these are unable to satisfactory predict the behavior of breakup in complex systems mainly due to a lack of accurate experimental data on breakage of fluid particles in turbulent flows.

In this project we perform experiments on the breakage of single fluid particles. The focus is on the mechanics of the breakage process, for which the results can be used to improve the predictiveness and accuracy of the breakage modelling. In turn, this could be used in the design process of separators and other processing equipment.

A NOVEL EXPERIMENTAL SETUP

The project har constructed an experimental rig in which single oil droplet is inserted into a continuous water phase and transported into a channel with an increased turbulence level. The full breakup event is observable by high-speed cameras, from which the breakage measurements are extracted. These measurements include breakage probability, mother and daughter size and number distribution, breakage time, deformation prior to breakage and breakage position. The breakage position is correlated with the turbulence characteristics of the flow by interpolating turbulence measurements at the breakage position. This association of breakage measurements with local turbulence characteristics is one of this works major advances over previous investigations.

Furthermore, the project has designed an automated system for running experiments and a semi-automated video interpretation system. The continuous water flow has been measured by Laser Doppler Velocimetry (LDV). With an experimental facility developed with model validation in mind, as well as rigorous statistical treatment, the results give valuable insight into the breakage phenomena and thus into breakage modeling. With a fully functional facility available, future work can investigate different droplet sizes or flow conditions. Additionally, it could study the impact of the data on developing new or updated model concepts.



Sequence of images of drop breakup as captured by the high-speed cameras.

FINAL PROJECT REPORT

H_2S and hydrate control

Solvent evaluation for the combined hydrogen sulfide removal and hydrate control for subsea application through experimental and modelling work.

PhD candidate:	**Eirini Skylogianni**
Start date:	15.10.2015
Thesis defense date:	26.06.2020
Title of thesis:	Combined Hydrogen Sulfide Removal and Hydrate Control for Subsea Application: Characterization of Selected Blends
Supervisor:	Professor Hanna K. Knuutila

1. BACKGROUND FOR THE PROJECT

Main processes during natural gas treatment is the removal of acidic gases, such as CO_2 and H_2S, and the removal of water in order to meet the pipeline specifications, gas quality specifications and environmental requirements. Non-regenerative chemicals, called scavengers, are commonly used to remove hydrogen sulfide from natural gas. However, their transportation, storage, use and disposal requirements are not ideal for fields in long-distance from the shore. Further, they cannot treat high H_2S concentrations. As a result, fields are abandoned due to high H_2S content. In addition, oil and gas fields experience reservoir souring, i.e. increase in sulfur content, due to EOR (Enhanced Oil Recovery) activities. Therefore, maintaining production and safe operation in increasingly sour fields is an important industrial challenge.

A solution to this challenge is the development of a regenerative process where hydrogen sulfide and water content can be removed simultaneously. Aqueous methyldiethanolamine (MDEA) and aqueous monoethylene glycol (MEG) are traditionally used today for the selective removal of H2S over CO2 and for hydrate control, respectively. Therefore, mixtures of MDEA-MEG as well as highly concentrated MDEA are promising candidates for such a process. Knowledge of the physical properties, kinetics and thermodynamic behavior of the proposed system is necessary for the successful process design, development and optimization.

2. WHAT I HAVE DONE

In this work, the thermodynamic behavior of the systems H_2S-CH_4-MDEA-MEG-H_2O and CO_2-MDEA-MEG-H_2O was mainly investigated through vapor-liquid equilibrium (VLE) measurements. The first system was studied with focus on the pressure effect on the removal capacity. Methane was used as the make-up gas since it is the main component of natural gas. The VLE measurements of the second system containing CO_2 were accompanied by Nuclear Magnetic Resonance (NMR) analysis to obtain speciation information and identify the chemical reactions undergone during the absorption of CO_2 into aqueous and non-aqueous MDEA-MEG blends. This project also studied the physical properties of aqueous and nonaqueous MDEA-MEG and produced density and viscosity data. Both experimental and modeling work was performed with the experimental studies being the core research activity.

The work is listed below:

EXPERIMENTAL

- **VLE measurements for H_2S-CH_4-MDEA-H_2O system.**
  Studied solvent concentration:
  50 wt% MDEA-H_2O and 70 wt% MDEA-H_2O.
  Temperatures: 283, 353 and 393 K.
  Total pressures: 20, 60 and 100 bar.

- **VLE measurements for H_2S-CH_4-MDEA-MEG-H_2O system.**
  Studied solvent concentration:
  30 wt% MDEA - 40 wt% MEG - 30wt% H_2O.
  Temperatures: 283, 353 and 393 K.
  Total pressures: 20, 60 and 100 bar.

- **VLE measurements for CO_2-MDEA-MEG system.**
  Studied solvent concentration:
  whole range from 100% pure MDEA to 100% MEG.
  Temperatures: 313 to 393 K.
  Total pressures: 0 to 6 bar.

- **VLE measurements for CO_2-MDEA-MEG-H_2O system.**
  Studied solvent concentrations:
  30 wt% MDEA - 60 wt% MEG - 10 wt% H_2O, 30 wt% MDEA - 60 wt% MEG - 10 wt% H_2O and 30 wt% MDEA - 60 wt% MEG - 10 wt% H_2O.
  Temperatures: 313 to 393 K.
  Total pressures: 0 to 6 bar.

- **Density and viscosity measurements for MDEA-MEG and MDEA-MEG-H_2O systems.**
  Studied solvent concentrations: whole range
  Temperatures: 303 to 353 K.
  Ambient pressure.

MODELING

- VLE model for H_2S-MDEA-H_2O system.
- Density model (NRTL-DVOL) for MDEA-MEG-H_2O system.
- Viscosity model (NRTL-DVIS) for MDEA-MEG-H_2O system.

INDUSTRIAL COOPERATION:

Industrial involvement was mainly by Equinor. Three meetings with Equinor were held. The topics of the meetings were:
- to share Equinor's experience and learnings related to HSE measures in working with H2S
- to discuss the experimental work plans
- to discuss the research findings.

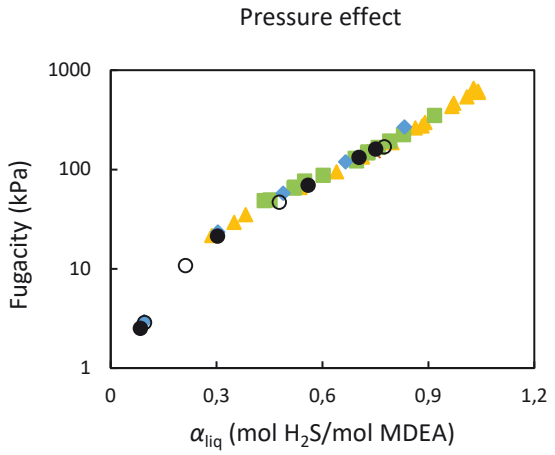
3. MAIN RESULTS

The main results from this project are:

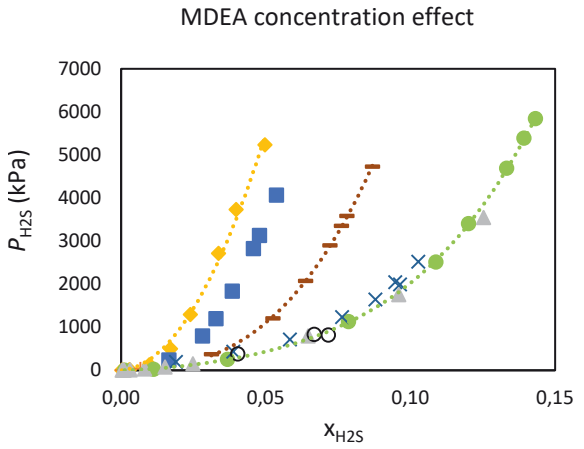
- **VLE data and model for systems relevant for the combined acid removal and hydrate control in natural gas for subsea application.**
  The available models used by the industry for design and simulation of process plants today cannot predict accurately the behavior of MDEA-MEG system, due to lack of experimental data. Experimental testing of the combined system at high pressures, up to 100 bar, was performed in collaboration with the School of Mines ParisTech in France, and its specialized Centre of Thermodynamics of Processes (CTP). The measurements show that the presence of methane, even at very high pressure, minimally affects the removal capacity of the proposed solvent. Moreover, it was found that the proposed solvent would be able to simultaneously remove H2S and inhibit hydrate formation. However, the concentration of the components in the solvent should be carefully selected, since the amount of glycol and substitution of water in the solvent reduces the H_2S removal capacity.

- **Demonstration of chemical reaction between CO_2 and MEG in the presence of MDEA.**
  We demonstrated that although carbon dioxide does not react with pure MEG, it does react with MEG in the presence of MDEA. This is the result of MEG autoproteolysis, which takes place in the alkaline environment formed by the presence of the amine. The chemical binding of CO_2 by the amine in the presence of water is known, however the CO_2 chemical binding by the glycol provides significant knowledge for the evaluation of the proposed process. For the industry, the importance of this knowledge obtained in work lies in the need to account for the CO_2 absorbed in the glycol as well in the amine during solvent regeneration. In a more fundamental level, this work provides new insights for the absorption of CO_2 into aqueous and non-aqueous MDEA-MEG blends at molecular level.

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



Equilibrium H_2S fugacities as a function of liquid loading and total pressure for 50 wt.% MDEA-H_2O at 323 K. ● P_{tot} = 500 kPa (This work), ○ P_{tot} = 500-600 kPa (This work), ♦ P_{tot} = 500-700 kPa, ■ P_{tot} = 1500 kPa, P_{tot} = 3000 kPa, ▲ P_{tot} = 7000 kPa.



Hydrogen sulfide molar concentration in the liquid phase for the system H_2S-MDEA-H_2O as a function of partial pressure and amine concentration at 393 K; MDEA composition: ♦ 11.8 wt.%, ■ 18.7 wt.%, + 23.1 wt.%, — 32.2 wt.%, ● 48.8 wt.%, 48.8 wt.%, ▲ 50 wt.%, ○ 70 wt.% (This work).

Analysis of VLE data obtained for hydrogen sulfide solubility in 70 wt.% MDEA-H_2O system for understanding the pressure effect and MDEA concentration effect.

4. INNOVATION AND INDUSTRY COLLABORATION

The importance of this project lies in providing new experimental data to the industry for better understanding of the governing phenomena in the studied solvents as well as for process development. The data obtained at high pressures and high loadings of hydrogen sulfide in the solvents are very challenging and time-consuming, as also shown by the few available data published in the literature.

Upon the employment of the solvents studied in this work, the models developed in this work can be useful in the future for both design and operation of a process suitable for the combined hydrogen sulfide removal and hydrate control of natural gas subsea.

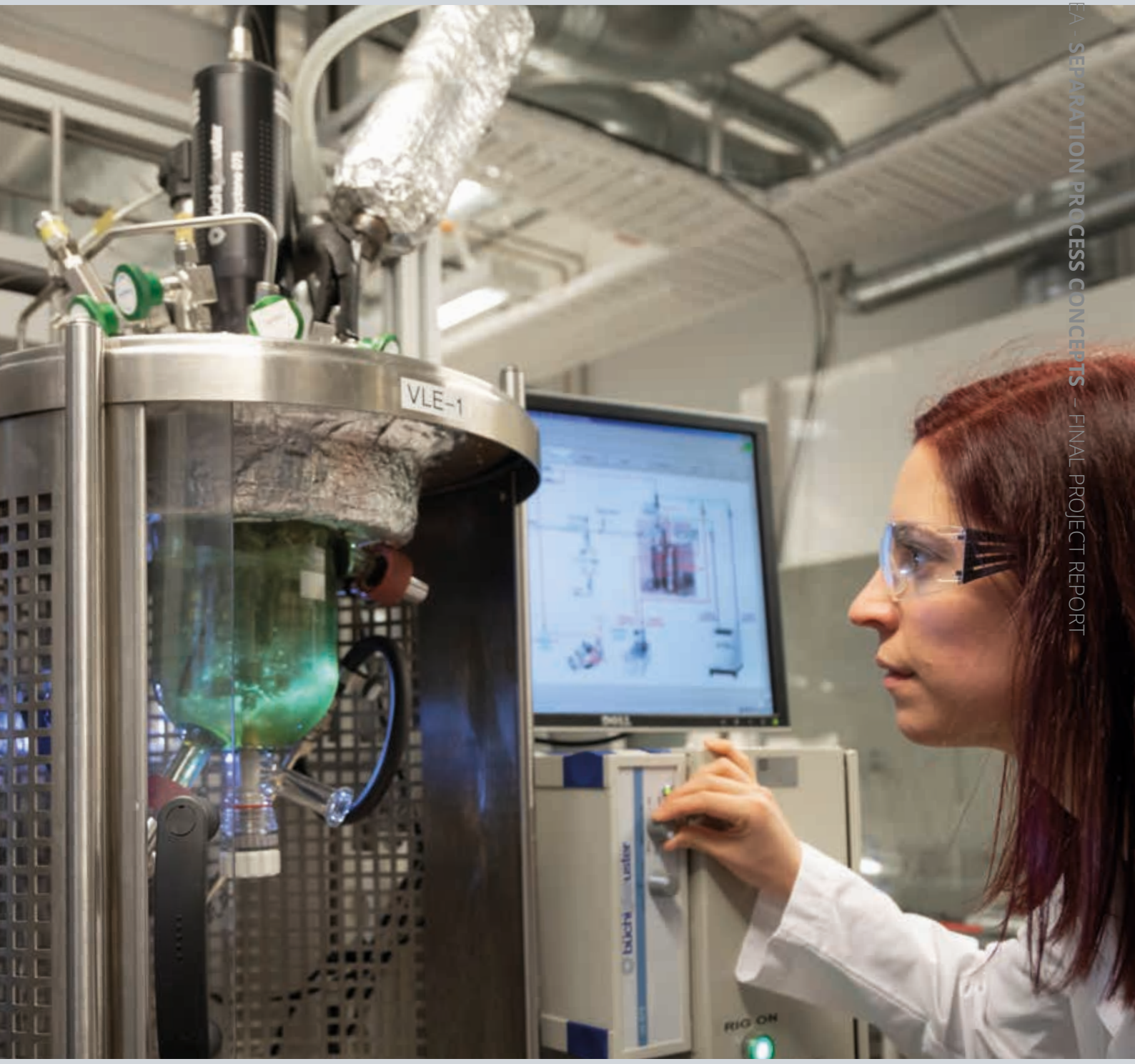
5. FURTHER WORK

This work focused on some aspects of solvent characterization, i.e. VLE data and physical properties. A complete characterization of the candidate solvents together with process configurations would be necessary for the evaluation of the combined H_2S removal and hydrate control process for subsea application. Further work could include:

- Extension of the vapor-liquid equilibrium study at high pressures using blends with various MDEA-MEG(-H_2O) compositions, in the presence of both H_2S and CO_2.
- Kinetic studies.
- Contactor studies and droplet distribution of the solvent in the pipeline gas stream.

6. MY NEW JOB

Company/institution: TNO (Netherlands organization for applied scientific research)
Position/area of work: Junior Scientist Innovator



PhD candidate Eirini Skylogianni testing the reactor for low-pressure vapor-liquid equilibrium experiment.

FINAL PROJECT REPORT

Compact Separation

Multiple Parallel Pipe Separator.

PhD candidate:	**Håvard Skjefstad**
Start date:	01.07.2016
Thesis defense date:	4.11.2019
Title of thesis:	Development and assessment of a multi-pipe oil-water bulk separator concept for subsea applications
Thesis committee members:	Neima Brauner, Najam Beg, Johannes Jäschke
Supervisor:	Associate Professor Milan Stanko

1. BACKGROUND FOR THE PROJECT

Subsea produced water separation has emerged as a viable technology for tackling challenges arising from increased water production rates. Removing produced water at the seabed will free up topside capacity constrained water processing facilities, increase production rates, prolong field lifetimes and secure greener and more energy efficient oil and gas production.

However, an important challenge connected to subsea produced water separation is that the cost of constructing, qualifying, transporting and installing subsea produced water separators often exceeds potential value gains in production. This is especially true for mature, marginal or deep-water fields. To make the business case of subsea produced water separation more attractive, there is a need for novel low-cost technologies suitable for standardization and modularization.

2. WHAT I HAVE DONE

- **Extensive state of the art review** of subsea produced water separator technology. Based on performed review, focus points for new technology developments were outlined. Focus points were aimed to close gaps in the current state of the art

- **Planning, design, construction and commissioning** of a two-phase oil water test facility. The facility was constructed to test and validate a novel separator concept

- **Design and construction** of a novel subsea produced water separator concept. Focus points in the development were:
  - o Compactness
  - o Standardization
  - o Capacity and operational range
  - o Modular design

- **Extensive experimental testing** of the developed separator concept:
  - o Design optimization
  - o Performance mapping
  - o Operational envelope determination
  - o Control strategy development and testing
  - o Investigation of inlet choke influence on separator performance
  - o Investigation of surfactant influence on separator performance

- **CFD modelling** of the developed separator concept

Figure 1: Developed Separator concept

Figure 2: Developed Separator concept

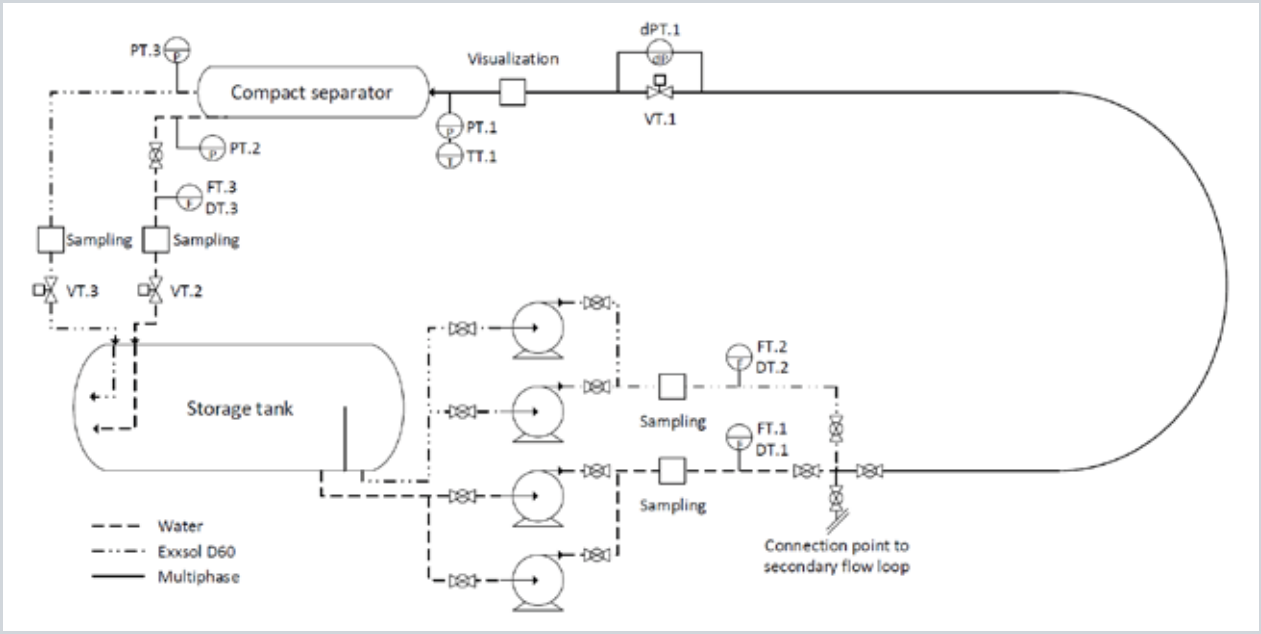


Figure 3: Test facility P&ID

Figure 4: Picture of prototype and experimental facility

3. MAIN RESULTS

During this project, four experimental campaigns have been completed, and a separate simulation study has been carried out. Main results from the respective campaigns are included below:

- **Experimental campaign 1:**
  The Campaign investigated preferred location of water extraction along the ascending outlet pipe (Illustrated in Figure 5). Re-entrainment of oil droplets along the length of the extraction pipe was observed. It was concluded that extraction of water should be performed close to the horizontal pipe section.

- **Experimental campaign 2:**
  The campaign investigated different inlet design options, and the effect these has on separator performance. A full performance mapping was performed with three different inlet arrangements (Normal inlet, tangential inlet and tangential inlet with novel phase re-arranging internals). Of the three inlet options tested, the tangential inlet with novel internals secured best separator performance, minimizing formation of dispersion which was observed to negatively affect separator performance.

- **Experimental campaign 3:**
  This campaign evaluated different control strategies for the developed separator concept. Two options were tested. The first controlled rate of water extraction by directly measuring the purity of extracted water. This option led to cyclic degradation in purity of extracted water, and was not preferred. The second approach was to use a differential pressure sensor over the ascending extraction pipe as a proxy level measurement. This assured a continuous buffer layer of water at the extraction point, and the cyclic behavior of the previous approach was eliminated.

- **Experimental campaign 4:**
  The study investigated the effect inlet choking and addition of surfactant had on separator performance. A limited experimental matrix was run without surfactants, for no choke, 50mbar choke pressure loss and 100 mbar choke pressure loss. The test matrix was repeated with added surfactants. Results displayed an overall decease in separator performance with increasing levels of inlet choking. Further performance decrease was observed when adding surfactant. Decrease in performance was seen in connection with an increased dispersion layer thickness at the separator outlet.

- **Modelling**
  A two-phase Euler-Euler CFD model considering one dispersed and one continuous phase provided an accurate prediction of extracted water quality for the water-continuous inlet regimes tested.

4. INNOVATION AND INDUSTRY COLLABORATION

A novel separator concept (the MPPS) has been designed, developed and tested. The developed concept exhibits good overall performance, and entails a significant size and weight reduction compared to traditional separator designs. A flow phenomenon involving uneven distribution of forming dispersion layers has been reported, and flow behavior within the separator has been analyzed. Better understanding of the reported phenomenon can assist development of novel technologies for targeted dispersion and emulsion breakage. Concept design improvements has been investigated, and a strategy for efficiently controlling separator performance has been outlined. The effect inlet choking and addition of surfactant has on separator performance has been evaluated. The presence of surfactant in combination with inlet choking was observed to give the largest degradation in separator performance. This illustrates a potential benefit of subsea produced water separation.

The developed separator concept provides a good foundation for further development and study. It is believed that the presented design can serve as a basis for the development and implementation of next generation subsea produced water separators, which overcomes outlined challenges with current designs. Additionally, the results of this research can be useful and relevant for the development and refinement other oil-water bulk separator concepts based on a parallel pipe design.

5. FURTHER WORK

Proposals for future work is divided between experimental and modelling activities.

EXPERIMENTAL:

Proposed future activities are related to enhancing the developed separator concept in terms of technology readiness, further study of discovered flow effects and design improvements of the current configuration.

- **Gas-liquid experiments:**
  Separator performance can be greatly affected by the presence of gas. Investigating separator performance with small amounts of gas (residual gas from upstream gas-liquid separation) in the inlet stream is therefore a natural next step in the development. In addition, the inlet section should be modified for gas-liquid separation, so the gas liquid separating capability of the concept can be evaluated. Required design improvements for gas-liquid separation should be identified, tested and implemented.

- **Solid-liquid experiments:**
  In real field operation, solids can accumulate in the separator pipes. Investigating how solids are transported in the separator, and identify locations for potential solids build up, are important steps for further concept development. This also includes developing strategies for solids removal if needed. Needed design improvements for solid-liquid separation should be identified, tested and implemented.

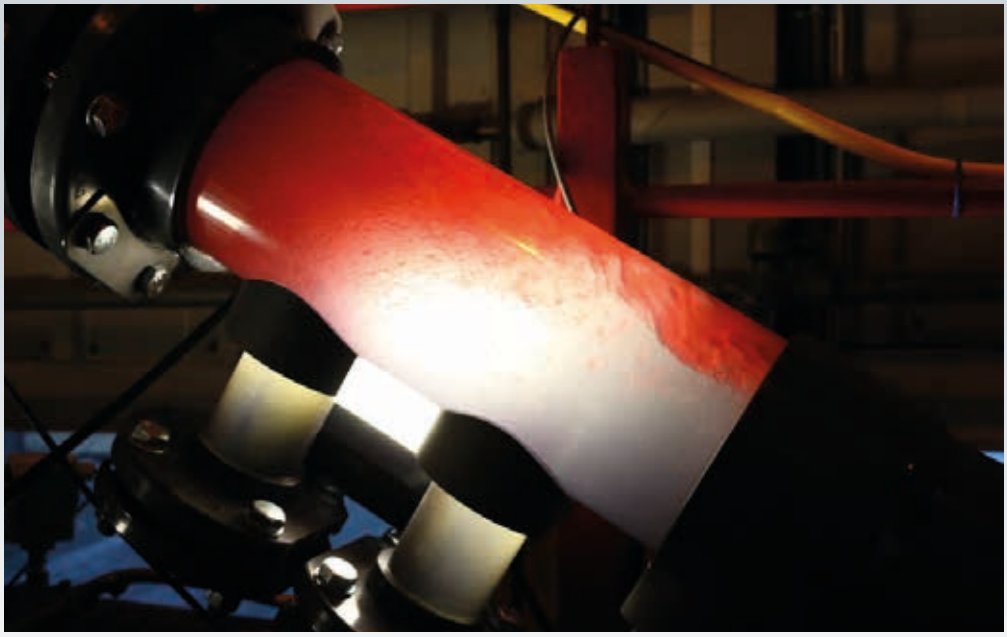


Figure 5: Picture of water extraction configuration

- **Design improvements:**
  Completed studies of the developed separator concept has revealed several areas for potential design improvements. The current extraction and tapping design causes re-entrainment of oil droplets into the established water layer. A more gradual transition from horizontal to inclined can reduce mixing and result in better separator efficiency. The effect of inclination angle can also be studied, to evaluate if there are better configurations for promoting water layer growth and minimizing mixing and re-entrainment. The effect descending pipe sections at the inlet has on liquid-liquid separation should be evaluated. If up-stream gas-liquid separation is installed, and no gas is present at the separator inlet, a horizontal inlet alignment with subsequent splitting might be preferred. This will reduce excessive mixing.

- **Effects for future study:**
  The discovered uneven splitting phenomenon is an effect that is attractive for further study. Possible topics include cause of occurrence, how migration can be controlled, and why installed internals prohibit uneven splitting to occur. Further understanding of this phenomenon can allow development of technologies for targeted breaking of formed oil-water emulsions.

- **Control:**
  The separator is subject to several constraints and control objectives. Model predictive control was therefore suggested as a more fitting controller approach, compared to the two decoupled controllers used in the reported study. Suggestions for future work includes development of a model predictive controller for the separator, and finding optimal setpoints and outputs to maximize separator performance within specified constraints.

MODELLING:
The developed model displayed good conformance to experimental results for water-continuous inlet regimes. As part of future work, the model should be used to evaluate proposals for separator design improvement. An improvement to the developed model is to use existing droplet size prediction models in literature to provide dv50 sizes based on input parameters and not droplet size measurements. Models should be validated against reported data in literature, for instance reported droplet size values in Paper V, Chapter 7. Further model improvement is needed for oil-continuous inlet regimes, where the current model fails to predict separator performance.

6. MY NEW JOB

Company/institution:	Equinor ASA
Position/area of work:	Researcher Subsea Technology and Operations

ASSOCIATE PROFESSOR
JOHANNES JÄSCHKE

RESEARCH AREA
MANAGER

RESEARCH AREA

System control

Automatic control systems and digital twins contribute to autonomous intelligent production systems that ensure safe and optimal operation of subsea production and processing systems.

Subsea production and processing installations are not easily accessible, and our vision is that they should be operated autonomously. This means that the equipment should regulate and monitor itself, hence reducing the need for human interaction and supervision. The research area Systems Control covers the development of new methods, models and tools related to autonomous, safe and optimal operation of such complex subsea processes.

Our current research focus is on

- Control algorithms for Energy-efficient production and processing
- Combining data-driven machine learning methods with first principles models to achieve optimal and autonomous system operations
- Operational strategies for short and medium-term production optimization
- Production optimization taking equipment condition into account
- Estimation algorithms for estimating unmeasured process quantities (e.g. VFM)

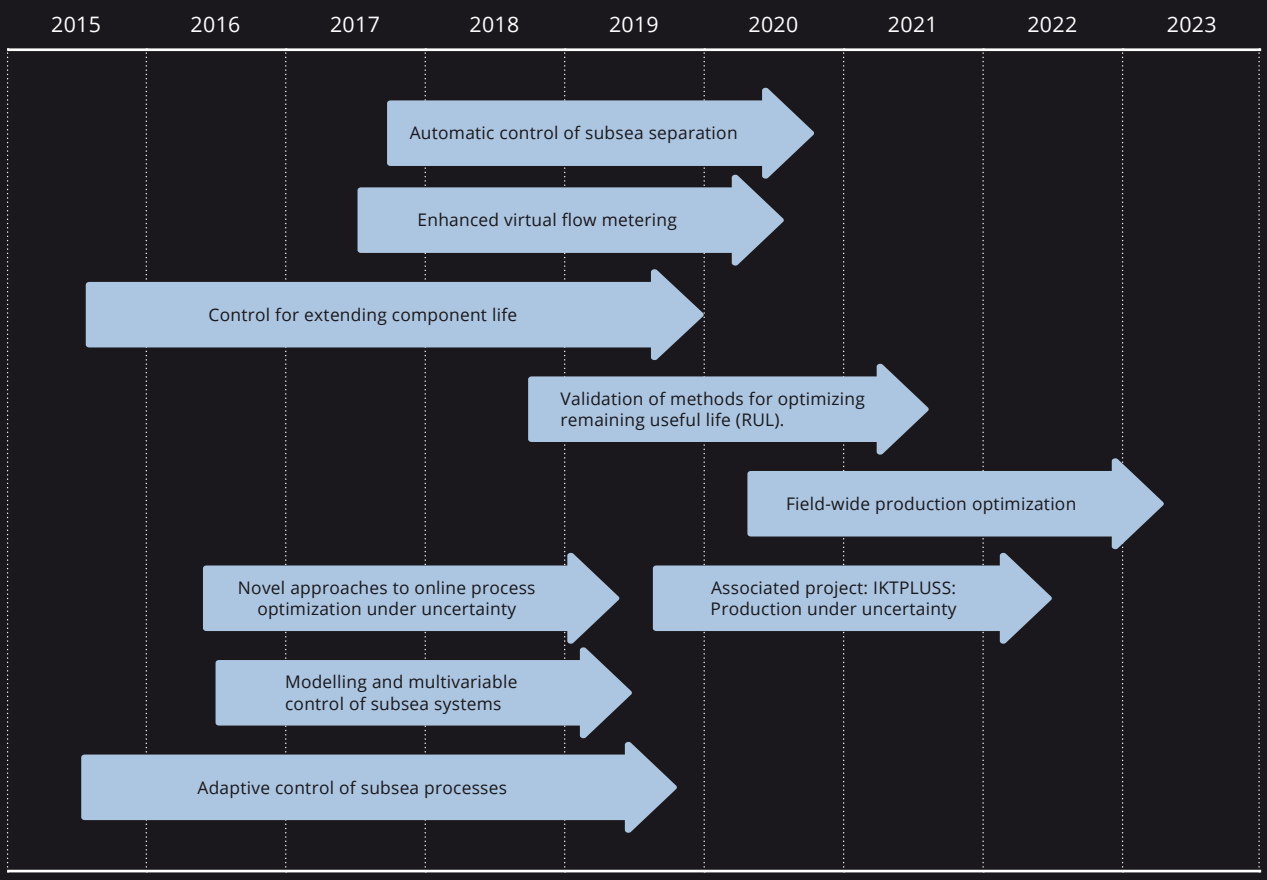
The developed models are based on first-principles physics as well as data and machine learning. Controller, estimation and optimization algorithms are developed using state-of-the-art methods and industrially relevant case studies. Among others, we consider applications in subsea separation processes, boosting (multiphase pumping and compression), as well as optimization of systems of gas-lifted wells. The overall aim is to develop tools and methods that are simple and robust enough for use in real subsea applications, and that react optimally to changing operating conditions.

During 2019, three projects were completed; “Novel approaches to online process optimization under uncertainty”, “Adaptive control of subsea processes” and “Modeling and multivariable control of Subsea systems”.

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

Consult page 60, for new projects with kick off planned in 2020.

Completed, current and planned projects



The system control team:
From the left: PhD student Leonardo Sales*, Postdoctoral fellow Dinesh Krishnamoorthy, visiting PhD student Felipo Doval Rojas Soares (Intpart project), PhD student Risvan Dirza (on the black board), Professor Sigurd Skogestad, Associate professor Johannes Jaschke, PhD student Mishiga Vallabhan, associate PhD student Allyne dos Santos (Faculty of Natural Sciences NTNU), associate PhD student Ana Carolina Ferreira da Silva Vaz (Intpart project), Postdoctoral fellow Jose Otavio Assumpcao Matias and Associate professor Christian Holden.

*The PhD student Leonardo Sales project is part of the Research area Field Architecture, being a PhD at department of Chemical Engineering, Leonardo is also associated with the System Control team.

Automatic control of subsea separation

Digital solution to reduce environmental footprint.

Green Shift:
- **Cleaner discharged water.**
- **Removal of water at subsea reduces energy consumption.**

PhD student:
Mishiga Vallabhan

Project manager
and main supervisor:
Associate Professor
Christian Holden

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

INDUSTRIAL CHALLENGE

Subsea production and processing units need to be compact in nature. Huge gravity separators used at the topside facilities are not a feasible choice at subsea with water depth of 3000 meters. Hence, compact separation solutions are a wise choice in deep-water subsea environments. One possible solution could be to use compact first stage separators such as pipe separators and then use a series of hydrocyclones. When the equipment becomes compact, there arises a need for advanced control technologies to optimize the operation. This project mainly focuses on the produced water treatment using hydrocyclones and methods to improve and optimize the operation of hydrocyclones.

Produced water can be used for water re-injection to build up pressure in oil wells and enhancing the production, or it can be discharged to sea, if oil contents can be reduced to the required level. The discharge of produced water to the sea is regulated internationally by the OSPAR commission, which has specified the limit as 30 mg of dispersed oil per liter of produced water. Hence it is important to maintain the efficiency of water treatment equipment in all operating environments.

The goal of this project is to:
1. Develop a mathematical model and model-based controllers and estimators for de-oiling hydrocyclones.
2. Build a test rig with three hydrocyclones connected in series and a pump system to emulate the first stage separation.
3. Validate newly developed models, controllers, and estimators using the laboratory experiments.

RESEARCH DONE SO FAR

A mathematical model based on first-principles has been developed for hydrocyclones. This model can give an estimate of oil in water concentration at the underflow of a hydrocyclone. The knowledge of oil content at the outlet enables the operation of hydrocyclones adhering to the governmental regulation. This model can also be utilized to maximize the throughput of hydrocyclones while keeping the outlet oil concentration at the required level. Close monitoring of oil content in the produced water treatment system ensures that oil discharge into the sea is always below the permitted level and hence, reducing the environmental footprints.

The compact separation laboratory is in the testing and commissioning phase. The pump system with a control valve can emulate a first-stage gravity separator, and is expected to deliver the oil droplet sizes and PPM of oil in water equivalent to that of a real gravity separator. Discussions with the industry partners (Equinor and Aker solutions) helped us to select the right control valve for the system.

INDUSTRIAL USAGE OF THE RESULTS

After validation, models, controllers and estimators for hydrocyclones could be used by industry as part of their control software. An oil-in-water sensor will be installed in the test rig and the possibility of controlling hydrocyclones using measurement from these sensors will be investigated. The experimental results could be useful for industry to improve the operational efficiency of produced water treatment systems.

INDUSTRIAL BENEFITS
- Enable subsea separation .
- Reduce the need for sending produced water topside.
- Pressure support by injection.

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

Enhanced Virtual Flow Metering

Applications of hybrid modelling approaches using modern machine learning techniques to accurately describe multiphase flow production.

PhD student:
Timur Bikmukhametov

Supervisor:
Associate Professor Johannes Jäschke

WHY DO WE NEED SUBSEA FLOW METERING?

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

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

This project aims to improve the understanding of this technology and develop of new methods for accurate and robust multiphase flowrate estimates. The project has a close collaboration with Equinor through developing and testing the models on real field data.

COMPLETED AND ONGOING WORK

So far, the following has been done:

- Hybrid modeling approaches using first principles and machine learning techniques have been developed
- A first principles VFM software based on OLGA and MATLAB has been developed
- Influence of sensor degradation on flowrate estimates based on statistical methods has been studied
- A study of applying machine learning algorithms for VFM has been performed

The ongoing work and future plans include:

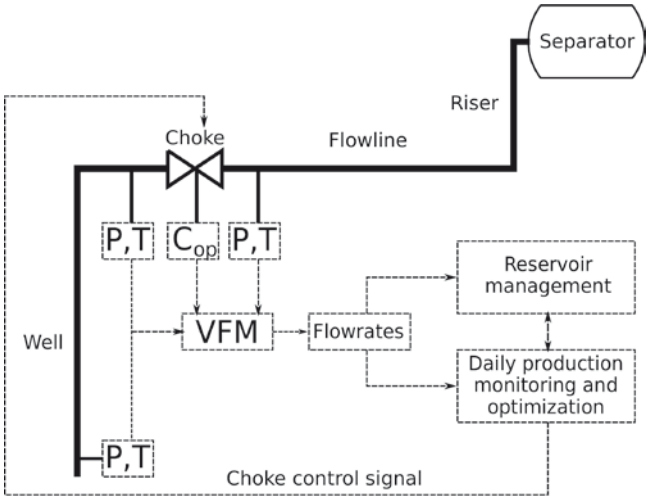
- Develop algorithms for estimation of first principles model uncertainty using machine learning techniques.

POTENTIAL FOR INDUSTRIAL APPLICATIONS

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

FUTURE WORK

The models developed in the project will further be used in a project of digital twin re-calibration and decision making under the supervision of Johannes Jäschke.



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

Control for extending component life

A new method for safe and economical operation.

Green shift impact: Safer and more reliable operation of O&G assets reduces environmental impact.

PhD student:
Adriaen Verheyleweghen

Project manager and main supervisor:
Associate Professor Johannes Jäschke

WHY DO WE NEED CONTROL FOR EXTENDING COMPONENT LIFE?

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

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

METHODS, TOOLS AND MODELS DEVELOPED IN THIS PROJECT:

So far, the following has been developed:

- A model for compressor degradation and the optimal control of a compression station
- A model for choke erosion and the optimal operation of a gas network
- Methods for systematic handling of model uncertainty
- A method for optimal scheduling of production and maintenance
- A controller for control of a Greitzer compressor model, subject to surge/oscillation-induced degradation
- An extension to a Greitzer model based on actuation by a close-coupled valve (CCV) as well as the drive torque applied to the compressor shaft (in collaboration with the project Dynamic simulation model library and project 3.9 Production optimization)

HOW CAN CONTROL FOR EXTENDING COMPONENT LIFE BE USED IN INDUSTRY?

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

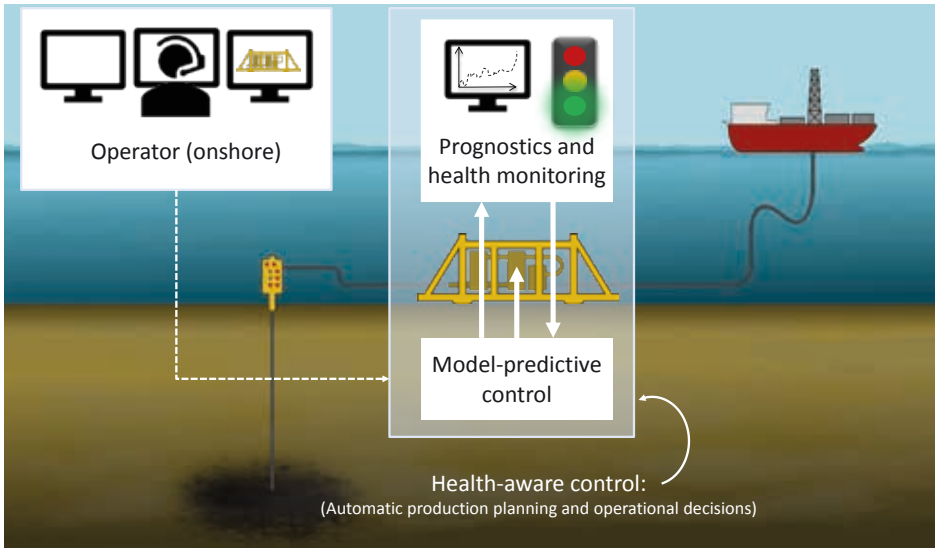
- Gas compressors / rotating machinery
- System-wide production and maintenance optimization
- Scheduling of gas turbine washing
- Test frequency for safety critical valves (see the project "Reliability and availability assessment in subsea design")

FURTHER WORK: EXPERIMENTAL VERIFICATION

The methods developed in my project are to be tested experimentally and further developed in project 3.8b by post.doc. José Matias.

MY NEW JOB

I now work as a senior control engineer in Cybernetica AS, where I develop non-linear model predictive control (NMPC) solutions for process industry. Currently I work on an O&G project where my background from SUBPRO is very useful.



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

Validation of Methods for Optimizing Remaining Useful Life (RUL)

Combining process optimization and equipment health monitoring leads to a cost-effective and safe operation.

Green shift impact: Assets that are properly managed can survive for longer periods, optimizing life cycle and reducing environmental impact.

Postdoc:
Jose Otavio Assumpcao Matias

Project manager and supervisor:
Associate prof. Johannes Jäschke

1. USING REAL-TIME DATA TO SUPPORT ACCURATE DECISION-MAKING ON OPTIMIZATION AND MAINTENANCE

There is an intuitive trade-off between optimizing production and minimizing equipment degradation. In oil wells, for example, we would like to extract as much oil as possible. However, such strategy has a negative effect on the remaining useful life of the equipment. Choke valves tend to degrade faster if we increase the throughput, for instance.

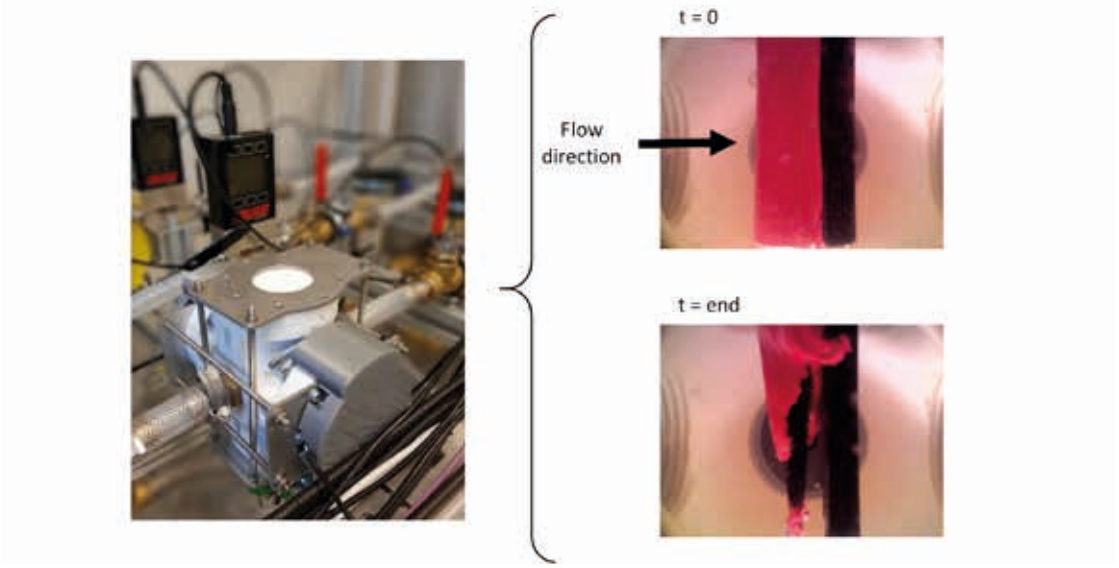
In the previous SUBPRO project "Control for extending component life", we proposed a robust model predictive control approach that incorporates degradation models in order to balance both objectives. The main idea is to proactively control the system degradation, rather than simply reacting to it, while optimizing production. The developed methods have been tested in simulated case studies. The results showed that, by applying our strategy, we will not only enhance operational performance but also prevent violation of health-critical constraints and improve planning of maintenance activities. Now, in this project we plan to test the approaches in a lab rig with eroding parts.

2. SETTING UP AN EXPERIMENTAL RIG TO VALIDATE OUR METHOD

An experimental rig has already been built in order to verify the proposed controller strategy in a more realistic environment. It emulates a 3-well network in which a mixture of water and air flows through an intrusive probe that represents the choke valves. After developing a reliable model for the remaining useful life of the probes, our control strategy is going to be implemented and tested, which is important for learning its pros and cons as well as possible implementational risks. Additionally, the rig can provide valuable data for studying how machine-learning techniques can be used to develop data-driven diagnostic and prognostic models.

3. HOW OUR APPROACH CAN BE USED BY THE INDUSTRY?

By monitoring how long critical assets, such as subsea equipment, can survive, our control approach can be important not only for a cost-effective but also for a safer operation. Potentially, it could prevent damage to valuable equipment, human life losses and even environmental disaster due to system overuse. Additionally, we can ensure that the facilities remain operational until the next planned maintenance, with no unplanned shutdowns due to premature equipment failures.



The left figure shows the "erosion box" of one the wells. The intrusive probe is placed inside this box, which also contains a set of cameras for monitoring the probe erosion. The figures on the right show the evolution of the probe during an experiment. By modeling the correlation between flowrates and pressures with the probe erosion, we can include this accurate model into the advanced control and test our approach in a more realistic setting.

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 in reducing the carbon footprint of the daily operations.

PhD Student:
Risvan Dirza

Project manager
and main supervisor:
Professor
Sigurd Skogestad

Co-supervisor:
Dr. Dinesh
Krishnamoorthy

THE ROLE OF FIELD-WIDE PRODUCTION OPTIMIZATION

With increasing energy demands, stringent emission regulations and volatile oil process, 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 on a day-to-day basis. With the recent focus on low carbon footprint of oil and gas operations, the daily production optimization must also aim to reduce the carbon footprint of day-to-day operations in addition to the main objective, increasing production rates.

In order to take into account, the carbon footprint of the subsea production network, it is important to consider a common end-to-end processing system such as subsea wells, subsea compact separators, subsea compressors and booster pumps in the daily production optimization problems. Therefore, this project will take a holistic view of the production field.

UTILIZING DATA MAY REDUCE THE COMPLEXITY OF THE MODELS

The production optimization requires detailed model of the system to determine the optimal operation of the field. However, as the complexity of the systems increases, the models used may be uncertain or may not be able to capture the real production system accurately. In order to address this issue, we propose to incorporate real time production data into real time decision making, by using machine-learning algorithms.

RESEARCH ACTIVITIES

In this project, we will deliver several activities as follows:

1. To apply newly developed algorithms in industrial case that may consider the holistic production system:
   - In the previous project, Production Optimization under Uncertainty (by- Dinesh Krishnammorthy: former SUBPRO PhD student), we have developed different algorithms that can use such transient measurements efficiently in the production optimization problem to increase the potential of real time production data.
2. To develop new machine learning based algorithms for online production optimization:
   - If the algorithm is combined with the existing first-principle models, it results in what is called a grey-box model. Such a model is more flexible and has potential for further savings.
3. To develop new distributed algorithms for shared resources among the wells operated by different companies.
   - Considering current volatile oil price, several companies decided to collaborate in operating oil production fields. Therefore, a certain strategy in coordination level should be developed as part of distributed algorithms.
4. To implement simple control loops in order to achieve optimal operation:
   - Simple feedback control loops, that do not require complex models nor additional software tools to implement, are beneficial. Especially in brownfield wells where the motivation to implement advanced optimization tools is low. This approach is also easy to implement, tune and maintain by production engineers and operators and hence is more likely to receive operator acceptance.

It is expected that the results from this project can be used for automated field-wide production optimization to increase daily operating income and to reduce operator workload. Resulting in a safer, environmental-friendly, and in a better optimized production.

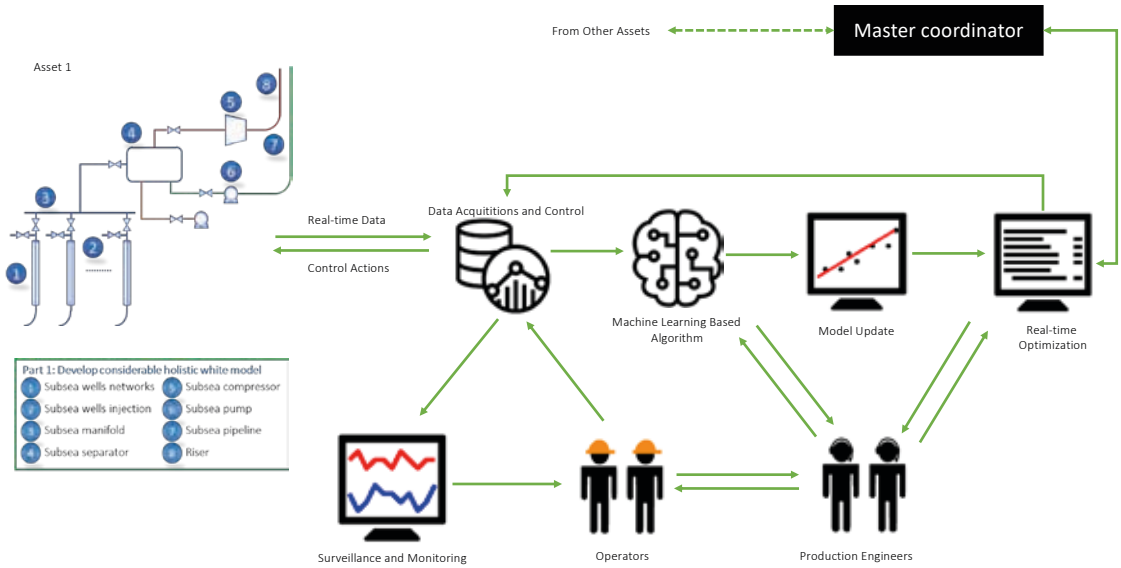


Illustration of the field-wide production optimization systems.

Production optimization under uncertainty

Enabling Industrial Symbiosis in subsea oil and gas production (An associated project with IKTPLUSS).

Post-doc:
Dinesh Krishnamoorthy

Project manager and main supervisor:
Professor
Sigurd Skogestad

INDUSTRIAL SYMBIOSIS IN SUBSEA OIL AND GAS PRODUCTION

As the era of easy oil is declining, the complexity of oil and gas operations is ever increasing. With increasing energy demands, stringent emission regulations and volatile oil prices, there is an increased focus on reducing capital expenditure (CAPEX). Consequently, the optimal operation of an oil and gas production network is becoming a challenging task, where decisions have to be taken in real-time to meet production goals and emission targets. Real-time optimization (RTO), also known as daily production optimization, plays an important role in optimizing the day-to-day operations of the oil and gas production network.

In order to stay competitive, the offshore oil and gas sector is embracing an "Industrial Symbiosis" setting, where several groups of wells operated by different companies produce to a common processing facility with shared resources, e.g. subsea tie-ins with shared processing. Such mutually beneficial exchange of materials and resources between different organization is known as Industrial symbiosis.

CURRENT INDUSTRIAL CHALLENGE

The overall optimal operation of subsea production system with tie-ins involves sharing detailed information about the production network, in the form of models, real time measurements, local constraints and the objective function across the different organizations involved, which may not be desirable due to several reasons such as intellectual property rights and market competitiveness. Therefore, there is a clear need to optimize such process with limited sharing of information across the different organizations, in order to enable optimal operation in an industrial symbiotic setting.

ACHIEVING OPTIMAL OPERATION THROUGH A NOVEL DISTRIBUTED OPTIMIZATION FRAMEWORK

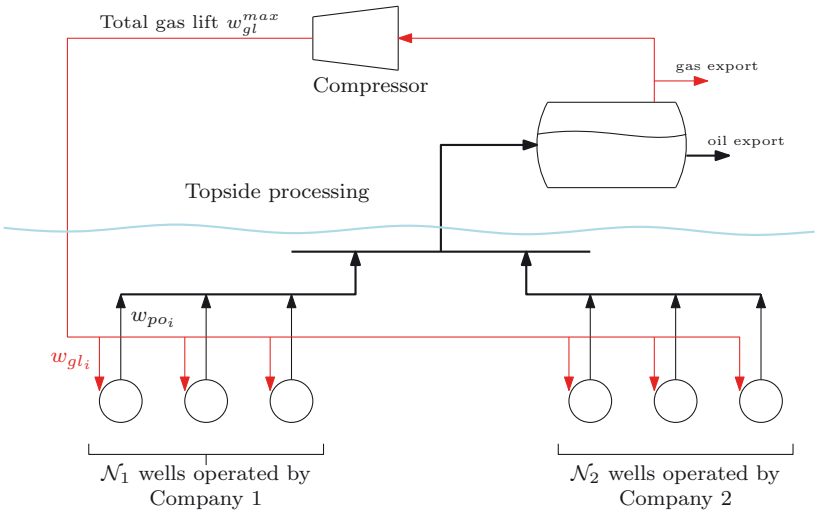
One potential solution that facilitates such industrial symbiosis is the distributed optimization framework, where the different subsystems are modelled and optimized individually. The subproblems report only limited information, such as the price and the shared resource consumption to a master co-ordinator, which then co-ordinates the different subsystems in order to achieve optimal operation. This way, the different operators avoid the need for sharing the detailed models, real time measurements and local constraints with one another.

In this project, we investigate different tools and methods in order to optimize production from a subsea production network with complex tie-ins involving several stakeholders.

RESULTS SO FAR:

- Distributed steady-state RTO framework using transient measurements with limited information sharing. (accepted for publication in the proceeding of 2020 American Control Conference).

This project will be lnked to the newly funded IKTPLUSS project from the research council of Norway, where the main objective is to efficiently utilize data for process optimization.



Industrial symbiosis in subsea oil and gas production. Illustration of the subsea wells operated by different companies, sharing the same processing facility.

FINAL PROJECT REPORT

Novel approaches to Online Process Optimization under Uncertainty

Addressing the limiting factors with current industrial practice.

PhD graduate: **Dinesh Krishnamoorthy**

Start date: 18.07.2016
Thesis defense date: 07.11.2019
Title of thesis: Novel approaches to online process optimization under uncertainty
Thesis committee members: Professor Manfred Morari (ETH Zürich/ U Penn),
Professor Jay H. Lee (KAIST, South Korea),
Professor Sebastian Gros (NTNU, Norway)
Supervisors: Professor Sigurd Skogestad - Professor Bjarne A. Foss - Associate Professor Johannes Jäschke

1. BACKGROUND FOR THE PROJECT

In the face of growing competition and the increased necessity to focus on sustainability and energy efficiency, there is a clear need to optimize the day-to-day operation of many industrial processes. One strategy for online process optimization is to use model-based real-time optimization (RTO). Despite the motivation and the potential, real-time optimization is not commonly used in practice as one would expect. This thesis takes a detailed look at the different challenges that impede practical implementation of real-time optimization and aims to address some of these challenges.

One of the fundamental limiting factors of traditional steady-state RTO is the steady-state wait time. This essentially discards transient measurements, which otherwise contains useful information. In part I of this thesis, we propose different approaches to use transient measurements for steady-state optimization, with the goal of minimizing the steady-state wait time. Moreover, different algorithms to real-time optimization that do not require the need to solve numerical optimization problems are proposed, thus alleviating many of the challenges which impede practical application of traditional RTO approaches.

The main challenges which limits the industrial use of RTO include:

- **Challenge 1** - Cost of developing the model (offline).
- **Challenge 2** - Model uncertainty, including wrong values of disturbances and parameters (online update of the model).
- **Challenge 3** - Numerical robustness, including computational issues of solving optimization problems.
- **Challenge 4** - Frequent grade changes, which makes steady-state optimization less relevant.
- **Challenge 5** - Dynamic limitations, including infeasibility due to (dynamic) constraint violation.
- **Challenge 6** - Problem formulation - choosing the right formulation for the right problem.

2. WHAT I HAVE DONE

The main contributions of this thesis are the novel methods and algorithms that are proposed in the different chapters to address the challenges listed above. The solutions proposed to address the limiting factors of current industrial practice are divided into two parts.

First, I propose a “hybrid” approach, where the model adaptation is done with transient measurements and dynamic models, and the optimization is performed using steady-state models. To further simplify the steady-state optimization, I then convert the hybrid RTO approach into a feedback RTO approach. Here, the transient measurements are used to estimate the steady-state gradient, which is controlled to a constant setpoint of zero using feedback controllers. The steady-state gradient is estimated using a novel method based on linearizing the nonlinear dynamic model around the current operating point.

To address the cost of developing models, I demonstrate the use of classical controllers along with simple logic blocks to achieve optimal operation over different active constraint regions. I also propose a novel extremum seeking scheme using transient measurements that converges significantly faster than the classical extremum seeking scheme. Finally, I conclude Part I of this thesis, by showing that the different methods work in different time scales and by hierarchically combining the different approaches, one can handle a wider class of uncertainties.

In the second part of the thesis, I take a different approach, and focus on addressing the computational cost of solving dynamic optimization problems under

uncertainty. In particular, I consider the multistage scenario-based formulation, where the evolution of uncertainty in the prediction horizon is represented via a discrete scenario tree. I show that the resulting large-scale optimization problem can be decomposed into several smaller subproblems and argue in favor of using primal decomposition over dual decomposition. Since the different scenarios differ only in the uncertain parameters, we show that the distributed scenario NMPC problem can be cast as a parametric nonlinear programming (NLP) problem. By using the NLP sensitivity, we do not need to solve all the subproblems as full NLPs. Instead they can be solved exploiting the parametric nature by a path-following predictor-corrector algorithm that approximates the NLP. To this end, I show that the computational cost of solving the multistage scenario-based problem can be significantly reduced.

Finally, I also present a stabilizing adaptive horizon economic NMPC framework, where the length of the prediction horizon is updated in order to reduce the problem size, thereby reducing the computational cost.

In addition, I also consider some important research questions related to the topics presented in my thesis and present some exploratory ideas that paves the way for future research. For example, for the multistage scenario-based NMPC problem, I show how data analytic tools can be exploited to select the discrete scenarios. I also present an adaptive-robust framework to update the scenarios online using recursive Bayesian likelihood. Finally, I discuss the promises and future research direction of using machine learning tools for online process optimization.

3. MAIN RESULTS

- Developed a "Hybrid" RTO approach – steady-state optimization using transient measurements
- Presented a feedback RTO approach using a novel, model-based gradient estimation using transient measurements
- Provided a systematic approach to using classical control structures along with simple logics to achieve optimal operation. This may be immediately applicable in practice, since this is based on tools that have been in use in the offshore industry for several years.
- Developed a fast-robust model-free optimization algorithm that effectively uses transient measurements
- Presented a synergetic combination of self-optimizing control and extremum seeking control.
- Showed that the multistage scenario-based approach is a promising method to handle uncertainty in dynamic optimization problems
- Developed a primal decomposition algorithm to decompose the scenario-based approach to tackle the problem size.
- Further improved the computation time, by recasting the scenario-based optimization problem into a parametric optimization problem and exploit the NLP sensitivities.
- Provided a computationally efficient framework for dynamic optimization based on truncating the length of the prediction horizon.
- Presented a data-analytics approach to select the scenarios of the multistage scenario-based optimization problem.
- Presented a robust-adaptive framework to update the uncertainty set online using recursive Bayesian probability.
- Provided a comparison of the different approach to online process optimization, which can be seen as a guideline to choosing the right formulation for the right problem.

4. INNOVATION AND COLLABORATION WITH INDUSTRY PARTNERS

The novelty of this project is the several different algorithms and methods presented to address the current industrial challenges. As mentioned earlier, the main research focus of this thesis is motivated by the realization that real-time optimization is not used as much in practice as one would expect. We consider the different challenges in detail and provide various solutions to address the different challenges listed above. Furthermore, the method proposed in Chapter 4 may be immediately applicable in practice, since this is based on classical feedback controllers and simple logic blocks that are used widely in process industries.

The different approaches and algorithms proposed in this thesis are based on control technologies that have a high impact on industry. In April 2019, the industrial committee of the International Federation of Automatic Control (IFAC) published a list of control technologies

Table 1.1: Control technologies used in the thesis, along with its impact based omn the industrial survey from the 2019 IFAC newsletter [170]

CONTROL TECHNOLOGY	CURRENT IMPACT	FUTURE IMPACT	USED IN CHAPTER
Pid Control	91%	78%	3,4,6
System Identification	65%	72%	5
Estimaton And Filtering	64%	63%	2,3,8
Model Predictive Control	62%	85%	2,7-13
Process Data Analytics	51%	70%	12,13
Fault Detection	48%	8%	-
Decentralized/Coordinated Control	29%	54%	9,10,App J
Robust Control	26%	42%	-
Intelligent Control	24%	59%	-
Nonlinear Control	21%	42%	-
Discrete-Event Systems	24%	39%	-
Adaptive Control	18%	44%	-
Repetitive Control	12%	17%	-
Other Advanced Control	11%	25%	-
Hybrid Dynamical Systems	11%	33%	-
Game Theory	5%	17%	-

along with its current and future impact. Comparing this survey results, it can be seen that the different methods and algorithms proposed in this thesis are in fact, based on the top five control technologies listed in this survey. This is shown in Table. 1.1, which is indicative of the industrial relevance and impact of this thesis, now and in the future.

5. FURTHER WORK

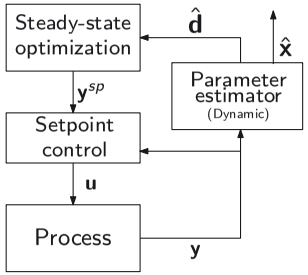
The study arises some question that may be for further research in several directions.

- A natural extension to the Hybrid RTO approach presented in Chapter 2, is to develop the Hybrid RTO approach for large-scale distributed process systems. Here, the optimization is performed for small clusters of process units and a master problem is used to co-ordinate the sub-problems.
- A fast extremum seeking control scheme was proposed for a class of Hammerstein plants in my work. One future research direction is then to extend this to any generic dynamic process. The adaptive horizon economic NMPC proposed in Chapter 11 considered a deterministic problem. Therefore, a natural step would be to apply the adaptive horizon algorithm to the multistage economic NMPC problem.
- Using purpose-built machine learning models to address the challenges of online process optimization.

6. MY NEW JOB

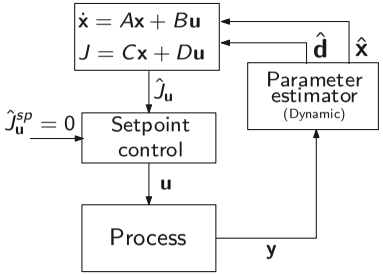
Company/institution: NTNU
Position/area of work: post-doc

Hybrid RTO



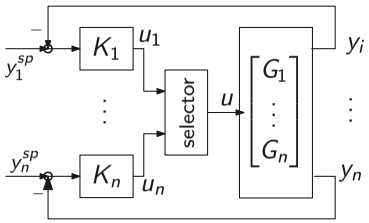
Challenge 2 & 5

Feedback RTO



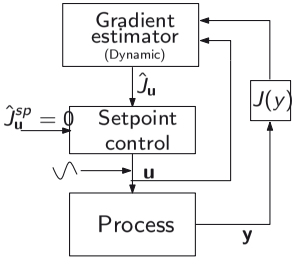
Challenge 2,3 & 5

Optimization using simple controllers



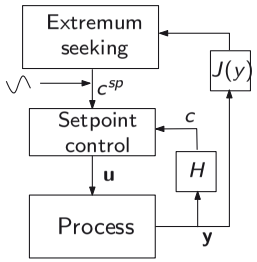
Challenge 1,2,3 & 5

Extremum seeking using transient measurements



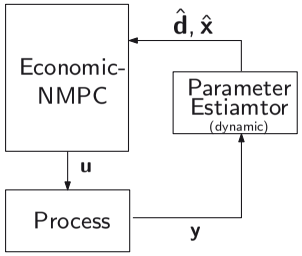
Challenge 1,2,3 & 5

Extremum seeking + Self-optimizing control



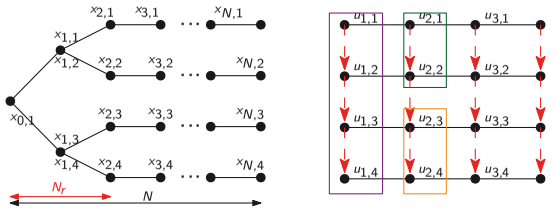
Challenge 1,2,3 & 5

economic MPC



Challenge 3,4& 5

Distributed multistage MPC using primal decomposition



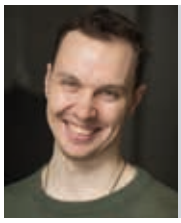
Challenge 3, 4 & 5

Schematic representation of the different approaches to online process optimization studied in the project, and the different challenges it addresses.

FINAL PROJECT REPORT

Modelling and multivariable control of subsea systems

Digital twins based on mathematical models are important for cost-efficient operation and the development of digital software solutions.



PhD graduate: **Torstein Thode Kristoffersen**

Start date: 01.02.2016
Thesis defense date: 12.04.2019
Title of thesis: Subsea Compact Separation and Wet Gas Compression
Thesis committee members: Professor John Bagterp Jørgensen (DTU, Denmark), Doctor Olav Slupphaug (ABB, Norway)
Supervisor: Christian Holden (NTNU, Norway)

1. BACKGROUND FOR THE PROJECT

Today most of the large oil and gas discoveries have been developed and are near exhausted with declining pressures. New oil and gas discoveries are smaller and located in more remote areas at deeper waters. The focus of the oil and gas industry is in cost-efficient increased hydrocarbon recovery (IHR) and development and production of these new discoveries.

The oil and gas industry visualize a complete subsea factory for cost-efficient production in remote areas and for IHR of existing fields. Cost-efficient operation is essential for the realization of the subsea factory. A digital twin of the subsea factory is a digital replica that simulates the physical behavior based on inputs and mathematical models of the subsea processing equipment. The digital twin allows for development of software tools for cost-efficient operation through:

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

The focus of this project has been the development of the mathematical models, based on first-principles, of separation and boosting processes required for the development of a digital twin. This also includes the development of estimators for estimation of unmeasured variables and development of controllers for safe and optimal operation.

2. WHAT I HAVE DONE

This project has resulted in the development of models of a compact gas-liquid separation and a wet gas compression system, as these are the most important and dynamic parts of a simple subsea factory. These models are derived from first-principles providing insight into the process dynamics and can be used for:

- prediction of the future behavior of these system for changing inputs
- design of estimation algorithms for estimation of unmeasured variables
- design of control algorithms for safe and optimal control.

A process flowsheet of a simple subsea factory is shown in Figure 1, illustrating the compact gas-liquid separator and wet gas compressor.

The developed models have been used for the development of several stochastic and deterministic algorithms for estimation of unmeasured variables, and for the development of optimal and provably safe control algorithms.

The models have also been used in cooperation with other projects within SUBPRO.

3. MAIN RESULTS

The main results of this project are:

1. the development of model of a gas-liquid cylindrical cyclone with only initial separation performance for prediction of the separation performance for varying inputs and for the design of estimation and control algorithms
2. the development of a provably safe control algorithm for noisy measurements of the model (1)
3. the development of an estimation algorithm of estimation of the separation performance of the model (1)

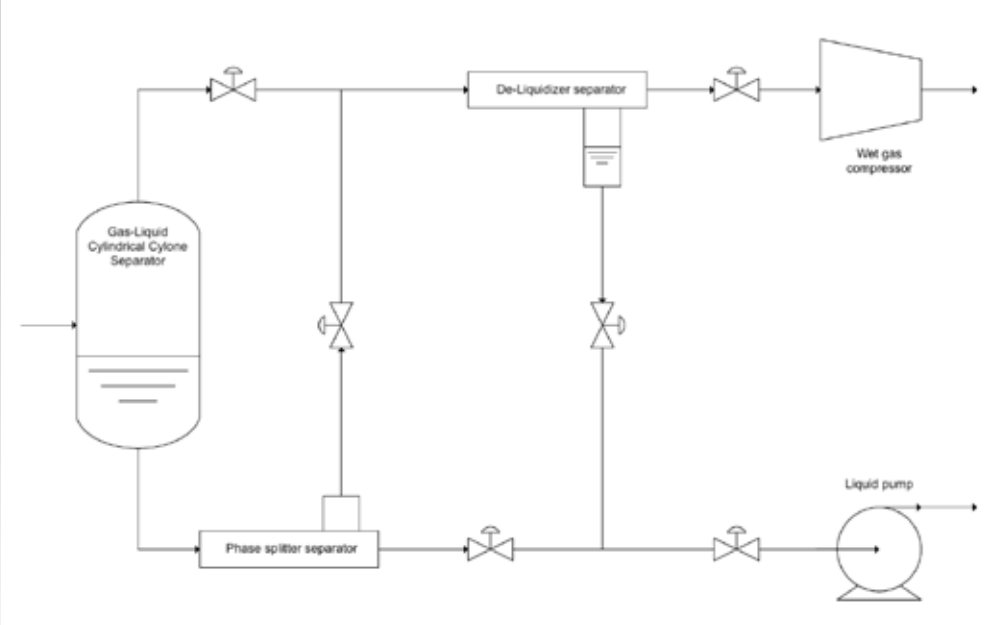


Figure 1: Process flowsheet overview of a simple subsea factory for gas-liquid separation, liquid boosting and wet gas compression. The models for Gas-Liquid Cylindrical Cyclone (GLCC) separator and the wet gas compressor have been developed as part of this thesis. The performance of the phase splitter and de-liquidizer separators can be modelled by conventional split models, while the performance over the liquid pump can be modelled by affinity laws.

4. the development of an optimal control algorithm for improved gas purity of the model (1)
5. the development of an improved provably safe control algorithm using fewer measurement of the control algorithm (2)
6. the development of an improved separation model of the model (1) including the continuous separation performance for improved prediction of the separation performance for varying inputs and for the enhanced design of estimation and control algorithms
7. the development of an optimal control algorithm for improved gas purity of the model (6)
8. the development of an optimal estimation algorithm of estimation of the separation performance of the model (6)
9. the development of a wet gas compression model for prediction of the compression performance for varying inputs and for the design of estimation and control algorithms
10. the development of a provably safe control algorithm for constant inputs for the wet gas compression model (9)
11. the development of a provably safe control algorithm for varying inputs for the wet gas compression model (9)
12. the development of a provable convergent estimation algorithm for the wet gas compression model (9)

4. INNOVATION AND INDUSTRY COLLABORATION

This project has been concerned with basis research and development of models for improved insight and for the development of estimation and control algorithms.

The initial industry collaboration has been the exchange of operation data for validation of the developed models.

Future collaboration including robustification of the developed estimation and control algorithms and application in laboratory and/or plants.

5. FURTHER WORK

Suggestion for future work include:

- Validation of the developed models
- Combining the developed models into a subsea processing system and study of optimal design (e.g., size of separators, compressor gradient, etc.) and design of estimation and multivariable control algorithms
- Use of estimation algorithms for condition monitoring and development of metrics for defining need for maintenance or replacement

6. MY NEW JOB

Company/institution: Equinor ASA, Trondheim, Norway
Position/area of work: Senior Automation Engineer

FINAL PROJECT REPORT

Adaptive control of subsea processes

Controlling uncertain systems.

PhD graduate: **Sveinung Johan Ohrem**

Start date: 10.08.2015
Thesis defense date: 06.12.2019
Title of thesis: Adaptive control of subsea processes
Thesis committee members: Jakob Stoustrup, Jing Zhou, Lars Tingelstad
Supervisor: Christian Holden, Sigurd Skogestad, Olav Egeland

1. BACKGROUND FOR THE PROJECT

Most subsea processes are governed by nonlinear dynamic equations with many uncertain, unknown or varying parameters. Furthermore, the operating ranges and external disturbances to the process changes over time. Designing a control algorithm capable of maintaining the desired level of stability and performance for such systems is not trivial. The control algorithms used today often require re-tuning and intervention from operators, hence, this project focuses on developing adaptive control algorithms capable of self-adjusting in order to meet the control objectives. Adaptive control algorithms are very similar to machine learning algorithms which plays a huge role in the digitalized future of the oil and gas industry.

2. WHAT I HAVE DONE

In this project, we have developed and applied adaptive control algorithms to various subsea processing and production equipment. One control algorithm is developed exclusively for the gas liquid cylindrical cyclone (GLCC). The stability of the control algorithm is proven through well-established stability theory and a newly developed model of the GLCC is used in the proof. We have also applied a model-free optimization method to the GLCC, showing that simple methods are capable of achieving close to optimal operation.

We have applied adaptive control methods to the anti-slug test rig and to the newly developed multi-pipe separator laboratory, showing that these methods also work in practice.

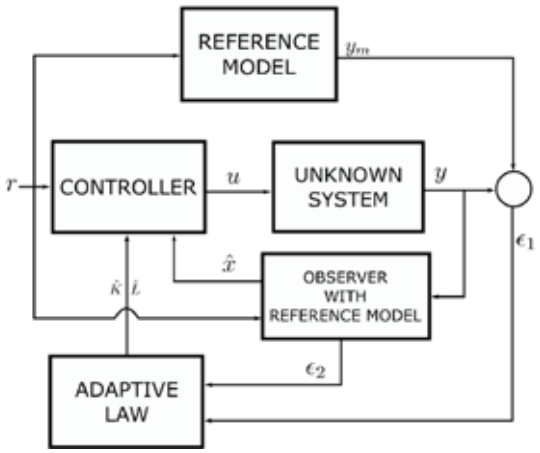


Figure 1: The novel controller and observer solution.

Our latest result is a new, combined adaptive controller and observer solution for systems with unknown parameters. This method has very interesting qualities, as it allows us to use measurements generated by a model, rather than the real measurements, which may be unavailable or contaminated, and still achieve the desired control objective with proven stability.

This project has collaborated with two other subprojects outside the control systems group in SUBPRO. A collaboration with HyungJu Kim from the RAMS group resulted in a conference paper where we compared adaptive control algorithms to conventional control algorithms from a safety perspective. The results showed that adaptive controllers are less prone to human errors. Furthermore, we found that it is important to consider what type of controller is used when performing a safety analysis.

3. MAIN RESULTS

- An adaptive controller for gas liquid cylindrical cyclones
- An adaptive controller for anti-slug control
- A control structure analysis, and controllers for the new multi-pipe separator
- An analysis of hazards and efficiencies of adaptive and conventional control algorithms
- A novel controller and observer scheme for systems with unknown parameters

4. INNOVATION AND INDUSTRY COLLABORATION

Adaptive control algorithms are readily available for industry partners. As these algorithms exist of some lines of code, they can be implemented if the company chooses to do so. One of the more important findings, in my own belief, stems from the hazard analysis. We are uncertain whether the type of control algorithm is considered when hazard analysis are performed today. Our results shows that this is important, and the industry partners should consider this.

5. FURTHER WORK

The new controller and observer scheme should be implemented in a laboratory for verification. This method could possibly be extended to nonlinear systems which would greatly improve the method. Some more mathematical analysis of the method should also be carried out, i.e., the transient behavior of the states should be evaluated mathematically.

6. MY NEW JOB

Company/institution: SINTEF Ocean
Position/area of work: Seafood technology

PhD education

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

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

INDUSTRIAL EXPOSURE

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

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

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

The PhD students present their work at industrial conferences like Subsea Valley 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. Gradually, this has become the working culture of SUBPRO. The PhD students arrange tech-lunches at regular intervals, and many of the projects collaborate on common development tasks.

INTERNATIONAL COLLABORATION

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

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

Postdoc Dinesh Krishnammorthy presenting a topic about "Optimization" in a SUBPRO Tech-Lunch.

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

Master students and summer jobs at SUBPRO

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

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

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

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

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

Picture taken in 2018: Group session In Experts in Teamwork. Group facilitator, Associate Professor Brian Arthur Grimes in the background. Students from left around the table: Anders Runningen, Siri Wetjen, Carita G. Ranvik, Kristine Maria Nettum, Martin Sanden and Rehema Kivuyo.

During the summer of 2019, SUBPRO offered (5) six weeks summer internships for fourth-graders students from NTNU.

Meanwhile, the option to continue with the industry-oriented specialization project during the fall of 2019 and the Master thesis during the spring of 2020, was offered to the students.

The topics of the internships covered various research areas from SUBPRO and were further defined by the supervisors and the elected students.

The final elected topics in 2019 summer internships, were the followings:

- 3D Printing for Microfluidics
- Fluid Particle Breakage Experiments
- System Machine Learning slug
- Python Toolbox Development for Effective Data Generation for Machine Learning Modeling
- Integrated Modeling and Optimization of Oil and Gas Production Systems

SUBPRO encourages its summer students to extend their assignments beyond summer internships and master thesis, by also offering possibilities to apply for a doctoral education at SUBPRO after the graduation from the master programs.

Social Experience

Through social events and excursions, the PhD students and NTNU staff get to know each other. During 2019, two types of Social events have been incorporated to the annual wheel of activities at SUBPRO, with the aim of strengthening internal and external collaboration.

SUBPRO AND BRU21 FIRST COMMON TRIP: 22ND- 23RD MARCH

BRU21 is a parallel NTNU's Research and Innovation Program that kicked off in 2018, with focus on Digital and Automation Solutions for the Oil and Gas Industry. SUBPRO and BRU21 are very similarly professional. And SUBPRO wants to expand social and professional network with members from BRU21.

During the combined technical and social event on 22-23 March 2019, PhD students and postdocs from SUBPRO were able to initiate communication and social interaction together with their fellows from BRU21, through a 2 days program that combined both technical content and a lot of fun!

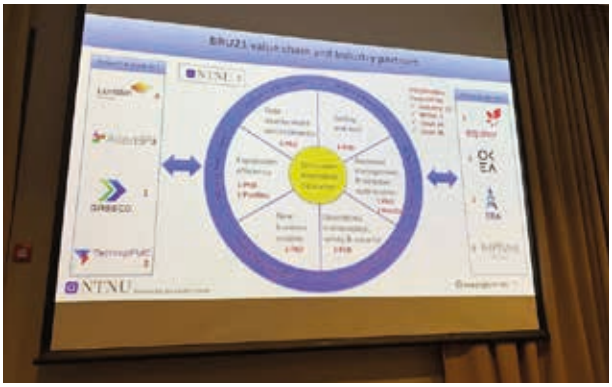


Photo taken on the 22nd March 2019 from the SUBPRO/BRU21 colloquium.

Members of SUBPRO and BRU21 socializing around a "Musical Chairs-context», at Quality Hotell Skifer. Oppdal. The fun was further extended the next day with a full skiing-day on Oppdal slopes.

Photo taken on the 22nd March 2019: PhD students from SUBPRO and BRU21 in front of the operating vessel of TechnipFMC- After a common visit to the FMC Spoolbase facilities at Orkanger. TechnipFMC has become an official partner of SUBPRO starting from 1st January 2020.

Picture from the second Tech-Lunch session at SUBPRO

SUBPRO TECH- LUNCH

The first session of SUBPRO Tech- Lunch has taken place on the 7th October 2019, it has since then been arranged on regular intervals. During that event SUBPRO PhD students and postdocs meet each other in an informal context combining social interaction and multi- discipline collaboration possibilities through knowledge sharing.

SUBPRO JULEBORD

At the end of every year members of the SUBPRO family: management members, project managers, PhD & postdoc fellows and master students, all together celebrate achievements of a full year while enjoying Christmas delights and announcing plans of the coming year.

SUBPRO 2019 Julebord: Centre Director Sigurd Skogestad thanks former Technical coordinator Gro Mogseth for her contributions to the Centre.

New projects – with kick off in 2020

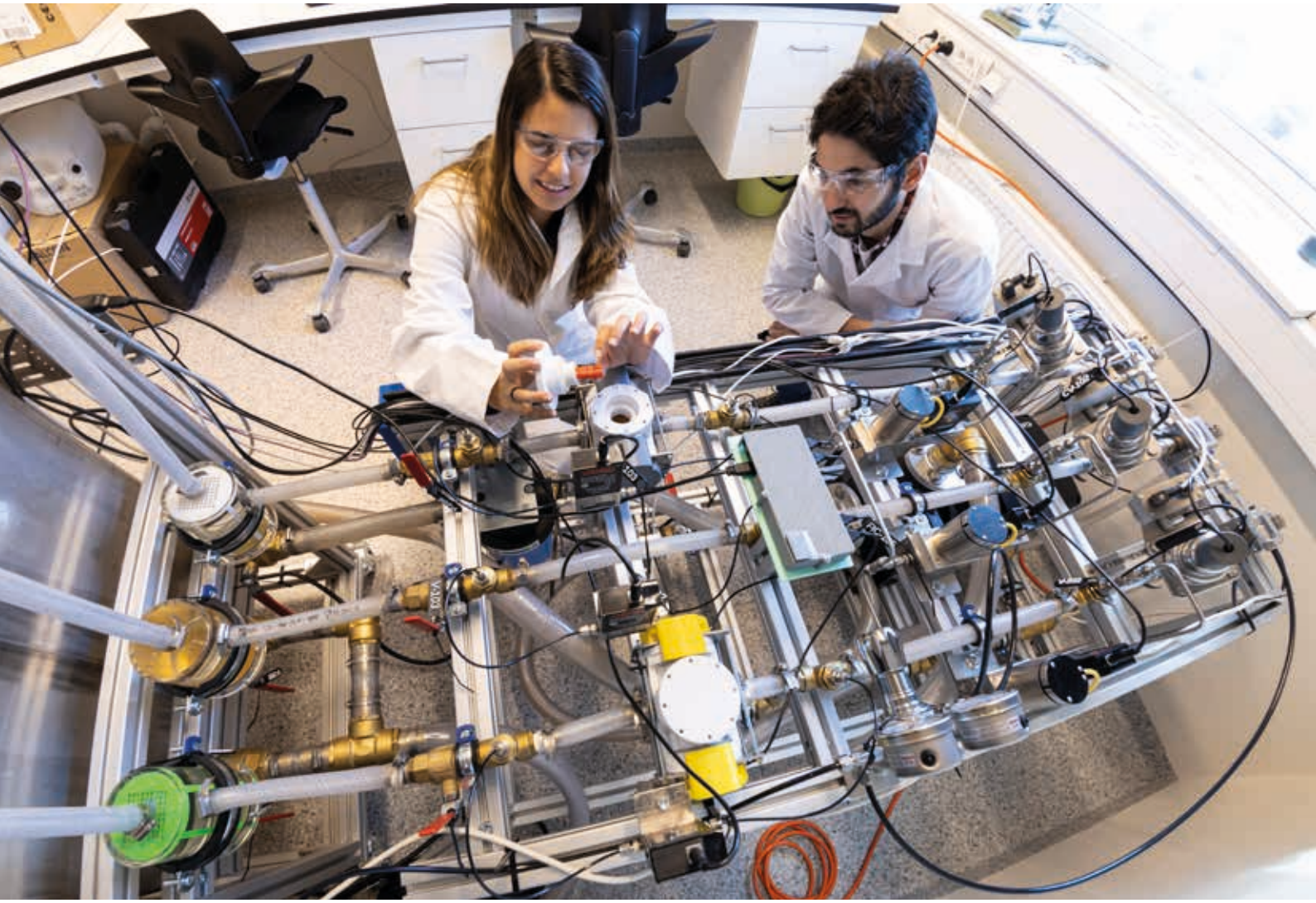
FIELD ARCHITECTURE
- Enabling technology for low cost subsea field development

RAMS
- Digital Twin for Safety Demonstration in the complete lifecycle; Case Study All Electric Control System
- Innovation project for estimation and optimization of remaining useful lifetime

SEPARATION - FLUID CHARACTERIZATION
- Flow Improvers for Waxy Crudes

SEPARATION - PROCESS CONCEPTS
- Natural gas dehydration with the use of membranes
- Experimental and numerical study of subsea bulk oil-water separation processing
- Fluid particle breakage experiments by high speed imaging

SYSTEM CONTROL
- Energy-optimal subsea production and processing by use of digital twins processing
- Digital Twins: Automatic calibration and decision making with uncertain and drifting sensors, and degrading

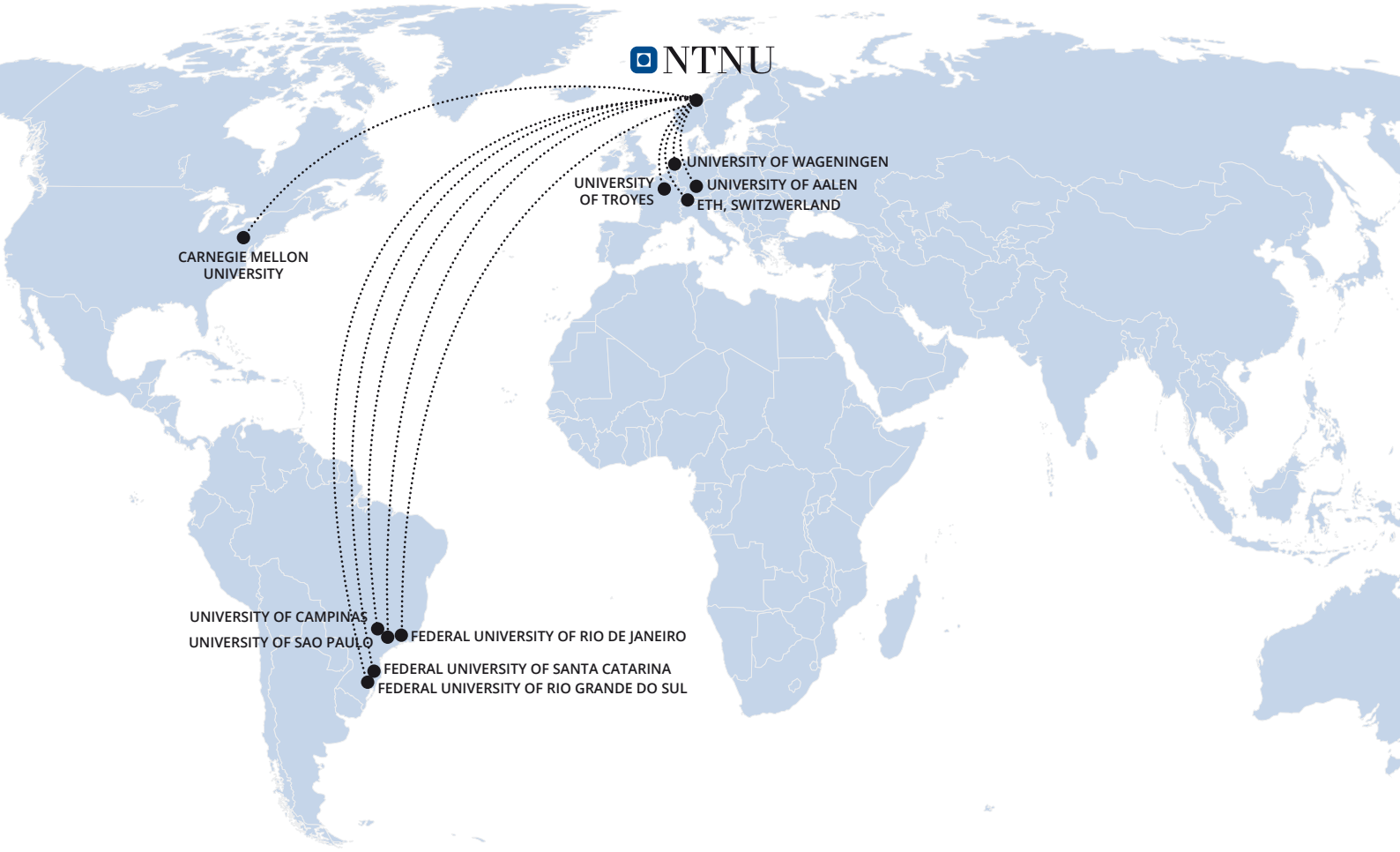


"During 2019, We have built the experimental rig for verifying the methods proposed by the SUBPRO project -Control for extending component life-. The rig has already been commissioned. Currently we are running exploratory experiments to obtain models for the system degradation that are crucial for implementing the methods of interest" - Postdoctoral fellow Jose Otavio Assumpcao Matias.
From left to right: associate PhD student Allyne dos Santos (Faculty of Natural Sciences NTNU) and Postdoctoral fellow Jose Otavio Assumpcao Matias

International Collaboration

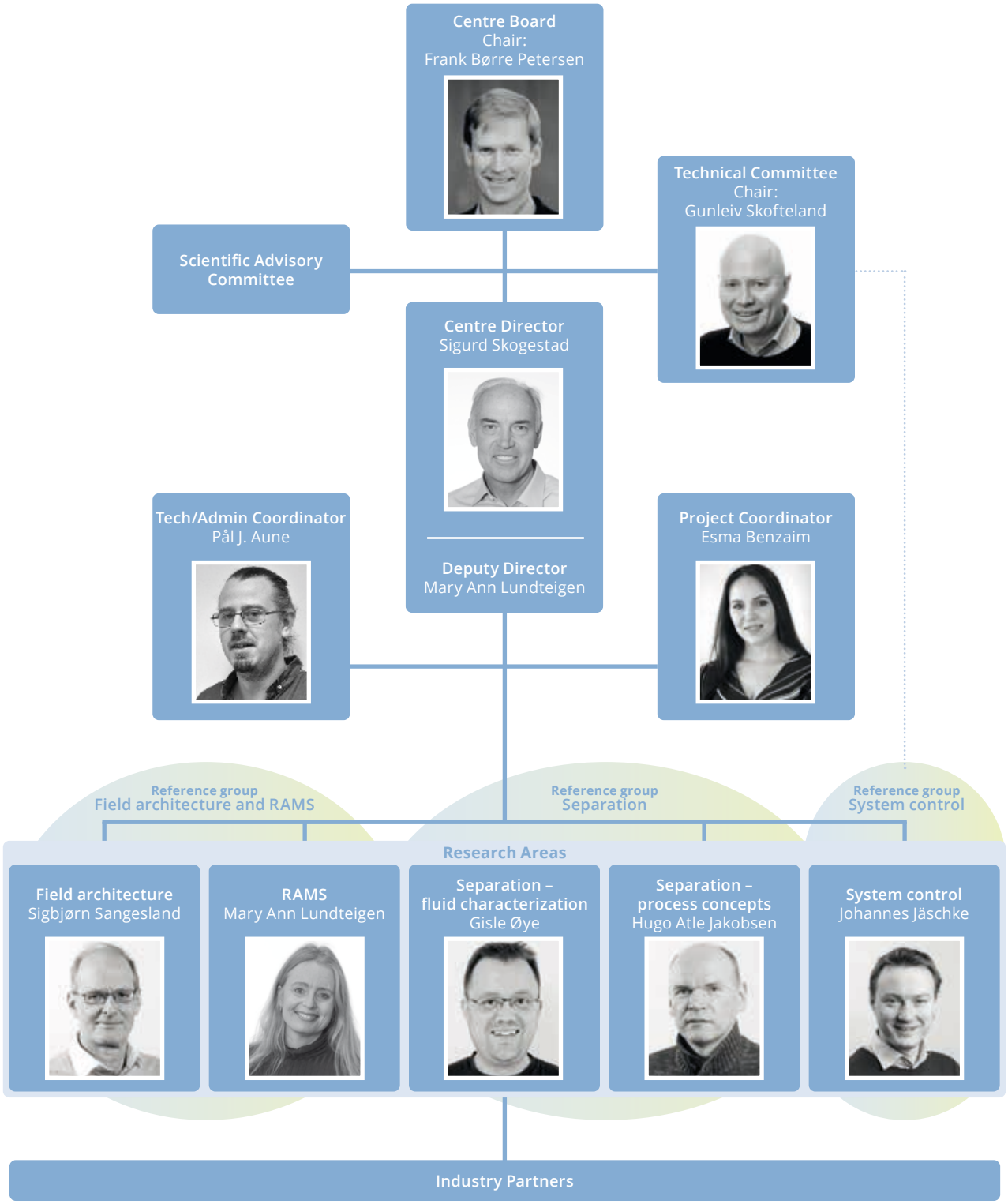
In 2019, SUBPRO has organized research collaboration with 10 renowned international universities. The collaboration involves mutual exchange programs for professors, PhD students and Master students, and leads to among others co-authoring of scientific papers

- Brazilian –Norwegian Subsea Operation Consortium and Brazil - Norway Production Optimization Consortium (two INTPART projects); exchange of PhD and Master students, guest lecturing, annual workshops in Brazil and Norway in 2019
  - o Federal University of Rio de Janeiro/COPPE
  - o Federal University of Santa Catarina
  - o University of Sao Paulo
  - o University of Campinas
- Federal University of Rio Grande do Sul and Petrobras/ CENPES research Centre; PhD student Fabio C. Diehl, 8 months visit to NTNU regarding production optimization (2019)
- University of Aalen, Germany, Professor Marcus Grazer, Collaboration on reliability of subsea systems. 6 months sabbatical stay at NTNU (2019)
- University of Troyes, France.
  - o Professor Antoine Grall, collaboration on reliability, availability, maintenance and safety (2019)
- University of Wageningen (Netherlands) and 5 other European university groups, 2 research institutes, 4 companies; Submitted MCSA application for Innovative Training Network. Topic: HPHT microfluidic studies of multiphase dispersions (2019).
- ETH, Switzerland; Professor Andrew DeMello. Exchange visit Postdoctoral fellow Marcin Dudek, Methods for monitoring of scaling, based on microfluidic experiments (2019).
- Carnegie Mellon university, USA, Professor Lawrence Biegler, Exchange visit, PhD Student Dinesh Krishnamoorthy (2019)



Organization of the Centre

GOVERNANCE STRUCTURE



Organization of the collaboration between NTNU and industry partners

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

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

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

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

THE SUBPRO DAY: TECHNICAL CONTRIBUTIONS TO THE RESEARCH ACTIVITIES
The SUBPRO day is a new yearly meeting – with first one held on 3rd October 2019 – where industry partners and members of the Scientific committee get an overview of ongoing and new project proposals and give their input and comments. Additionally, through the whole year, the industry partners contribute directly to the research projects through industrial cases, field data, technical knowledge and advice and co-supervision of PhD projects.

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

INNOVATION PROJECTS: RESEARCHERS FROM SUBPRO WORKING WITH THE INDUSTRY PARTNERS ORGANIZATIONS
An Innovation project is where the PhD projects are extended in order to enable implementation of project results in the industry.

PhD student Diana Gonzales had six months in an Innovation project in 2019, to develop a software tool for decision support on field development optimization, in collaboration with Aker BP, Equinor and Lundin. The six months were followed with an extension of two months in collaboration with Aker Solutions to generate forecast production profiles in a cloud-based module. The intension is that Aker Solutions can implement this profile generator in their online platform.

CENTRE BOARD 2019-2020


Frank Børre Pedersen
DNV GL
Chair of the Centre board


Audun Faanes
Equinor

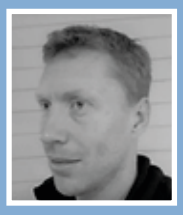

Trine Boyer
Total E&P Norge


Olav Dolonen
Neptune Energy Norge


Tom Widerøte
Lundin Norway


Lars-Erik Svabø
Kongsberg Digital


Jostein Kolbu
Aker Solutions


Lachlan McKenzie
TechnipFMC
(from 01.01.2020)


Håkon Skofteland
Aker BP
(until 01.01.2020)


Kimberly C. Mayes
Research Council of Norway, observer


Øyvind Weiby Gregersen
NTNU


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

Health, Safety and Environment (HSE)

During 2019, three HSE related events have been reported within the SUBPRO laboratory projects. In one of the events, it was reported that the gutter glugged from broken parts, dirt, screws, glass etc. While water was pouring in the gutter continuously. There were no injuries or damage to equipment. This has been added in the laboratory cleaning day's procedure and the gutter had to be emptied on every laboratory cleaning day.

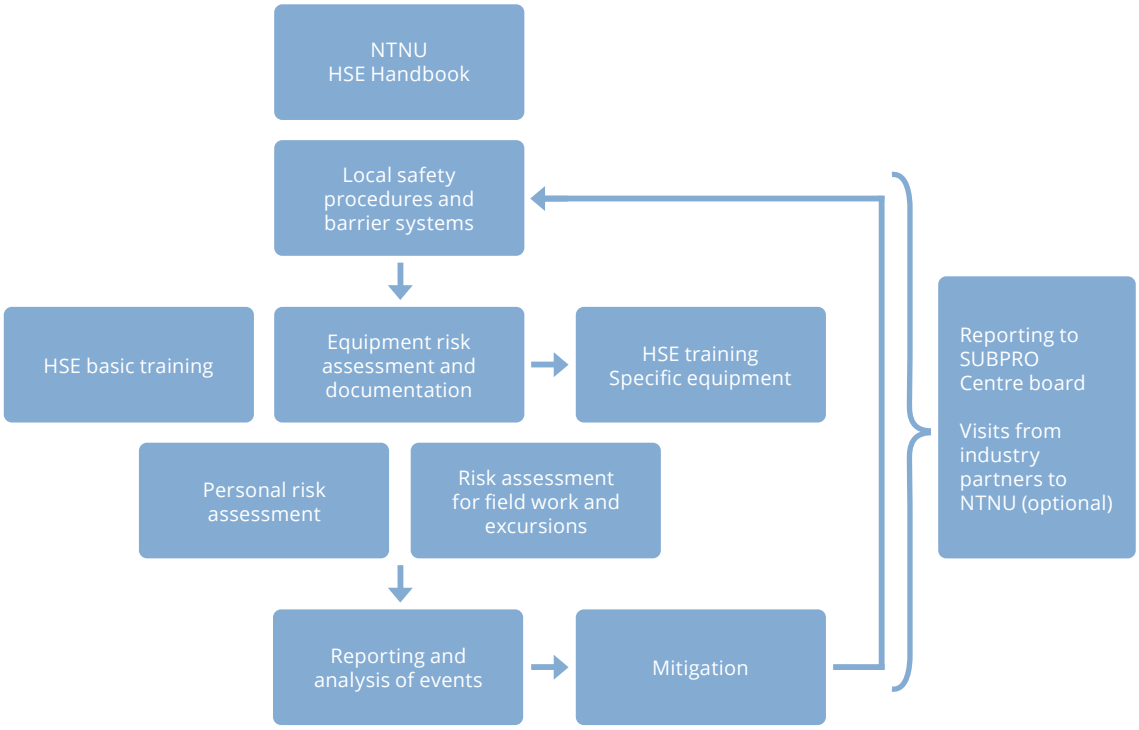
For the two remaining events, no personnel injuries or damage to equipment have been reported. All events have been systematically followed up with a post-event analysis and preventive mitigations.

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

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

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

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



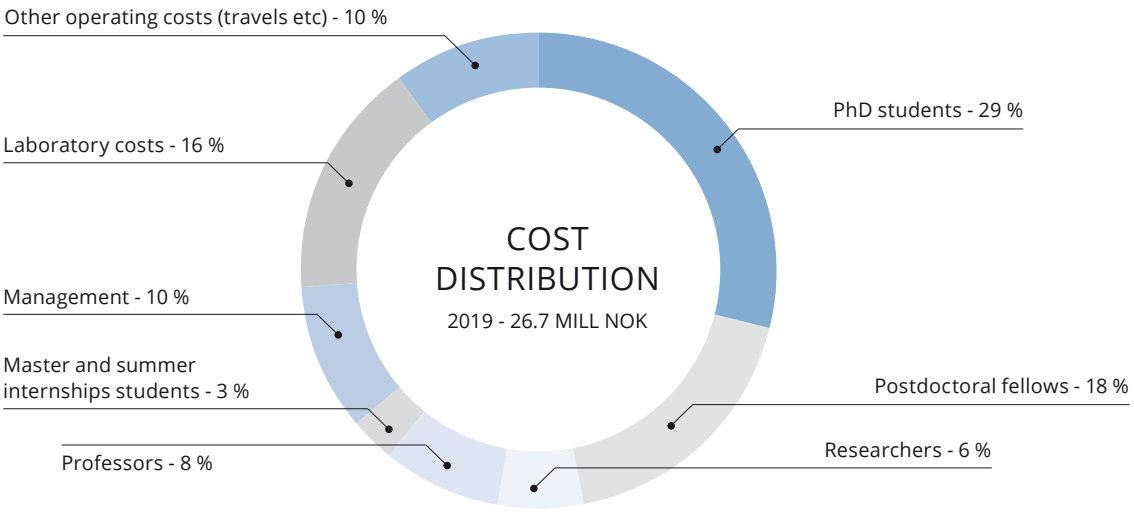
NTNU/SUBPRO HSE system

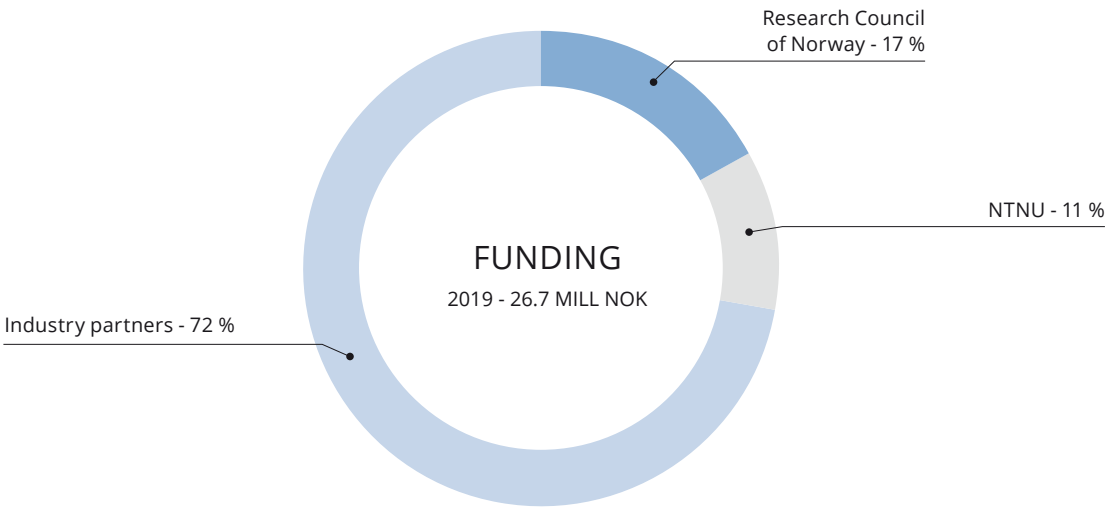
Key figures

PROJECT DURATION	AUGUST 2015 – AUGUST 2023*		
Total annual budget (annual average, 2015-2023)	32 mill. NOK		
Personnel	Planned 2015-2023	Currently engaged 2019	Female percentage
PhD students	34[1]	19	21 %
Postdoctoral scholars	9[1]	5	40 %
Researchers (full or part time)	7[1]	7	15 %
Professors	22	21	19 %
MSc students (per year)	25	17	30 %

[1] Accumulated over 8 years

PUBLICATION 2019	
Journal and conference papers	37





Publications

Journal papers and conference papers published in 2019

FIELD ARCHITECTURE

González, D., Stanko, M. & Hoffmann, A.
"Decision support method for early-phase design of offshore hydrocarbon fields using model- based optimization".
J Petrol Explor Prod Technol (2019)

Hoffmann, A., Stanko, M. & González, D.
"Optimized production profile using a coupled reservoir-network model".
J Petrol Explor Prod Technol 9, 2123–2137 (2019)

Refsnes, H., Diaz, M. & Stanko, M.
"Performance evaluation of a multi-branch gas–liquid pipe separator using computational fluid dynamics".
J Petrol Explor Prod Technol 9, 3103–3112 (2019)

RELIABILITY, AVAILABILITY, MAINTENANCE AND SAFETY

Srivastav, H.; Barros, A.& Lundteigen, M A.
"Modelling framework for performance analysis of SIS subject to degradation due to proof tests".
Reliability Engineering & System Safety (2019); Vol 195. (106702) p. 1-15

Zhang, N.; Fouladirad, M. & Barros, A.
"Reliability-based measures and prognostic analysis of a K-out-of-N system in random environments".
European Journal of operational Research (2019); Vol 272. (3) p. 1120-1131

Zhang, J.; Kim, H.; Liu, Y. & Lundteigen, M A.
"Combining system-theoretic process analysis and availability assessment: A subsea case study. Proceedings of the Institution of Mechanical Engineers".
Part O, Journal of risk and reliability (2019); Vol 233. (4). p.520-536

Zikrullah, N A.; Kim, H.; Lundteigen, M A. & van der Meulen, Meine J. P.
"Clarifying Implementation of Safe Design Principles in IEC 61508: Challenges of Novel Subsea Technology Development".
I: Proceedings of the 29th European Safety and Reliability Conference (ESREL). 22 – 26 September (2019) Hannover, Germany. Research Publishing Services 2019 ISBN 978-981-11-2724-3. p. 2928-2936

Zikrullah, N A.; van der Meulen, Meine J. P.; K, H. & Lundteigen, M A.
"Clarifying Implementation of Safe Design Principles in IEC 61508: Challenges of Novel Subsea Technology Development".
29th European Safety and Reliability Conference (2019); 2019-09-22 - 2019-09-26

SEPARATION – FLUID CHARACTERIZATION

Dudek, M.; Chicault, J. & Øye, G.
"Microfluidic Investigation of Crude Oil Droplet Coalescence: Effect of Oil/Water Composition and Droplet Aging".
Energy & Fuels 2019. p. 1-11

Ruwoldt, J.; Kurniawan, M.; Sørland, G.; Simon, S C. & Sjøblom, J.
"Influence of wax inhibitor molecular weight: Fractionation and effect on crystallization of polydisperse waxes".
Journal of Dispersion Science and Technology (2019)

Ruwoldt, J.; Sørland, G.; Simon, S C.; Oschmann, H-J. & Sjøblom, J.
"Inhibitor-wax interactions and PPD effect on wax crystallization: New approaches for GC/MS and NMR, and comparison with DSC, CPM, and rheometry".
Journal of Petroleum Science and Engineering (2019); Vol 177. p. 53-68

SEPARATION – PROCESS CONCEPTS

Dalane, K.; Hillestad, M. & Deng, L.
" Subsea natural gas dehydration with membrane processes: Simulation and process optimization".
Chemical engineering research & design (2019); Vol 142. p. 257-267

Herø, E H.; La Forgia, N.; Solsvik, J. & Jakobsen, H A.
"Determination of Breakage Parameters in Turbulent Fluid-Fluid Breakage".
Chemical Engineering & Technology (2019); Vol 42. (4). p.903-909

Skjefstad, H S. & Stanko, M.
"Experimental performance evaluation and design optimization of a horizontal multi-pipe separator for subsea oil-water bulk separation".
Journal of Petroleum Science and Engineering (2019); Vol 176. p.203-219

Skylogianni, E. & Knuutila, H K.
"Process Intensification: H2S and Hydrate Control for Subsea Application".
GPA Europe Spring Conference (2019); 2019-05-14 - 2019-05-17

Skylogianni, E.; Wanderley, R R.; Austad, S S. & Knuutila, H K.
"Density and Viscosity of the Nonaqueous and Aqueous Mixtures of Methyldiethanolamine and Monoethylene Glycol at Temperatures 3 from 283.15 to 353.15 K".
Journal of Chemical and Engineering Data; November (2019). vol 64 (12), p 5415-5431

SYSTEM CONTROL

Assumpcao Matias, J O. & Jäschke, J.
"Online Model Maintenance via Output Modifier Adaptation".
Industrial & Engineering Chemistry Research (2019). vol. 58 (30)

Assumpcao Matias, J O.& Jäschke, J.
"Using a neural network for estimating plant gradients in real-time optimization with modifier adaptation".
IFAC-PapersOnLine (2019). vol. 52 (1)

Backi, C J.; Emebu, S.; Skogestad, S. & Grimes, B A.
"A simple modeling approach to control emulsion layers in gravity separators".
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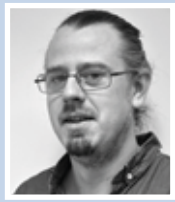

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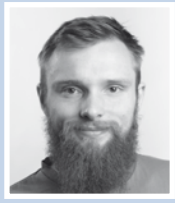
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SUBPRO team at NTNU,
in front of a Subsea Distribution Unit
from the Njord field, Equinor.

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