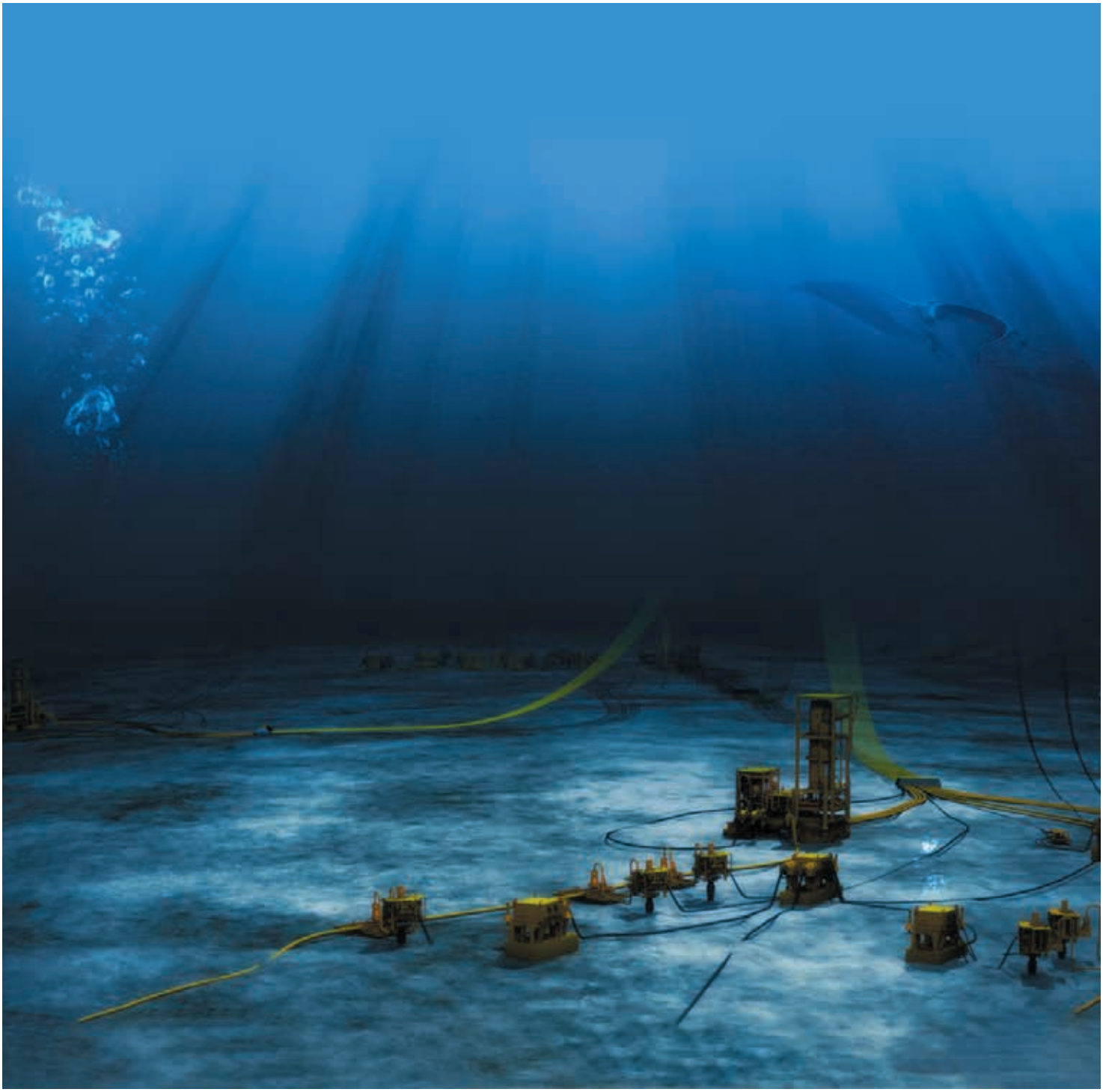
SUBPRO

SUBSEA PRODUCTION AND PROCESSING

Annual Report

2020

2021



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 nine industrial partners. Norwegian companies have been in the forefront of developing and implementing subsea technology for many years, and the purpose of starting up SUBPRO was to bring the academic community in Norway to a similar top international level in selected areas of subsea technology, and use this as a basis for further innovation in the industry. Subsea technology covers many areas, and in SUBPRO we focus on five main areas:

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

SUBPRO started up in August 2015, so we are now five 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 24 full time PhD students and Postdoctoral fellows in 2020 supervised by 22 professors and 5 researchers who contribute to the projects on a part time bases.

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: Pazflor field. Courtesy of Total.

CONTENT

Vega field. Courtesy of Equinor.

Vision and goals

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

- **International excellence in fundamental and applied research**
- **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

2020 has been a year marked by the covid-19 pandemic. This has affected all parts of the world, all industries and also SUBPRO. Despite a challenging year, the progress of SUBPRO has been impressive. And the importance of innovations in new ways of working in general and subsea developments in particular has been highlighted by the pandemic.

FRANK BØRRE PEDERSEN
VICE PRESIDENT AND PROGRAMME DIRECTOR DNV

CHAIRMAN OF THE SUBPRO CENTRE BOARD

The risk of a global pandemic had been on most Global Risk Reports over the years. And the oil and gas industry has demonstrated over and over again the ability to manage different kinds of risks. Still, this pandemic represented a risk that could not be fully managed by the industry or individual companies alone. We have therefore seen several consequences from the pandemic affecting our industry. For the first time in history, we saw negative oil prices in April 2020. The uncertainty from the covid-19 situation came on top of a more long-term structural uncertainty related to the supply-demand balance arising from the energy transition. But since the situation in April, the oil price has been steadily increasing and is currently hovering above $60 per barrel.

In Norway, the situation has been managed well. Governmental stimulus packages and a collaborative industry response has ensured a high activity level. And the recent years focus on digitalisation and work-process efficiency has been instrumental during times of working from home. While "corona" was voted as top new word in Norway 2020, the statement "You are muted" must have been a strong runner up. Almost overnight, a big part of the industry (SUBPRO included) switched over to working from home. In additions to changes in work processes, we have seen increased use of digitalisation in general: Accelerated use of digital models and digital twins, more use of drones for inspections, and more remote operations. And working with remote systems is of course exactly what we do within the area of subsea – so in many ways we have paved the way for such technologies and work processes.

The importance of subsea is no less than it was before the covid-19. Today, around half of the production on the Norwegian Continental Shelf comes from subsea wells. And the NCS development pipeline is dominated by tie-backs. 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.

During a challenging year, SUBPRO is progressing well and 2020 was another good year. Important research has been carried out and new innovations have been developed. We also welcomed back AkerBP. Their expertise and contributions will be very valuable to SUBPRO.

A total of 11 new research projects have been approved in 2020, where 9 have already started. And 5 projects were successfully completed. We congratulate the new PhDs.

Going forward, the 11 new projects will be important. They range from fundamental chemistry, flow improvements, remaining useful life estimations, energy-optimal production, low cost developments to applications of digital twins. I am very happy to see these new projects move forward and confident that they will help the industry to maintain our strong position within subsea.

Centre director

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

PROFESSOR
SIGURD SKOGESTAD

SUBPRO
CENTRE DIRECTOR

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 Aker BP rejoined SUBPRO in January 2021 after having been out for one year. One postdoc project finished in 2020 (Mariana Diaz) and four PhD candidates graduated the same year (Diana Gonzalez, Mahdi Ahmadi, Timur Bikmukhametov and Adriaen Verheylewegen). Final project reports for all five finalized projects are found in this annual report on pages 22, 26, 58, 76 and 78, respectively.

In this report one year ago, I wrote that the Corona virus had just hit the world with full power and that oil prices had dropped from 60 USD per barrel to less than 30 USD. Since then oil prices have recovered and it seems we may have entered the last phase of the Corona lockdowns. However, as I wrote one year ago, the future is uncertain, and this still holds.

Overall, SUBPRO has done well during the last year, in spite of the Corona pandemic. There has been some delays, for example in experiments and start-ups, but most people have been working as normal, except that most have been working from home. The largest change is that there has been no travels the last year, which means that there has been no physical international conferences and we have had much fewer international visits. However, international exchange has not stopped up completely.

SUBPRO started up a record number of 11 new projects in 2020, plus one new in January 2021

- Leonardo Sales, PhD student, from Jan. 2020: **Optimization of field development and subsea layout.**
- Martina Piccioli, PhD student, from Jan. 2020: **Gas flotation for subsea produced water treatment.**
- Risvan Dirza, PhD student, from Feb. 2020: **Field-wide Production Optimization.**
- Hamidreza Asaadian, PhD student, from March 2020: **Subsea bulk oil-water separation.**
- Ludvig Bjørklund, PhD student, from summer 2020: **Digital twin for safety demonstrations during the complete life cycle.**
- Halvor Krog, PhD student, from summer 2020: **Digital Twins: automatic calibration and decision making with uncertain and drifting sensors.**
- George Claudiu Savulescu, PhD student, from summer 2020: **Flow Improvers for the transportation of waxy crudes.**
- Asli Karacelik, PhD student, from Sept. 2020: **Energy-optimal subsea production and processing by use of digital twins.**
- Xingheng Liu, postdoc, from Oct. 2020: **Remaining useful life estimation and predictive maintenance.**
- Lucas Sevillano, postdoc, from Nov. 2020: **Enabling technology for low cost subsea field development.**
- Mahdi Ahmadi, postdoc, from Dec. 2020 (continues his PhD project): **Natural gas dehydration with the use of membranes.**
- Md Riswan, PhD student, from Jan. 2021: **High- accuracy virtual flow metering with machine learning and first principles models**

We are also happy to welcome Professor Shen Yin (Oct. 2020) as a replacement for Professor Anne Barros in the RAMS area. In addition, three new PhD students (Sandeep Prakash, Evren Turan, Mohsin Abbas) started in the autumn of 2020 on the AutoPRO spin-off project. We still have two more SUBPRO projects to start in 2021, but with the present funding, these will be our two last new SUBPRO projects.

The industrial partners are generally very happy with the SUBPRO project and plans for extensions are being discussed, including projects that can be the basis for a more sustainable and greener future.

Partners

STATEMENTS FROM TWO OF OUR INDUSTRY PARTNERS

RORY MACKENZIE

DEEP OFFSHORE R&D PROGRAM

HEAD OF SUBSEA ELECTRICAL TECHNOLOGIES

TOTAL E&P NORGE

"A lot of topics that we are covering here in SUBPRO are exactly the kind technologies we need to embrace. We need to embrace methods and build our capability to further develop our operations such that they are safe, clean and more efficient. So, this gives a wide scope for R&D. It's a very positive story for us".

SUBPRO Reference group meeting- February 2021.

MARTIN LAURITZSEN

SENIOR CPM ENGINEER

FIELD PERFORMANCE, CONDITION & PERFORMANCE MONITORING

TECHNIPFMC

"The use of machine learning has been very popular in recent years. Uncritical use of machine learning without understanding the underlying physics or underlying system typically can lead you astray. These projects that you are doing here at SUBPRO use machine leaning in a more restrictive manner and study the way you can get actual benefit from it".

SUBPRO Reference group meeting- February 2021.

Project structure

RESEARCH AREAS

FIELD ARCHITECTURE Sigbjørn Sangesland	RELIABILITY, AVAILABILITY, MAINTENANCE AND SAFETY Mary Ann Lundteigen	SEPARATION – FLUID CHARACTERIZATION Gisle Øye	SEPARATION – PROCESS CONCEPTS Hugo Jakobsen	SYSTEM CONTROL Johannes Jäschke

PROJECTS

Optimization of field development and subsea layout	Performance management of safety-critical systems at unmanned facilities With restricted access	Influence of production and EOR chemicals on produced water quality	Natural gas dehydration with the use of membranes	Automatic control of subsea separation
Enabling technology for low cost subsea field development	Digital Twin for Safety Demonstrations During the Complete Life Cycle	Re-injection of produced water – dispersions in porous media	Mechanistic modeling of fluid particle breakage	Energy-Optimal Subsea Production and Processing by Use of Digital Twins
Optimizing subsea layout to minimize risk and cost	Remaining useful life estimation and predictive maintenance	Gas flotation for subsea produced water treatment	Experiments on fluid particle breakage	High- accuracy virtual flow metering with machine learning and first principles models
The subsea gate box	Associated project: Safety 4.0: Demonstrating safety of novel subsea technologies	A digital twin library for oil/water emulsion separation and transport processes	Subsea bulk oil-water separation	Validation of methods for optimizing remaining useful Life (RUL)
Field development concepts	Optimizing condition monitoring	Flow Improvers for the Transportation of Waxy Crudes	Subsea membrane gas dehydration technology offers an energy-saving and green process, supplying a dehydrated gas stream directly to pipelines	Field-wide production optimization
				Digital Twins: automatic calibration and decision making with uncertain and drifting sensors
				Associated project: IKTPLUSS: Production optimization under uncertainty
				Spin-off project: AutoPRO: Digitalization for Autonomous Prognosis and Production Optimization in Offshore Production Systems
				Enhanced virtual flow metering
				Control for extending component life

SUBPRO full time PhD/Postdoctoral projects.

SUBPRO associated and spin-off projects.

SUBPRO finalized PhD/postdoctoral projects.

COVID-19 – A different kind of challenge

2020 presented a new set of challenges for the members of SUBPRO. The lockdown in Norway began on the 12th of March. Initially, many expected the restrictions to be lifted quickly, but with time we realized this was not the case, and we were forced to adapt and to create new routines, both at home and at the (home)office. We have talked to four people at SUBPRO to understand more about the challenges that arose because of the pandemic and how they went about to solve them.

There is no doubt that the restrictions have taken their toll on social coherence. COVID also delayed deliveries of necessary equipment and limited students' access to labs. However, interviewees emphasized that by working flexible hours and reprioritizing their doctoral to-do list, they could stay both motivated and efficient while working from home.

Collaboration with NTNU and industry partners kept going through e-meetings, virtual conferences to some degree replaced physical ones, and were attended digitally.

Students have, amongst other things, arranged small-scale, regulation-compliant dinners. Students also hosted digital tech lunches in collaboration with the industry partners to maintain input from the industry and to stay social.

Corona regulations were in place during the matriculation ceremony at the Faculty of Natural Sciences in 2020.
Photo: Per Henning/NTNU

Two researchers conducting an experiment in the lab.
Photo: Per Henning/NTNU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MARTINA PICCIOLI PH.D. STUDENT

Piccioli is a Ph.D. student researching gas flotation for subsea produced water treatment.
(Read more about Piccioli's research on page 44).

TAKING A SATURDAY ON A WEDNESDAY

My lab work was postponed for some time because of delays in the deliveries of parts that I needed. Spending 2.5 months at home before coming back to NTNU also forced me to begin the writing process earlier than planned and enabled me to publish an article. In terms of communications, digital meetings have indeed become the new default, but I still try to meet people in person when possible. Seeing a real face from time to time helps me stay motivated as I enjoy working in collaboration with my colleagues. COVID took a toll on my work routine. To keep things fresh, I started flexing the work schedule, sometimes working all weekend, and sometimes taking a Saturday on a Wednesday. All in all, I feel satisfied with how I managed to structure my work to stay efficient. To be fair, there have also been some positive outcomes of COVID, being able to publish an article early on was nice. It also enabled me to make thorough preparations before starting my lab work.

FROM ITALY TO NORWAY, JUST BEFORE THE PANDEMIC HIT

I arrived in Norway to start at SUBPRO in January last year, leaving my family in Milan just before Covid hit Italy. In the beginning, I felt sad that I could not be with my family back home, but after a while, I realized that the apartment in Milan only would be more crowded with me there and that the extra space may have been good for the rest of my family. We stay connected through a very active family WhatsApp-chat where we talk every day and video chat several times a week. My dad had to close his business due to COVID, and my brother had to study from home, giving them both extra time on their hands that first spring. While I love talking to my family, they sometimes call me when they are bored, and I have to remind them that I have work to do.

FOLLOWING ITALIAN LOCKDOWN RULES

Mostly reading Italian news, I followed the Italian lockdown guidelines when Norway shut down in March. Consequently, I only went outside to shop for essentials. No outdoor work-outs, no cafes, no socializing whatsoever. However, it turns out lockdown in Italy and Lockdown in Norway were very different things. After three weeks, I realized that malls and restaurants were still open and that it was OK to go for a run. The realization made me feel both a bit stupid and a bit happy at the same time.

LONGING FOR THE SOCIAL PART OF SUBPRO

Our last get-together before COVID was a ski trip to Røros in March. Having seen and talked to people face to face at least once was very valuable when we suddenly became limited to digital means of communication. Starting in August, some PhD-students began meeting again, cooking dinners together when restrictions allowed it. It has been nice, but I definitely look forward to socializing more when we go back to normal.

Martina Piccioli outside her office at NTNU Gløshaugen in March 2021. Photo: Lars Erik Haukedal Andreassen

Ph.D. student Michigan Vallabhan in front of her lab at NTNU in March 2021.

MISHIGA VALLABHAN PH.D. STUDENT

Mishiga Vallabhan is a Ph.D. student researching Automatic Control of Subsea Separation.
(Read more about Valabhan's research on page 64).

HOW DID THE FIRST LOCKDOWN IN MARCH 2020 AFFECT YOU?
I was about to start my experiments, and suddenly I lost access to my Lab. Luckily, and thanks to help from my supervisors, I was given special permission to come back to work after only three weeks, however, essential equipment was delayed, and installments were slower than planned. Instead, I started writing, and in digital collaboration with my supervisors Christian Holden and Sigurd Skogestad, we published an article. They also helped me obtain lab access relatively quickly so that I could continue my research. Because of the delays, SUBPRO and my department gave me a 3-month extension to finish my thesis.

A few weeks before the lockdown, my husband had moved from Kristiansund to Trondheim to live with our son and me. When the kindergartens closed in march, we suddenly had to balance our day jobs with taking care of our five-year-old. We quickly adopted a shift-solution where one of us would take parent-duty in the mornings and one of us would to evenings. While we both sometimes had to work evenings, it helped us make the best of it and to be both parents and professionals at the same time.

SOLVING PROBLEMS TO STAY EFFICIENT
My lab has a running time of two hours because of the storage limitations. I have to wait for residue oil to settle, empty and refill tanks and wash the system. Finding ways to maximize the number of readings and tests I can do every time I run the experiment has been crucial for my efficiency, and it has helped me acquire more data per test. Covid actually had some positive effects on my work. It enabled me to do more thorough preparations for my lab work and focus more on publishing.

MEMORIES FROM THE HOME OFFICE
Being able to cook a decent meal whenever I felt hungry and access to good, homemade coffee was for sure some of the boons of working from home. I would run simulations with my curious five-year-old son on my lap. He would ask questions about my work, and I had to try to explain how I was simulating the separation between water and oil in a subsea environment. He was also very fond of watching the progress of the simulation move towards 100%.

2020, A DIFFERENT YEAR FOR SUBPRO
I miss the social dimension of working at SUBPRO for sure. We used to eat lunch together in the canteen, and there are many social events such as Tech lunch, industrial visits, ski trips etc. While we have tried to do some of these activities digitally, it is hard to replace the real thing. I can't wait until the day we can start meeting more freely again.

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PhD student Tae Hwan Lee outside his office at NTNU Gløshaugen in March 2021. Photo: Lars Erik Haukedal Andreassen

How a tech lunch looks like during a pandemic. Despite the limitations of e-conferences, the meeting managed to spark enthusiasm amongst its attendees. Photo: Pål J. Aune

TAE HWAN LEE PH.D. STUDENT

Lee is a Ph.D. student researching the performance management of safety-critical systems at unmanned facilities with restricted access. (Read more about Lee's research on page 32)

THE DARK MONTHS...

II moved to Norway in late 2019 to start my Ph.D. At the time, my wife still lived in South Korea and was pregnant with our first child. Naturally, I planned to go back for her due date in February, but at that time, there were already travel restrictions and lockdowns back home. Instead, I had to make do with shifting my sleeping schedule to make sure I was available for her as much as possible. I would wake up around noon and go to sleep around 5 AM to overlap with the Norwegian working hours and still be there for my wife. While becoming a father was amazing, not being with my wife and child was tough, so was the shifted sleep schedule and working from home. I refer to the first few months of COVID as the dark months... I will always remember becoming a father without being able to be there. A more pleasant memory is getting to meet my child when I went back to South Korea for a few weeks of paternity leave last summer. Last fall, my wife and child moved to Norway, so they are here with me in Trondheim now. Finally, I can help out with the parenting and set my sleep schedule to the Norwegian time zone only.

Jobwise I can do all of my work from a computer, so while I had plenty of distractions and other things to think about during the lockdown, I managed to stay somewhat productive even during the dark months.

ADAPTING TO A DIGITAL WORKFLOW

I guess I adapted the same way as everyone else. E-meetings are more efficient, and it is easier to find time slots where everyone can attend however, it is my opinion that video calls cannot completely replace a physical meeting. I am a social person, and while I will certainly enjoy the simplicity of being able to more easily schedule digital meetings, I look forward to meeting more people in person again. One unexpected positive effect on the research project was that the importance of a digital twin and unmanned system has become emphasized naturally since life after COVID-19 has changed in a more digitalized way.

SUBPRO VIRTUAL TECH LUNCH

Socially, this last year has been meagre. We had a SUBPRO-trip to Røros in March last year just before the lockdown where I got to know many of my colleagues, but during COVID, not much has been going on. One of the things I have been missing is input on other people's projects and the industry's problems and needs. That is why I decided to host a Virtual SUBPRO Tech Lunch. We had representatives from KDI (Kongsberg Digital) introduce their commercial products, K-SPICE & Ledaflow, which are widely used in industry but are not as known in academia. Attendees included not only PhD candidates but also postdoctoral staff and professors, and many of them showed interest in the presentation. An exciting opportunity to collaborate with industrial partners was also suggested during this event. Around 25 people attended, and while I can't speak for the rest of the attendees, people seemed to like it. The attendees had many interesting questions for the speakers sparking a good discussion. For our next Virtual Tech Lunch, we have invited DNV.

SIGURD SKOGESTAD, CENTRE DIRECTOR

In his foreword to last years annual report, Skogestad wrote:
"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."

12 months later, the future looks a bit brighter, vaccinations are well underway, the Brent has gradually risen to 69USD, NTNU has mostly opened, at least for the time being, and people have mostly been able to emerge from their home offices, with new and valuable knowledge of how to operate a video-call.

Sigurd Skogestad. Taken at an industry onboarding session for new employees at SUBPRO. Photo: Private

WHEN THE PANDEMIC HIT

Not much changed for me regarding my work. Most of it can be done from a computer, so working from home had no significant impact on my efficiency. However, COVID has changed my to-dos slightly. For instance, there have been some challenges related to making sure that people that need lab access get it. Overall it is hard to say if the pandemic made me more or less effective. On the one hand, I travel less, and thus I have more time to do work. We have had Skype for almost 15 years. Teams and Zoom are not so different. Digital meetings have certainly saved me some travel time, and my impression is that it is possible to get a lot done in an e-meeting. However, I don't feel like I have accomplished substantially more this year than before. Personally, it had some setbacks. I haven't been able to see my grandchildren as often as I wished. For instance, we had planned to meet at the cabin for Easter last year, but because of the pandemic, we had to cancel.

THE SOCIAL ASPECT OF SUBPRO

The social aspect of working at SUBPRO is essential. Getting to know your co-workers and their projects have been an important part of SUBPRO since the beginning. While I believe we will survive and recover after a year without much socialization, it could be damaging for the working environment if we cannot start socializing again soon. One of my worries regarding the lack of social meeting grounds is the fact that the Ph.D. students have not been able to attend any conferences. You never know what synergies may emerge from learning more about what other researchers and the industry are up to. I know some people have tried to do digital conferences, but I haven't seen any that fully deliver the value of meeting and mingling physically.

WHAT HAS BEEN THE BEST THING ABOUT WORKING FROM HOME?

Hmm, I would have to answer that working from home, I don't have to make my "matpakke" (homemade lunch sandwich) to bring to work.

Sigurd Skogestad's office is full of souvenirs from travels to conferences worldwide, but the last year has been spent staying in Norway, Managing SUBPROs 40+ projects from home. Photo: Lars Erik Haukedal Andreassen- March 2021

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.
- Fundamental requirements for Health, Safety and Environment (HSE) in a life-cycle perspective. How to implement principles for safety thinking, reevaluation of barrier philosophy to identify technical and economic opportunities for design simplifications of subsea trees and manifolds and minimizing the use of resources (e.g. materials and energy consumption) for operations and installations while securing a responsible exploitation of the hydrocarbon over the life of the field.

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

Case 1: Gas field with low Gas Oil Ratio (GOR)
Case 2: Remote, low energy oil field (typical example: Barents Sea)
Case 3: Oil field with future tie-ins

PROJECTS OF FIELD ARCHITECTURE
During 2020, the following projects have been completed:

PhD project:
- Field development concepts

Innovation project:
- Methods for decision support in early field development using proxy modeling and optimization

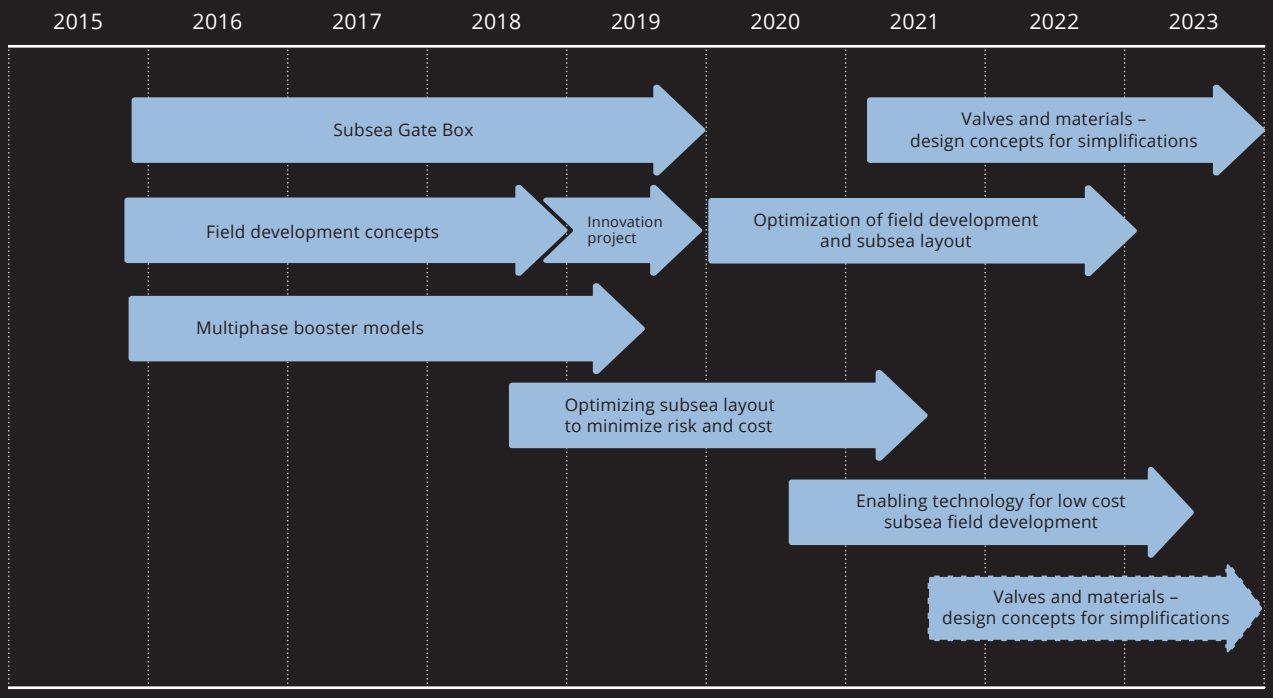
Postdoc project:
- Subsea Gate box

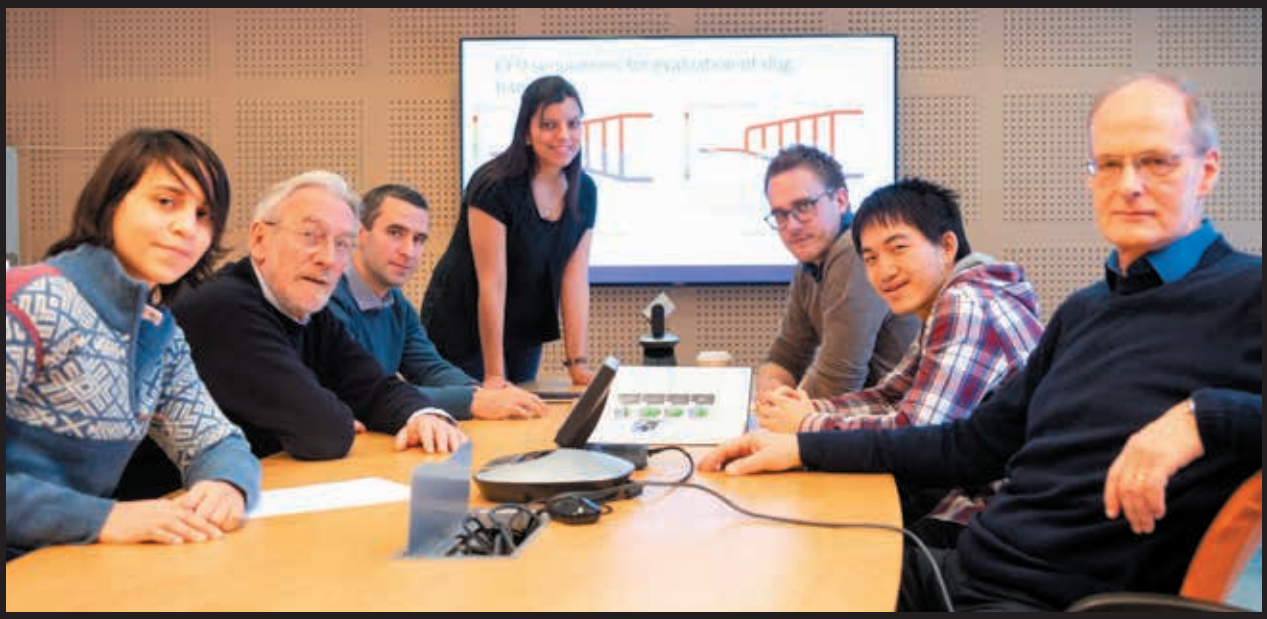
During 2020, the following projects have started:

PhD project:
- Optimization of layout of subsea production systems with subsea processing

Postdoc project:
- Enabling technology for low cost subsea field development

Completed, current and planned projects





The Field architecture team
From left: PhD graduate Diana Gonzáles, Professor Tor Berge Gjersvik, Associate professor Milan Stanko, Postdoctoral Mariana Diaz, former PhD graduate Håvard S. Skjefstad, PhD student Haoge Li and Professor Sigbjørn Sangesland.
(PhD student Leonardo Sales and postdoctoral Lucas Cantinelli Sevillano were not present when the present was taken – in early 2019).

Optimization of field development and subsea layout

Developing methods and obtaining insights for early field planning and 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:
Associate Professor
Milan Stanko

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

1. IMPACT OF EARLY FIELD DEVELOPMENT IN SUBSEA LAYOUT

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

2. EVALUATING UNCERTAINTIES IN FIELD DEVELOPMENT

In the first stage of this work, we employ non-linear numerical optimization, latin hypercube sampling and the Schwartz & Smith oil price model to compute probability distributions of the optimal number of wells, plateau rate and project value. We apply the optimization on an analytical model that computes production profiles and project value. The uncertainties considered are in-place oil volumes of oil, well productivity and oil price. Then, we generate estimates of how do these distributions change from early field planning until when the field is abandoned, when uncertainties are reduced to a minimum, as shown in Figure 1. For the study case, a total of 20 251 problems were optimised.

3. THE METHOD ALLOWS TO QUANTIFY THE EFFECT OF UNCERTAINTIES IN FIELD DESIGN

Figure 2 shows that the optimal design changes when more information is gathered about the field and the actual oil price is known. For the case studied, the optimal field design at the beginning of development (represented by the average value of the initial distribution) represents a smaller investment when compared against the optimal field design with perfect information. The decision-makers should invest 30-60% more in capital expenditures to obtain the optimal field design.

Although the designs are different, the value of perfect information is modest for the cases studied in this paper, around 3-15% of the project economic value. In a real scenario, it could be that this payback is not worth the risks of investing 30-60% more in field development. We conclude that the initial design is conservative. Overall, the proposed method seems to be a robust approach to quantify uncertainties while computing optimal design and is therefore suitable to provide decision support in early field development.

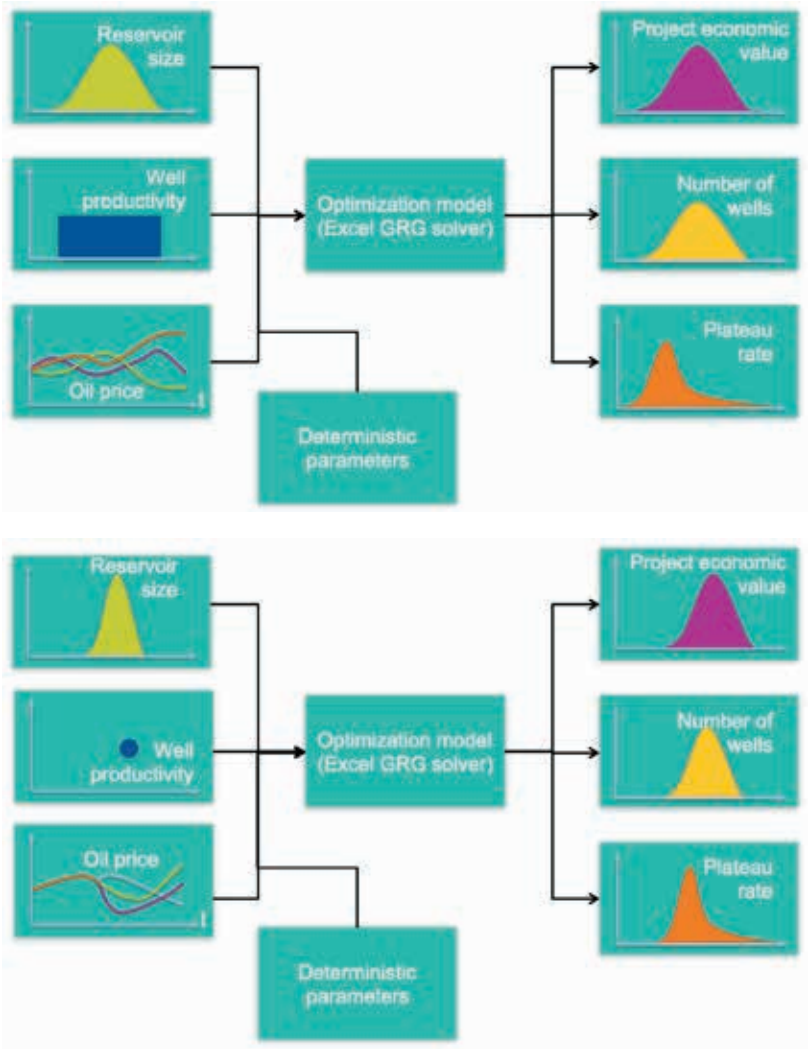


Figure 1. Overall view of the proposed method, in (a) early field development and (b) when uncertainties are reduced at a later stage.

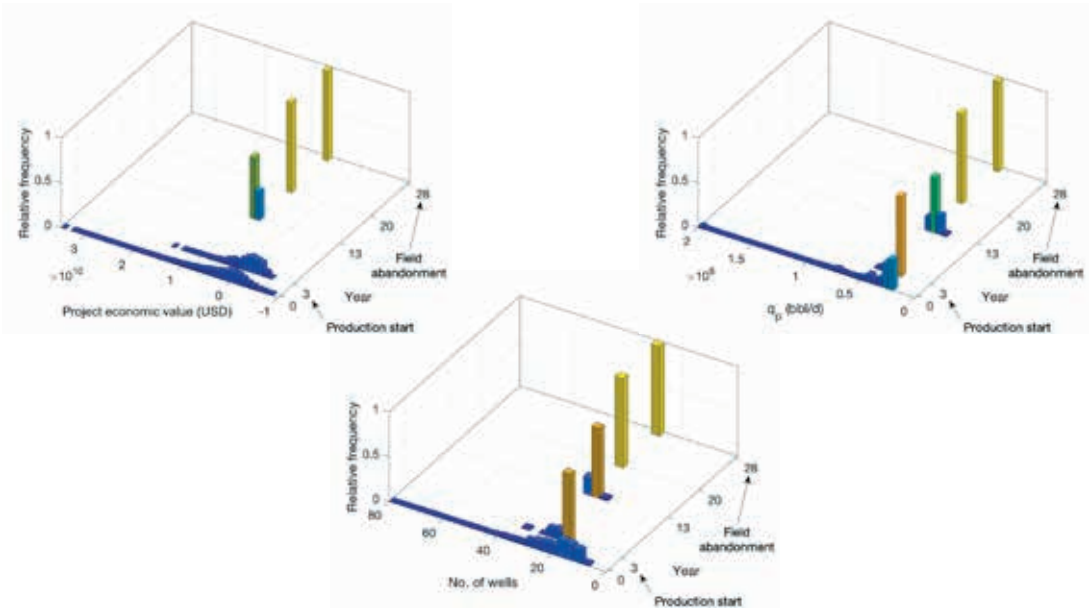


Figure 2. Uncertainty about project economic value, well plateau rate (qp) and number of wells decreases as more information is provided.

Enabling technology for low cost subsea field development

To investigate the impact of implementing new technologies in the design of subsea production systems and formalize the technical, environmental and economic benefits, and to propose a suitable methodology for applying the findings into the design of new subsea developments.

GREEN SHIFT IMPACT: New technologies can reduce the carbon footprint of subsea production systems by enabling leaner designs and making said systems less dependent on topside facilities.

Postdoctoral fellow:
Lucas Cantinelli Sevillano

Project manager:
Professor
Sigbjørn Sangesland

Supervisors:
Prof. Sigbjørn Sangesland, Prof. Tor Berge Gjersvik and Prof. Audun Faanes (Equinor)

1. BACKGROUND

Despite the ongoing transition to renewables and battery storage, it is still expected of the oil and gas (O&G) industry to play a major role in providing energy during the next decades. Moreover, the industry must address the challenges from climate change and declining oil prices by reducing both carbon emissions and costs throughout the chain of production.

As offshore O&G moves to marginal and deep-water fields, subsea production systems (SPS) have become the norm to address technical and economic challenges. SPS consists of a completed well, seabed wellhead, subsea production tree, a tie-in to a flowline system, and the equipment for production processing and control. It can range in complexity from a satellite well, to several wells either on a template or clustered around a manifold.

The costs and carbon footprint of a SPS are associated with the manufacture, handling, and installation of individual components, as well as the energy consumption needed to operate, monitor, and intervene on the system. Deep-water SPSs already present low energy consumption, and therefore low carbon emissions per barrel produced, yet further reductions are feasible. The solution envelope for a SPS is restricted by guidelines and practices of the O&G industry, but ongoing technological developments open the possibility for challenging industry practices and rethinking the design solutions applied to subsea field development.

2. RESEARCH ACTIVITIES AND DELIVERABLES

The objective of this research is to perform structural and fundamental analysis of subsea production and injection systems and address the question:

How ongoing technological developments can be exploited to design an overall better subsea production system so the industry may fully benefit from the economic and ecological impact brought by these new technologies combined?

Another important research topic is the reevaluation of barrier philosophy to identify technical and economic opportunities for design simplifications of subsea trees that still leave enough pressure barriers in all operational modes (completion, production and intervention).

Literature survey will be done on various applications both in academia and industry such as company standards, industry regulations, new products, review articles on journal or conference proceedings, and so forth.

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

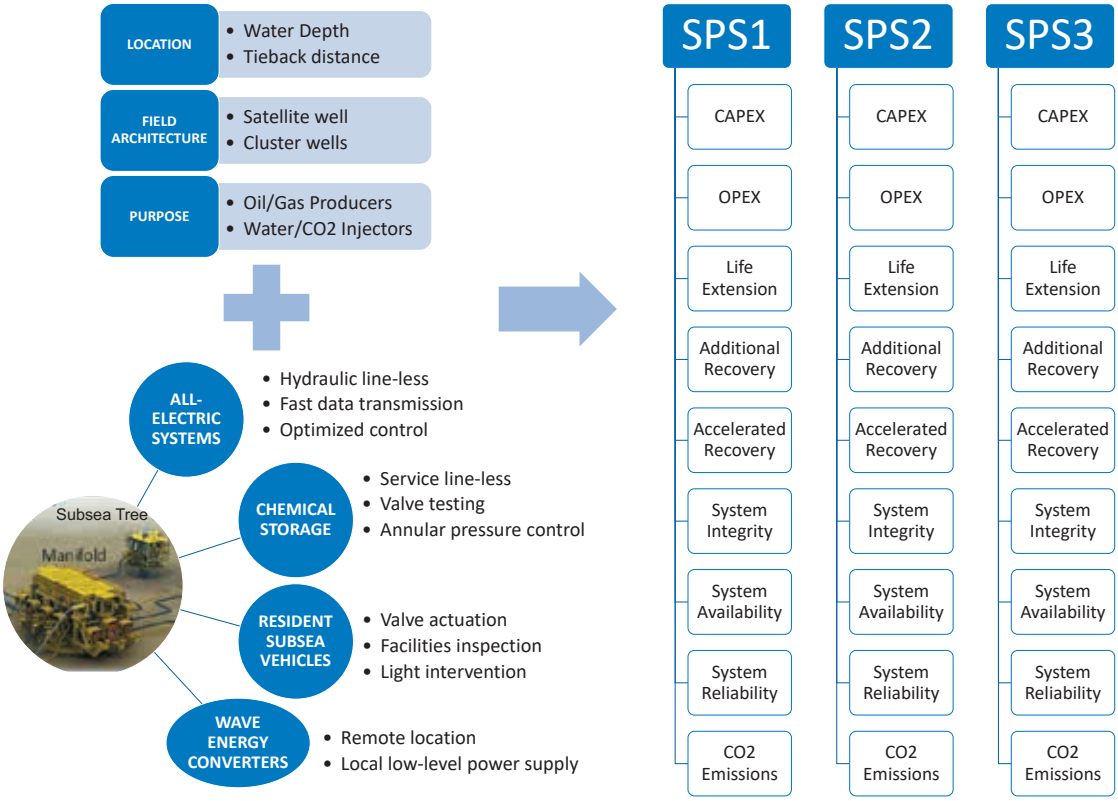
- All-electric control
- Chemical storage
- Resident subsea vehicles
- Subsea communication systems
- Localized heating
- Wave energy converters
- Additive manufacturing

Individual milestones reached during the research will be submitted for publication in conference and journal papers. The development of a design methodology that groups the findings and main conclusions of the research is planned and aimed towards providing technical solutions for more compact subsea systems with low footprint, reduced costs and CO_2 emission.

3. INDUSTRY PARTICIPATION

Currently, Equinor is 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 the development of new subsea fields or the extension of old ones, particularly by improving the decision-making process regarding the potential of reducing cost/carbon in oil and gas production.



The combined technologies when adapted to the characteristics of a subsea field will provide different design options for the subsea production system. This research will identify the most promising solutions and rank them based on multiple parameters: technical, operational and environmental.

Optimizing subsea layout to minimize risk and cost

Directional well planning based on 3D Dubins Curve.

PhD student:
Haoge Liu

Project manager:
Professor
Tor Berge Gjersvik

Supervisors:
Prof. Tor Berge Gjersvik,
Prof. Audun Faanes
and Prof. Sigbjørn
Sangesland

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

Last year, we successfully designed an efficient method to obtain the global optimum for the location-allocation problem. In order to achieve the global minimum cost for the overall development cost, we also need a method for the directional well planning problem which can be regarded as a two-level optimization problem. The first level is to find the optimal trajectory from a given drilling site to a given completion interval. The second level is to find the optimal drilling site location along with the optimal trajectories to all the given completion intervals.

2. BORROW THE "DUBINS CURVE" FROM AUTOPILOT INDUSTRY AS THE OPTIMAL WELL TRAJECTORY

- We found that the "Dubins Curve" which is widely used in autopilot industry, also perfect for the optimal well trajectory whose main constraint is the dogleg severity, i.e. turning rate. Using the principles of Dubins, the shortest possible wellbore length is guarantied with the given constraints of pre-defined planned completion interval, given planned turn rates and subsea wellhead position. And the total wellbore length of "steering" is also minimized.

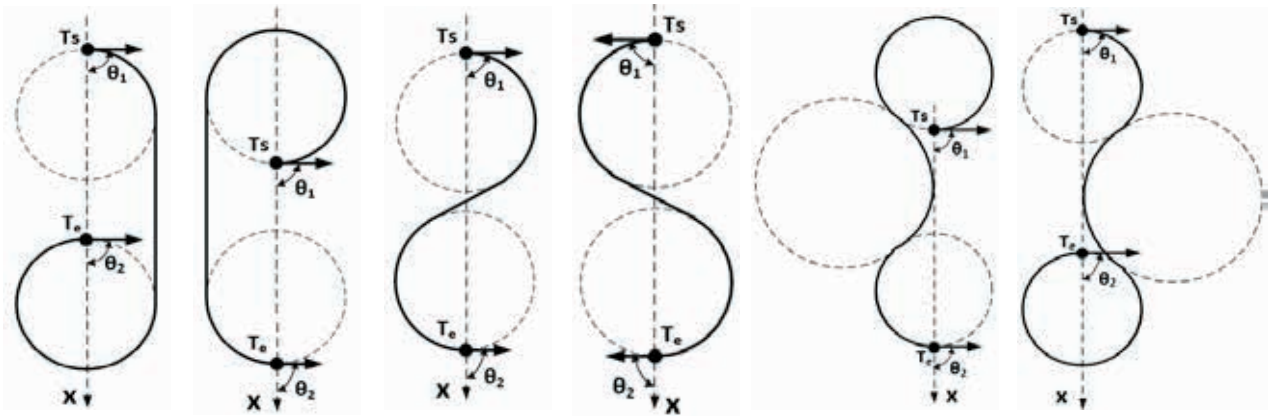
- Based on the practical situation of drilling, we modified the original Dubins Curve system (as shown in Fig. 1): abandoned the "CCC" family, only adopted and extended the "CSC" family to 3D scenario. ("C" stands for circular section, "S" means straight section).

- Based on 3D Dubins Curve, we can get the solution to the first level. Then embed the first level into the second level and use the gradient decent algorithm to find the optimal drilling site for multiple completion intervals. Hence, we have a method for solving the well planning optimization problem of "1-site-n-wells", as shown in Fig. 2 and Fig. 3.

3. FROM "1-SITE-N-WELLS" TO "M-SITES-N-WELLS"

Combining the method we designed last year for the location-allocation problem and the 3D Dubins Curve method for directional well planning, we can form a systematic method for solving the "m-sites-n-wells" optimization problem which is practically meaningful to cut the overall development cost. We will finalize this in the coming year.

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



(a) CSC-RSR (b)CSC-LSL (c)CSC-RSL (d) CSC-LSR (e)CCC-LRL (F)CCC-RLR

Figure 1 Patterns of original 2D Dubins Curve

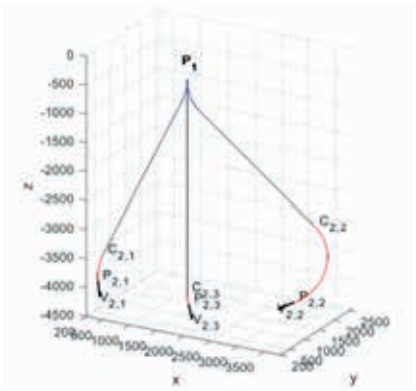


Figure 2 Example of Optimal Layout for "1-site-n-wells"

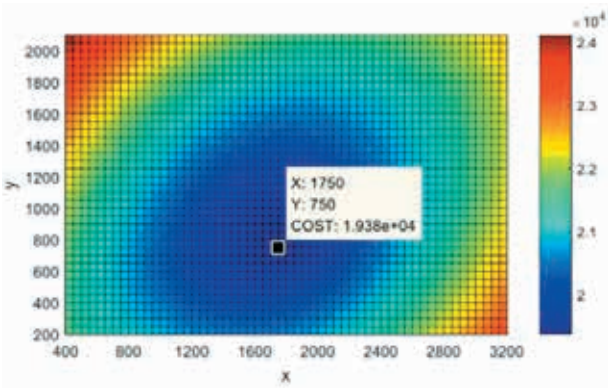
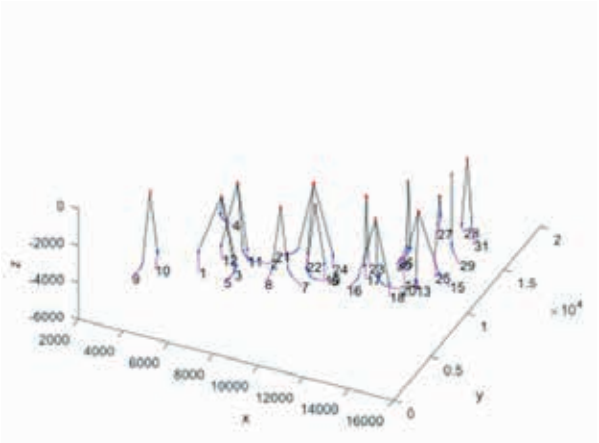


Figure 3 Example of Optimal Cost Distribution for "1-site-n-wells"



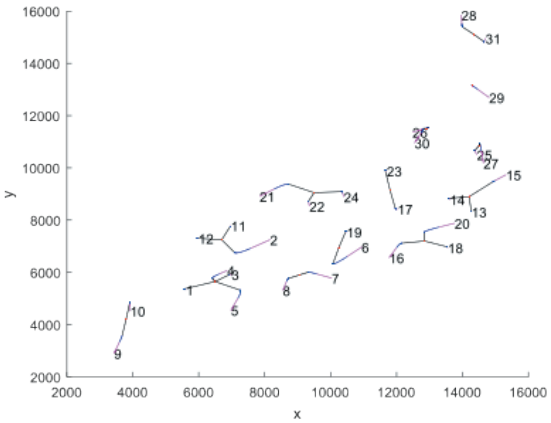


Figure 4 Example of Optimal Layout for "m-sites-n-wells"

FINAL PROJECT REPORT

The Subsea gate box

A possible way to enhanced production.

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

Postdoctoral fellow:	**Mariana Diaz**
Start date:	01.12.2015
Thesis defense date:	20.06.2020
Title of thesis:	The Subsea gate box. A possible way to enhanced production
Project manager:	Professor Sigbjørn Sangesland
Co-supervisor:	Prof. Sigbjørn Sangesland and Associated Prof. Milan Stanko

1. BACKGROUND FOR THE PROJECT

During the early phases of field development, important decisions are taken while the knowledge about 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 effectively manage 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. Therefore, this project presented a novel concept where wells or regions of the field with large heterogeneous performance are decoupled from the main network by installing decentralized subsea processing modules in the field architecture. This approach, called the Subsea Gate Box (SGB), is addressed to increase the production management flexibility by expanding the possible production strategies, considering both production constraints and reservoir dynamics, and increasing energy efficiency to improve the resource utilization. The project aimed to evaluate the SGB concept in terms of its applicability and contributions within subsea field developments.

2. WHAT I HAVE DONE

- ***Feasibility analysis of the subsea gate box concept (SGB)***. A performance evaluation of the SGB was carried out using an integrated production model for a synthetic case.

- ***Gap analysis and review of the state-of-the-art of the technology available for subsea processing.*** The work was aimed to evaluate existing technology and operational methods for subsea developments, including a revision of the common configurations used in subsea architectures as well as technologies used topside

- ***Concept definition.*** The work was addressed to describe the subsea gate box proposal at a conceptual design level. An evaluation was conducted of the potential benefits and possible limitations of the subsea gate box as an alternative for subsea field developments.

- Performing a ***cost evaluation*** of different field architectures. The study analyzed the additional cost associated to the development of a central boosting system and cost associated to the SGB approach for two operational philosophies: “System demand” and “Simultaneous running” versus a base case scenario without any boosting.

- Developing a ***methodology and framework for scenario screening of field architectures*** applying the Subsea Gate Box concept.

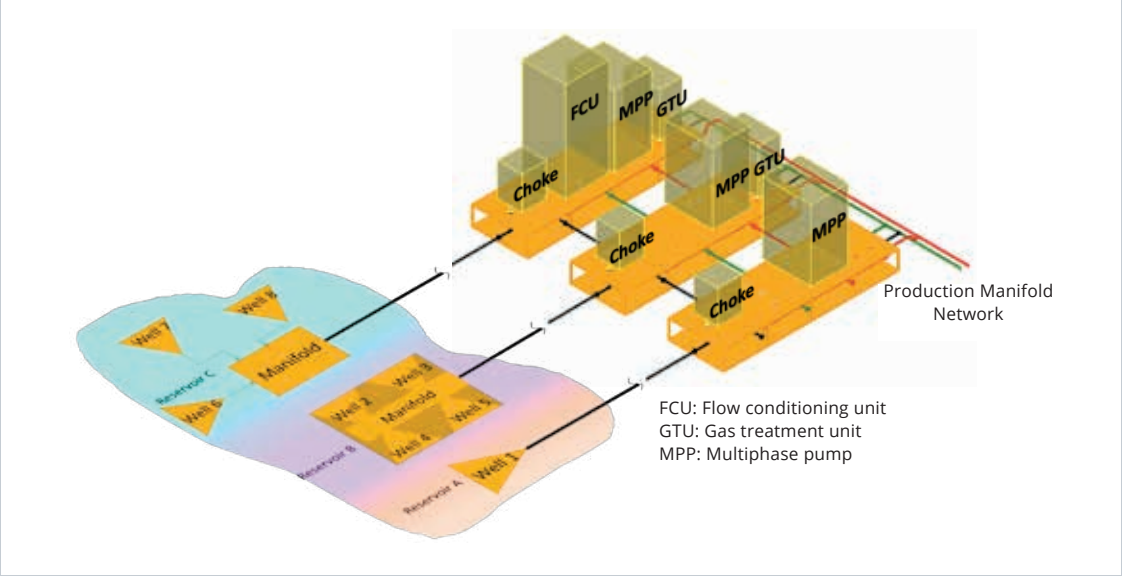


Figure 1. The Subsea gate box concept targets different well configurations (satellite, clusters, or template). Each module of the SGB will offer the opportunity of handling the different streams according to their own specific operating conditions by means of customized processing trains over the lifetime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

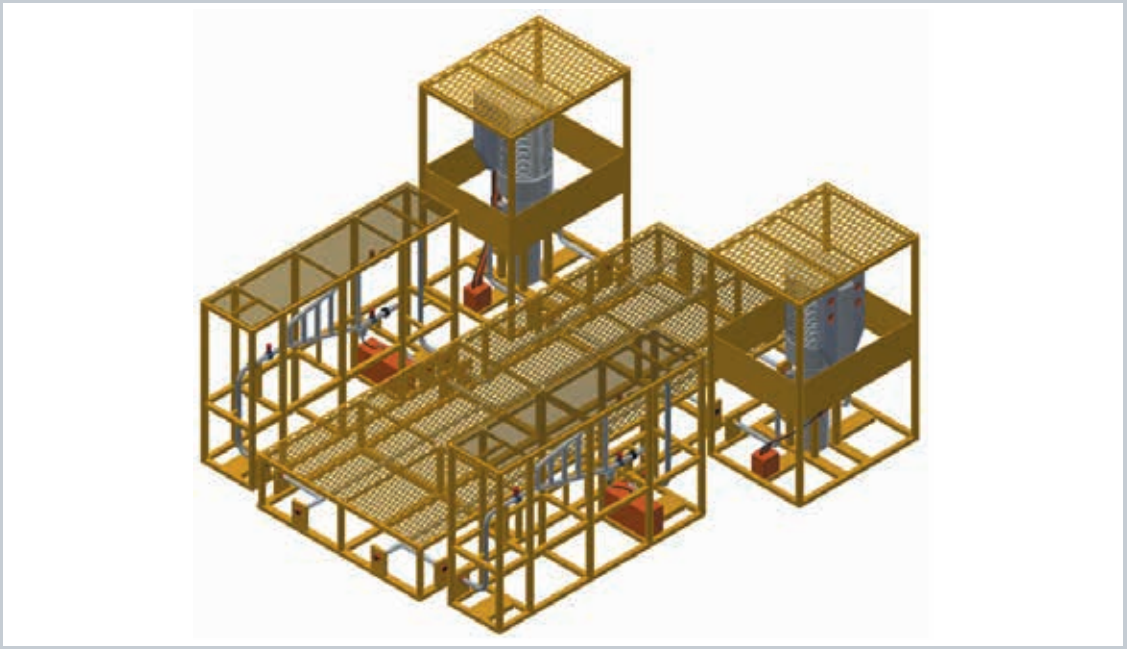


Figure 2. 3D sketch of horizontal-connection-type of the subsea gate box.

3. MAIN RESULTS

- The feasibility study demonstrated the possibility to increase the overall production by around 10% when comparing the SGB to a typical central boosting station.

- The technology evaluation revealed the compatibility of novel solutions by service providers with the subsea gate box concept. Examples are the Power Jump, skid mounted electrical submerged pump, and the contra-rotating pump. The technology evaluation can be used as a support document in the concept screening process for evaluating and comparing available technologies when considering subsea processing.

- A spreadsheet to calculate and size a gas-liquid gravity vessel and a cyclonic separator.

- A Computational Flow Dynamics model for a pipe-type gas-liquid separator. The model offers an interesting tool to explore the performance maps and separation efficiencies for such separators.

- Proposals for the subsea gate box design in terms of the field configuration layout and assembly interphase, as well as some IMR (inspection, maintenance, and repair) considerations. (See Figure 1 and Figure 2)

- Base on the concept and cost evaluation, the subsea gate box could be an attractive solution for cases with large heterogeneity among wells connected to the same production network, where a central processing system will over constrain production of certain regions. For such scenarios, the life cycle cost of the subsea gate box could be comparable to the central station with the advantage of enabling higher production flexibility and efficiency. The most relevant contribution of the SGB is the potential flexibility in the long and short-term production strategies.

- A scenario screening methodology based on a combination of Evolutionary Algorithms (EA) and Integrated Production Modelling (IPM) approach to automate case generation, field architecture scenario screening, and optimization using the subsea gate box concept during field development. The methodology proposed enables a systematic and automated screening process that allows exploring the entire domain, ranking the alternatives, and identifies the optimal or near optimal suitable solutions in a consistent manner. See (Figure 3 and Figure 4)

- The project results comprise a collection of master theses, technical reports, and scientific papers that outline the principle of the concept as well as their advantage and limitations. Such a collection could be used as reference material for defining new strategies within field development.

4. INNOVATION AND INDUSTRY COLLABORATION

The subsea gate box 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. Our partners and specially Equinor, AkerBP, Aker Solution, and Lundin have been key collaborators to outline the scope of the project and identify the necessities of the industry in this area.
The methodology proposed for automate case generation, field architecture scenario screening, and optimization of the Subsea Gate box it is the starting point to contribute with a building block for a future asset development digital twin.

5. FURTHER WORK

- Perform an evaluation of the value of the flexibility achieved by the SGB. This analysis requires information on the performances of the different processing modules, in terms of equipment efficiency, availability, and maintenance. The study should be able to capture the effect of the SGB under uncertainties including both operating and development uncertainties.

- The concept development requires a dedicated RAMS analysis. Furthermore, the risk and RAMS variables could be included as part of multi-objective function in the screening methodology.

- The scenario screening methodology could be adapted to screen other variables within the field architecture. (Artificial lift methods, well routing, delivery/export alternatives). This will need different encoding of the solution, test, and verification of the relevant genetic operators and evolution strategies for the additional variables.

- The EA algorithm developed at this stage, does not guarantee a global optimal solution, because it is a meta-heuristic optimization method, therefore a hybrid strategy could be considered to achieve a real optimum.

- Perform an uncertainty analysis of the fitness function of the screening methodology.

- The screening methodology was developed for a fixed initial field condition; therefore, future work could explore the evolution of the SGB configuration through field life.

- Use a real field case scenario to assess the performance evaluation, the cost analysis, and the screening methodology carried out during this project.

6. MY NEW JOB

I am currently looking for new opportunities and eager to work for and make significant contributions to the industry.

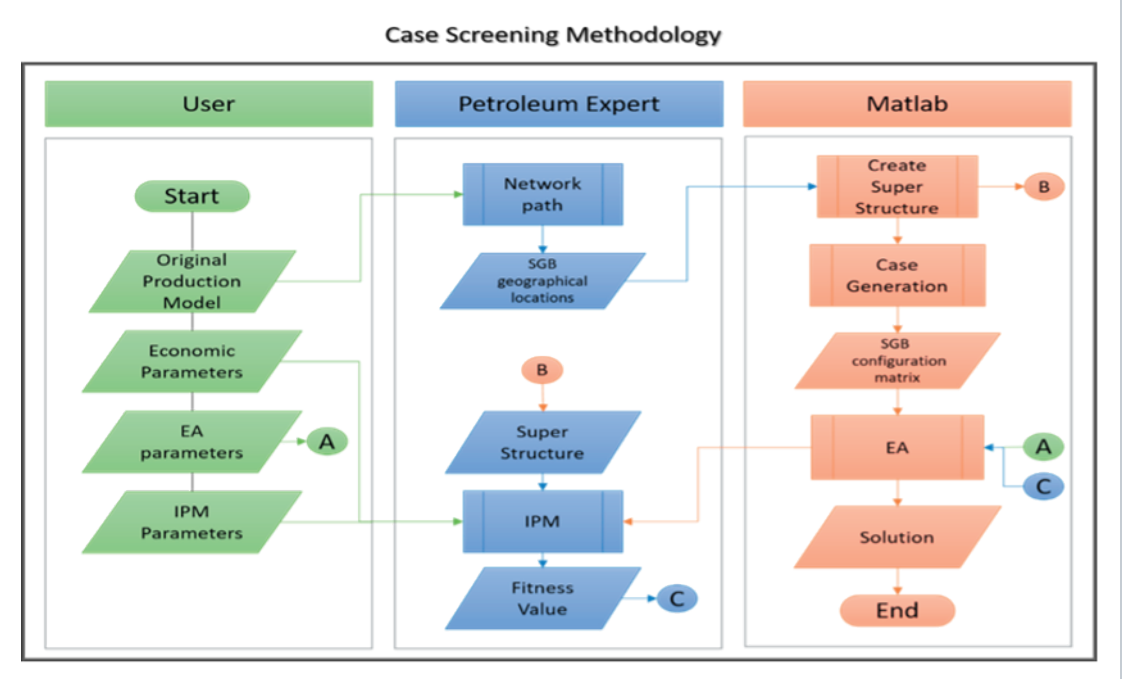


Figure 3 Flow diagram of the Case Generation and Scenario Screening Methodology.
(* Petroleum Experts is a commercially available software for the study of hydrocarbon production systems).

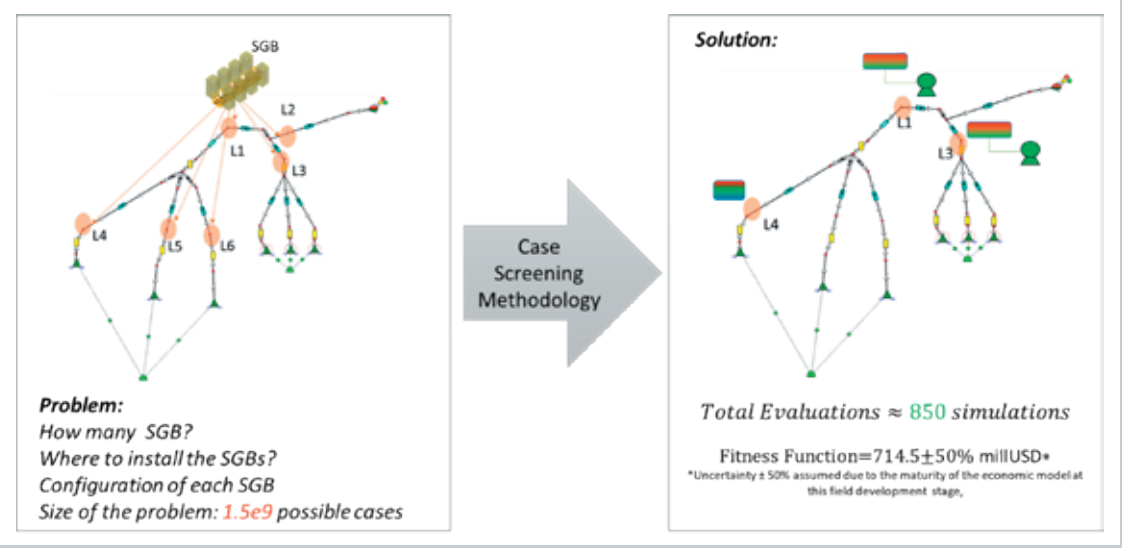


Figure 4 Example of defining the field architecture of a given development using the screening methodology.

FINAL PROJECT REPORT

Field development concepts

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

PhD graduate:	**Diana Gonzáles**
Start date:	22.10.2015
Thesis defense date:	26.02.2020
Title of thesis:	Methodologies to determine cost-effective development strategies for offshore fields during early-phase studies using proxy models and optimization.
Thesis committee members:	Bamshad Nazarian (Equinor ASA, Norway), Phaneendra B. Kondapi (University of Houston, USA), Sigve Hovda (NTNU, Norway)
Supervisors:	Associate Professor Milan Stanko, Professor Sigbjørn Sangesland, Professor Emeritus Michael Golan

1. BACKGROUND

The purpose of field development planning is to identify the best strategy to exploit an asset by finding concepts that are technically feasible and provide the best economic performance. Methodologies to provide decision support to field development have evolved over time from a simple intuitive "poke and hope" approach at the early stage of the petroleum era to a more sophisticated, modeling and engineering-based approach, nowadays. The global nature of the petroleum upstream industry drives the decision-support methodologies to converge gradually to a universal global pattern satisfying all stockholders.

The need to refine the methodology has been enhanced in the current era of the petroleum industry where newly discovered reservoirs and the associated development schemes become more challenging. Typical challenges encountered nowadays are related to deep and ultra-deep waters fields, longer offset and tiebacks of satellite fields and well clusters, arctic environments, high pressure and high temperature reservoirs, heavy oils, low-energy reservoirs, unstable oil and gas market (demands and processes).

Universal developments of IT capabilities with quick computational algorithms, quick data management (storage, transfer, analysis, visualization), and better data acquisition and transfer allow great improvement of the decision working processes during field development. Furthermore, the current transformation of the global upstream industry with many new, small and lean entities entering the role of field developers and field operators creates the need to provide simple, structured, and transparent decision methodologies.

The main objective of the field design team is to find the best development strategy that provides maximum profit and fulfills the technical constraints. This, however, is challenging because the value chain model is often not fully integrated on a digital platform, thus information transfer between disciplines is performed manually, it is time consuming and consistency is often not achieved. There are also working processes that are not easily automated and require performing labor-intensive tasks if input is modified. Moreover, the time frame allocated for feasibility studies and concept planning is typically short. Therefore, an exhaustive evaluation of all development alternatives and a proper analysis of the effect of uncertainties is seldom performed, which might lead to poor decision making and subsequently to a suboptimal field development strategy.

2. WHAT I HAVE DONE

This project looks into developing a method to provide decision-support to field planners during the early phases of field development when defining the field production profile, drilling schedule, type of offshore structure, pressure support method and selection of artificial lift. The method should have a low running time suitable to perform exhaustive evaluations and probabilistic analyses during the field planning process. This is performed by the following steps:

- Creating an efficient (low running time) integrated proxy model of the value chain model that contains all relevant field design features and computation of most relevant performance indicators to consider in the evaluation. The proxy model is intended to capture the first order of magnitude effects and not being a high-fidelity proxy.
- Perform efficient (low running time) numerical optimization on the proxy model of the value chain to find optimal development strategies that provide the most cost-effective solution.
- Evaluate the effect of uncertainties on the results of the numerical optimization using probabilistic methods.

This research has made special emphasis on capturing the interaction between the subsurface (reservoir)

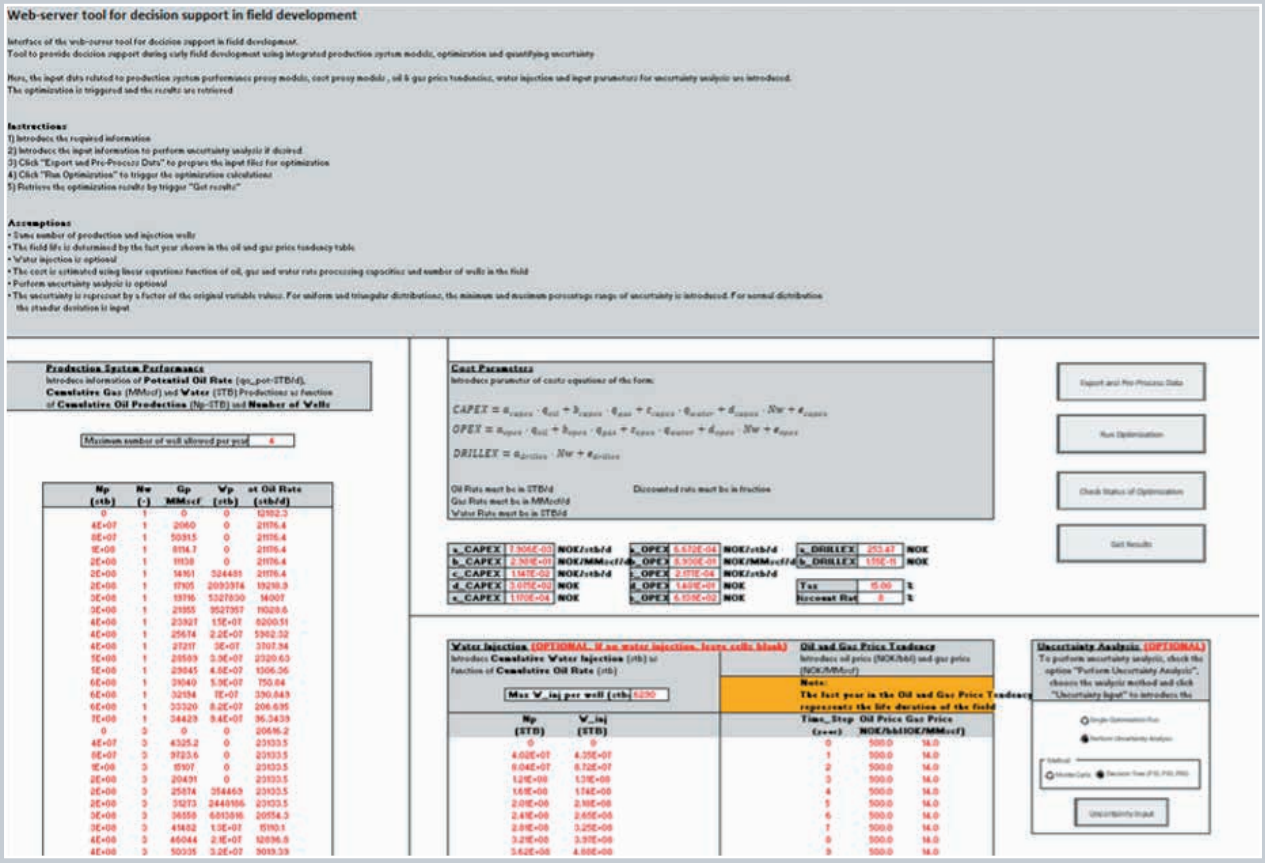


Figure 1. Interface of server-based tool for early field development decision support

system and the well and surface piping transportation system to the offshore structure when computing the field production profiles. The de-coupling between reservoir models and production system models has been flagged by previous researches and by oil and gas companies as a deficiency existing in current working processes in the industry. This can add up to the inability to study more field development strategies during the field development process.

There has been extensive researches into this topic in the past, with a varying degree of model complexity, model execution and optimization methods to quantify uncertainty and variables of interest, such as well control, drilling schedule, well placement, reservoir realizations, economic model, etc. However, the differentiating characteristics and contributions of the present research are as follow:

- Representing the production performance of the integrated reservoir-well network system with a proxy model. The proxy model consists of oil production potential, GOR and WC tables expressed as function of the cumulative oil produced and the number of production wells. These proxy models are obtained by coupling a reservoir tank model with a steady-state well/network model.
- Develop linear models for cost figures such as CAPEX, OPEX and DRILLEX by applying linear regression on cost values for varying number of wells, maximum oil, water and gas rates.
- Formulate an efficient mathematical optimization problem to find optimal production and drilling schedule that maximize NPV using the proxy model of the production system and linear cost functions for CAPEX, OPEX and DRILLEX. The non-linearities are represented with piece-wise linear functions using SOS2 variables.
- Uncertainty analysis on the results of the optimization using probability trees.

The methodology was tested on a synthetic case based on publicly available data of the Wisting field, which is currently under development. The business case has been suggested by the industry partners in the SUBPRO research program of which this project is a part of. Additionally, a master thesis has successfully applied the methodology developed in this PhD research work to another synthetic field named “Safari” proposed by AkerSolutions.

3. MAIN RESULTS

The main result obtained is a verification and a substantiation on a field scale methodology to provide decision support on field design in early stages of the field development process. While the overall methodology might be similar to the conventional ones practiced by the industry or presented in previous research, the details of the modeling and the formulation of the optimization, as suggested and verified in this project, are novel and constitute improvement.

The methodology was applied to produce and monetize a synthetic reservoir based on data on the Wisting Field. Nine (9) development strategies were compared and ranked. The strategies were obtained from the combination of three recovery methods (gas lifted wells, gas lifted wells with water injection and multiphase boosting with water injection) and three topside facilities (TLP, FPSO and Tie-Back). The best-case strategy, i.e. the one that gives the highest profit, was determined.

Based on the results obtained from testing the methodology it was concluded that it successfully finds optimal field design features while quantifying the effect of uncertainty with running times suitable for current field development workflows.

4. INNOVATION AND COLLABORATION WITH INDUSTRY PARTNERS

The results at the end of the study and the testing of the results provided a template and an input for developing a software package for performing structured feasibility studies and concept planning during the engineering design of oil and gas fields.

The potential value of the methodology has been recognized by AkerBP and by AkerSolutions in multiple occasions. For this, the PhD project has been followed up by a 6 months innovation project, which consists of create a server-based tool with a user-friendly interface that allows engineers and field planners to use the method for their cases (Figure 1). The user uploads proxy models of production and cost, and other relevant information like hydrocarbon price, and trigger the optimization calculation and gets back the results.

This will allow for SUBPRO partners and other companies to test the methodology with their data (thus effectively assimilating the results of the SUBPRO SFI) and to validate and improve the methodology generated in the PhD project.

5. FURTHER WORK

For future works it is recommended to:

- Increase the flexibility of the methodology by adding the option to choose the objective variable. Besides NPV, possible objective variables could be oil/gas recovery, operational flexibility, CO_2 emissions, break-even point, etc.
- Explore formulations for performing multi-objective optimization.
- Improve the optimization formulation to reduce the running time. For this, it is suggested to perform a study on the optimal number of break points used for the piecewise linear approximation of the non-linear functions, as well as perform a study comparing different PWL approximation models.
- Modify the methodology to allow the option of work with multiple independent reservoirs.
- Analyze the effect of the reservoir model used by comparing the results obtained using reservoir simulator versus material balance.
- For the uncertainty analysis, include additional uncertainties like water breakthrough time, water coning, oil price, etc. In addition, perform the uncertainty analysis using stochastic methods, like Monte Carlo or Latin Hypercube, instead of probability trees.
- Include the effect of flow assurance technologies on the proxy models of the production potential and costs.

PROFESSOR
JØRN VATN

RESEARCH AREA
MANAGER

RESEARCH AREA

Reliability, Availability, Maintenance and Safety (RAMS)

Cost efficient solutions without compromising safety and environment.

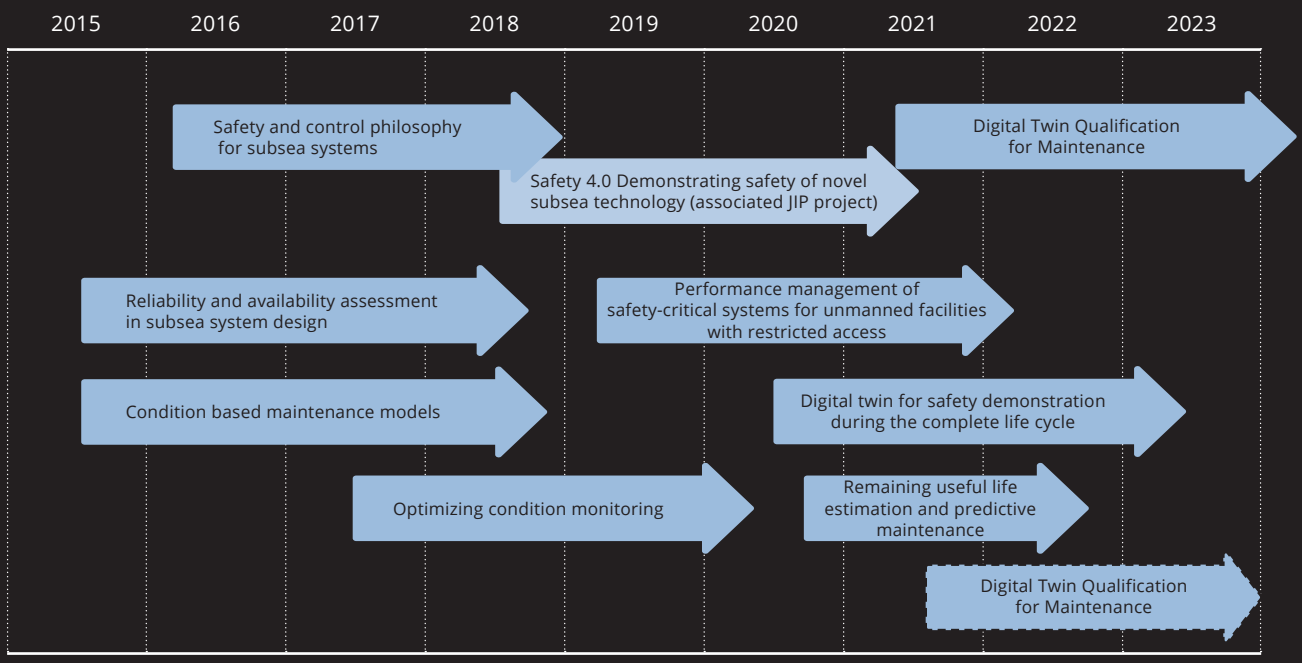
2020 was a year for the continuation of ongoing research and initiation of new research within the established topics of the RAMS research area. Professor Shen Yin was recruited under the DNV-GL sponsored professorship as part of the SUBPRO / DNV-GL agreement. Due to Covid-19 professor Shen Yin could not arrive to Norway before late October. To support the DNV-GL professorship the IV-faculty at NTNU has financed a PhD position. Muhammad Gibran Alfarizi was recruited to this position. Gibran wrote his MSc thesis at NTNU and started his PhD in September.

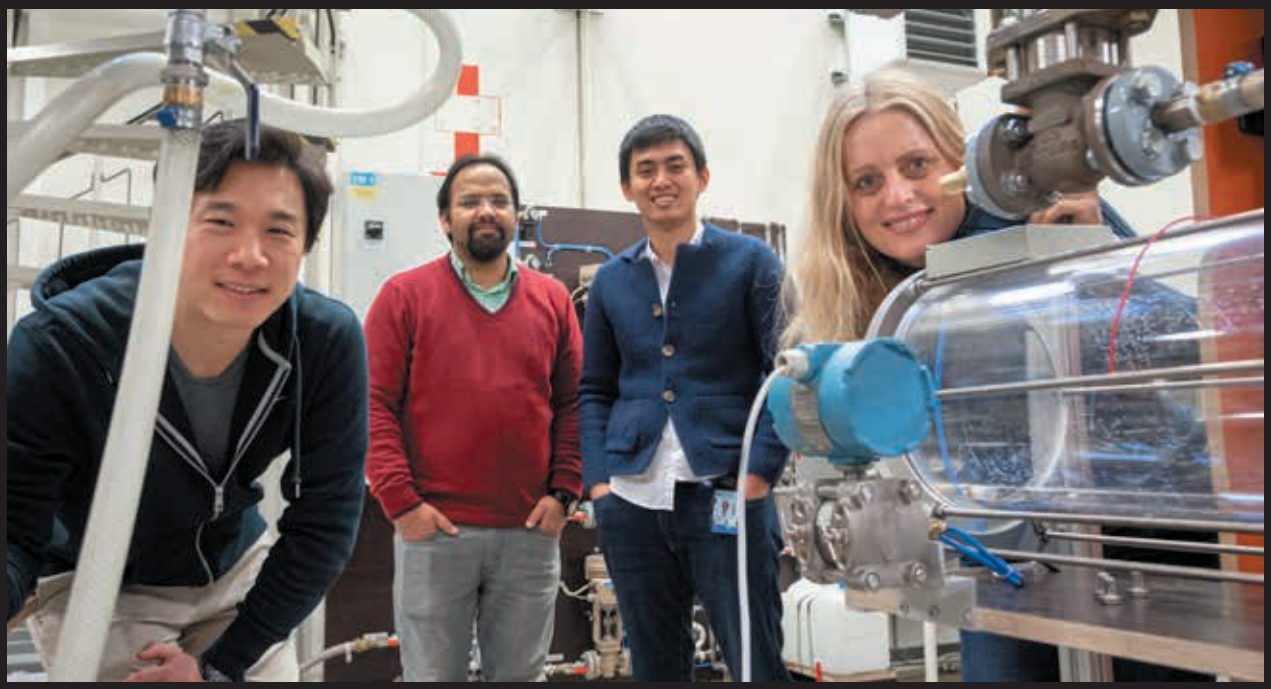
Xingheng Liu was recruited as a Post.Doc. for the innovation project on estimation and optimization of remaining useful lifetime. Xingheng completed a double degree at UTT (France) and NTNU in September and started his Post.Doc. just after the PhD defence. Within the RAMS field there are synergies between SUBPRO and the BRU21 program. We have therefore established what we call a "quartet" with Gibran and Xingheng from SUBPRO and Tom Ivar Pedersen and Ewa Maria Laskowska from BRU21. A first meeting was arranged in October with participants from DNV-GL, Equinor and Lundin. We plan such a joint meeting each semester.

SUBPRO arranged a seminar on Digital Twins in November. The disciplinary area addressed was system control, safety, reliability and maintainability and the interaction between these. The plan was to have a physical seminar, but due to Covid-19 the seminar was arranged as a Webinar. At the most it was more than 80 participants joining the seminar. The feedback from the industry partners was very positive. The seminar also gave inspiration to propose a PhD position on qualification of digital twins for maintenance. The proposal was approved by the SUBPRO partners and the position has now been announced.

From an administrative point of view, Professor Jørn Vatn has now taken over the leadership as research area manager from Mary Ann Lundteigen. Thanks to Mary Ann for her effort to coordinate the RAMS activity within SUBPRO in a very efficient manner. Mary Ann is now the director of SFI Autoship and we look forward to a fruitful collaboration in the future.

Completed, current and planned projects





The Reliability, Availability, Maintenance and Safety team
From left : PhD student TaeHwan Lee, PhD student Himanshu Sriva stav, PhD student Nanda Anugrah Zrikullah and professor Mary Ann Lundteigen.
(PhD student Ludvig Bjørklund, Postdoc Xingheng Liu and professor Jørn Vatn were not present when the picture was taken – in early 2020).

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. 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:
Professor
Mary Ann Lundteigen

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

1. 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.

2. 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.

As a part of PhD academic training, essential courses in performing the research have been taken such as System Reliability, Multivariate Data Analysis – Advanced Topic, and Petroleum Cybernetics.

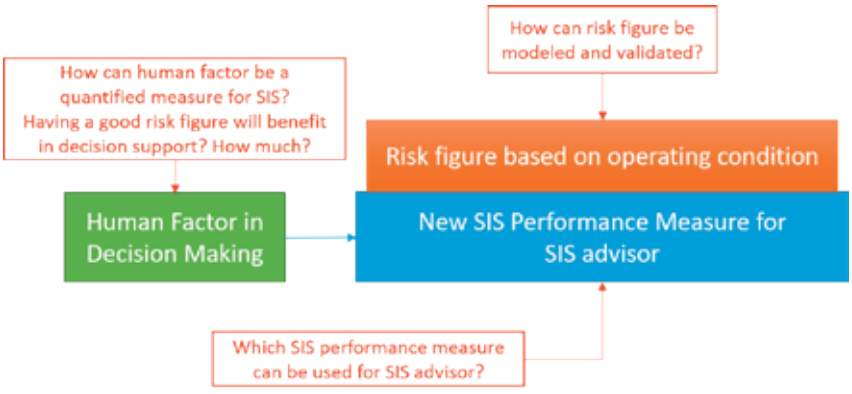
Research focus on this year was given on Advisor on SIF action, so-called SIS advisor. SIS advisor is proposed to support operator's decision in case of emergency as well as ordinary tasks such as maintenance work. A literature review has been carried out to identify theoretical basis for the performance index, so that we can measure how much risk can be reduced if SIS advisor is introduced.

To aid the operator to make better decision, SIS advisor needs to be able to classify current operating condition as normal or dangerous. Identifying normal operating envelope can be obtained by analyzing historical operating data, and machine learning techniques can be beneficial for this task considering the huge amount of historical data. Research on how to build a model, which types of data to be used, how to utilize simulation data into training data is under investigation. As a part of this research, a paper on how machine learning can be used to enhance operator's awareness on the system will be submitted to ESREL 2021.

3. 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.



Overall structure of SIS Advisor research project

Digital Twin for Safety Demonstrations During the Complete Life Cycle

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

Green shift impact: A shift to all-electric control system (incl. actuator) mitigates risk of leakage and removes the HPUs and transportation of fluids.

PhD student:
Ludvig Bjørklund

Project manager:
Professor
Mary Ann Lundteigen

Supervisors:
Prof. Mary Ann Lundteigen
Prof. Gunleiv Skofteland (Equinor) and
Prof. Markus Glaser (Aalen University)

1. BACKGROUND

The technology in the Oil and Gas industry for subsea safety valves is changing from hydraulic actuation to all-electric actuation due to the following reasons:

- CAPEX reduction (reduced umbilical cost, no HPU, reduced system cost)
- Environmental impact (pollution free technology, no HPU, transportation of fluids)
- Deep water capability
- OPEX reduction (maintenance free technology)
- Improved HSE (no high pressure)

The actuation system is required to isolate the well and the environment with a safety integrity level (SIL) equivalent to realized solutions. To achieve SIL 2, according to the IEC 61508, the system needs to be able to detect more than 90% of all possible faults.

2. RESEARCH ACTIVITIES AND DELIVERABLES

The detailed research plan was accepted by NTNU in December 2020. The upcoming project research activities will include:

- Analysis of the state of the art from other industries, related to software validation methods in safety-critical systems.
- Research the characteristics and features which are required to comply to demonstrate safety for an all-electric control system.
- Develop an implementation and realization strategy for a suitable Digital Twin.
- Academic collaboration includes Aalen university with Professor Markus Glaser, a previously visiting researcher in SFI SUBPRO who are working with all-electric valve concepts and solutions.

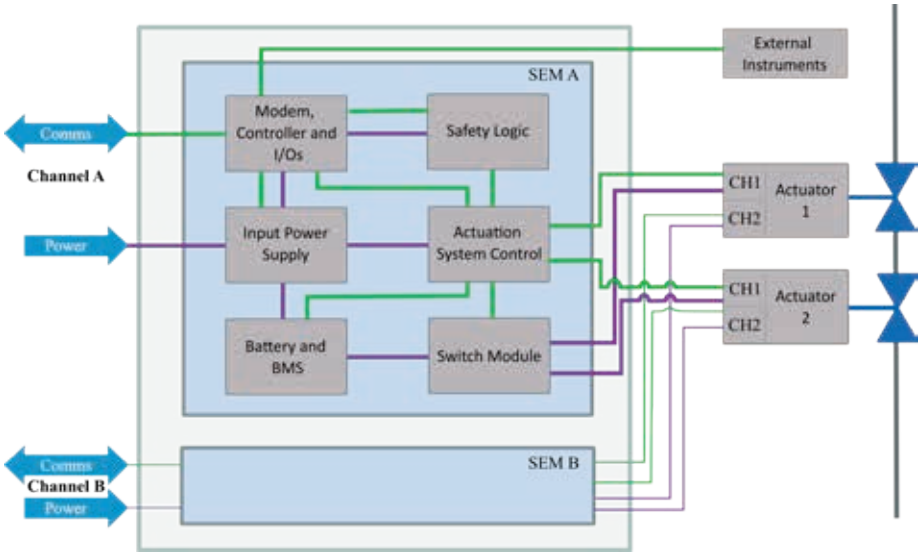
The expected deliverables:

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

3. INDUSTRY PARTICIPATION

A collaboration has been established with Equinor, and in 2021 it is planned to also interact with Total, DNV-GL and Aker Solutions who are all working with all-electric concepts for subsea valves.

Results of this research can be used as foundation for improved development process with reduced time and costs.



Architecture for all electric control system.

Remaining useful life estimation and predictive maintenance

Stochastic process degradation modelling applied to subsea systems.

Green shift: An accurate remaining useful life estimation leads to a better organization of maintenance resources and less energy and materials consumption.

Postdoctoral fellow:
Xingheng Liu

Project manager
and supervisor:
Professor Jørn Vatn

1. PROGNOSTIC AND HEALTH MANAGEMENT FOR SUBSEA SYSTEMS

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

2. RUL ESTIMATION FOR SUBSEA CHOKE VALVES

This project's main objective is to develop prototype simulators for the estimation of RUL for subsea components and systems. Following the work of a former SUBPRO member in 2018, we first investigate the subsea choke valves that control liquid and gas mixtures' flow rate and prevent the equipment from unusual pressure fluctuations.

Choke valves suffer from erosion due to sand production in mature fields. One health indicator of the erosion process is the difference between the theoretical and estimated valve flow coefficients (Cv). When the difference finally passes a predefined threshold, the choke is no longer reliable and needs to be inspected. Considering the degradation mechanism, the accessibility of data, and the models' complexity and interpretability, two prototypes are being developed:

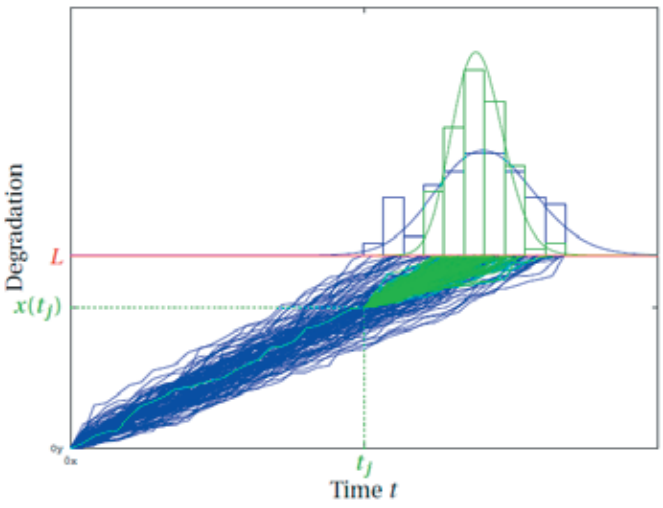
Prototype A: several single-mechanism degradation models (Weiner process, noisy Gamma process, noisy Inverse-Gaussian process...) are implemented. The input data is a sequence of historical Cv differences. The prototype automatically estimates the model parameters and compare the model relative weights using Akaike information criteria. The expectation, median, and confidence interval of RUL are given according to each model.

Prototype B: a shock-associated degradation model is implemented. This model accounts for sand production, which is the main factor in choke erosion. Sand production appears in two forms: continuous and burst. The latter occurs when the well is suddenly exposed to sand loosening from the reservoir. Using sand monitoring data and the choke valves' degradation paths located at the same well, one can quantify the influence of sand burst on the deterioration and obtain a more accurate estimation of the RUL.

Both prototypes will be tested with the data provided by the industrial partners, namely Equinor, DNV-GL and Lundin.

3. RESULTS AND DELIVERABLES

Prototype A is partially completed. Fed with only Cv data, the prototype could be easily utilized by the industrial partners. Users do not need specific statistic/reliability knowledge.



By considering the historical degradation data, the RUL could be more accurately estimated with a narrower confidence interval (green curve).

Demonstrating safety of novel subsea technologies

An associated Safety 4.0 project.

PhD student:
Nanda Anugrah Zikrullah

Main Supervisor:
Professor
Mary Ann Lundteigen

Co-Supervisors:
Associate Prof.
Hyungju Kim (USN)
Meine J.P. Van Der Meulen (DNV)

Project manager
Tore Myhrvold DNV

1. 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 joint-industry research project is headed by DNV 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 Safety 4.0 project's objective is to enable and accelerate the 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.

2. PHD PROJECT - ENSURING FUNCTIONAL SAFETY OF NOVEL TECHNOLOGIES

The project intends to develop a safety demonstration method for systems considering integration between process control and safety. The study cases are from the subsea oil & gas industry, focusing on the subsea processing system.

The research focuses on:

(1) Identification of safe design principle

(2) Investigation of qualitative safety assessment methods

(3) Development of quantitative safety assessment approaches considering uncertainties

(4) Development of the framework for the safety assessment of system considering dependency

Two years have passed since the starting of the PhD project. We are currently in the middle of the third phase of the research and planned to finalize the research work by autumn.

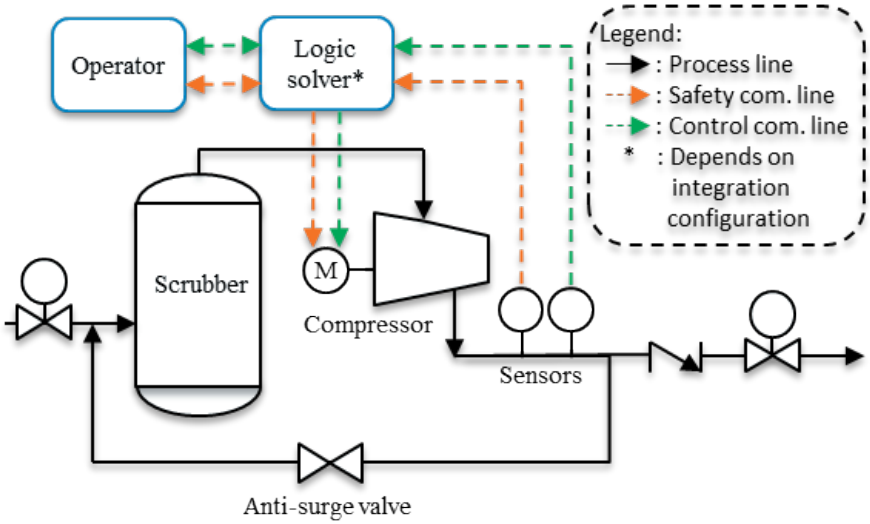
3. ON UNDERSTANDING THE EFFECT OF INTEGRATION FOR A SAFETY SYSTEM

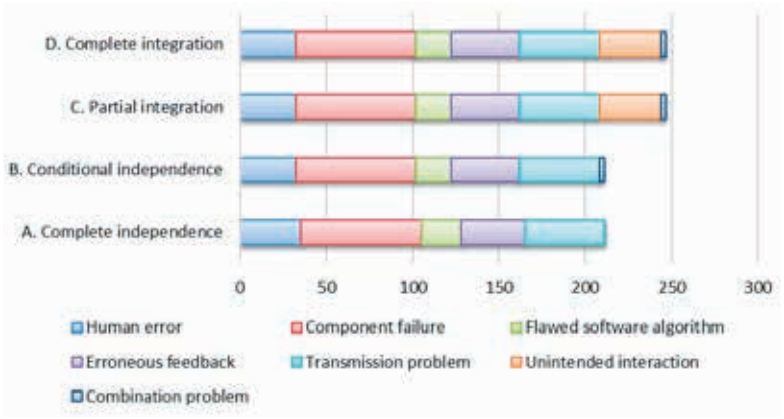
The proposed qualitative method had been applied to identify the effect of integration (between process control and safety) on the system's safety. While this sheds light on critical areas to be focused on, challenges related to the integrated system's demonstration processes remain. Utilization of the quantitative method while considering the uncertainties in the novel technology is expected to solve some of the remaining problems.

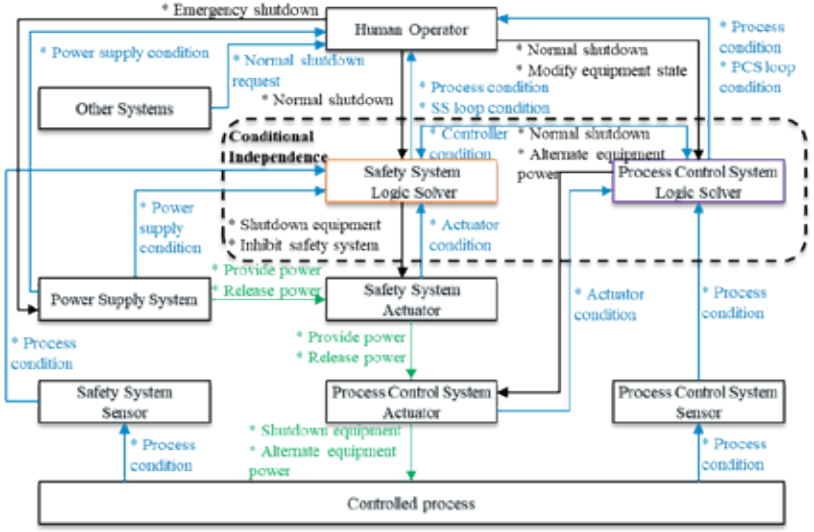
DNV and partners from the Safety 4.0 project have contributed a lot during the research work by providing inputs and platforms to discuss the results with experienced practitioners.

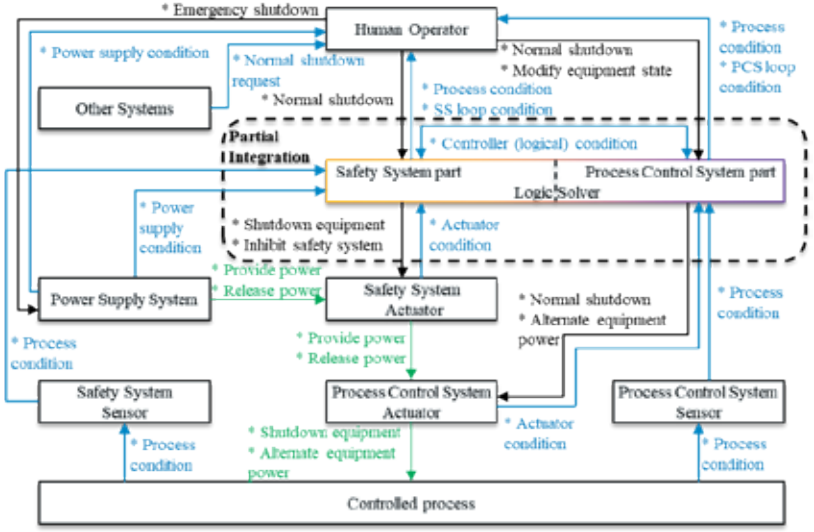
4. POTENTIAL FOR INDUSTRIAL APPLICATIONS

An increase in complexity due to the digitalization of equipment affects the safety demonstration process. The method has shown its potential to be used for the safety assessment during complex systems' design and operation.









A comparison (top-right) for the total number of loss scenarios identified from a typical subsea processing system (top-left) with different integration levels. The results are obtained from assessing individual systems' models (bottom-left and -right) as part of the safety assessment method. For more detailed information, please refer to the publication by Zikullah (2020).

FINAL PROJECT REPORT

Optimizing condition monitoring

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

PhD graduate:	**Himanshu Srivastav**
Start date:	01.07.2017
Thesis defense date:	17.03.2021
Title of thesis:	Optimizing condition monitoring for dynamic health and risk management
Thesis committee members:	Professor Enrico Zio (Politecnico di Milano, Italy), Professor Roger Flage (Universitetet of Stavanger, Norway), Cecilia Haskins (NTNU, Norway)
Supervisors:	Professor Anne Barros Professor Mary Ann Lundteigen

1. BACKGROUND FOR THE 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.

2. WHAT I HAVE DONE

This project's objective is to develop systematic frameworks to assess the performance of the subsea system considering its degradation phenomenon. The primary focus was on modelling the degradation behaviour of the subsea safety systems. We also extended the degradation modelling concepts to study the subsea production systems. We have addressed four research questions explicitly:

- In the first research question, we developed a framework to assess the reliability of a safety instrumented system that is subjected to destructive periodic tests. We developed a dynamic failure rate model that depends on the current degradation level and the number of tests experienced. We also performed the case study on Down-hole safety valves (DHSV) to determine the optimum number of periodic tests that maximize the average availability of DHSV in given mission time. A high frequency of tests will reduce the probability for DHSV to be in an undetected failed state and not to act on demand. On the other side, the cumulative stress experienced due to tests may degrade the performance to failure. This trade-off is shown in the figure 1.

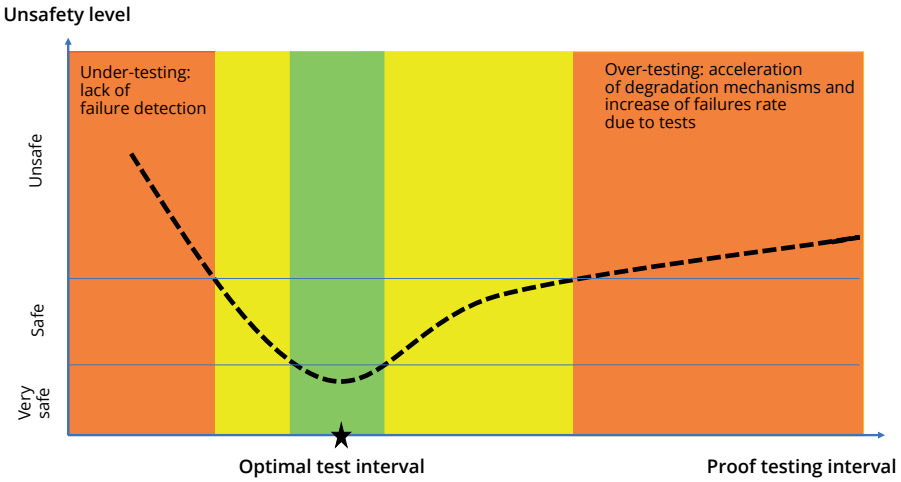


Figure1: Trade-off between added condition information and increased wear.

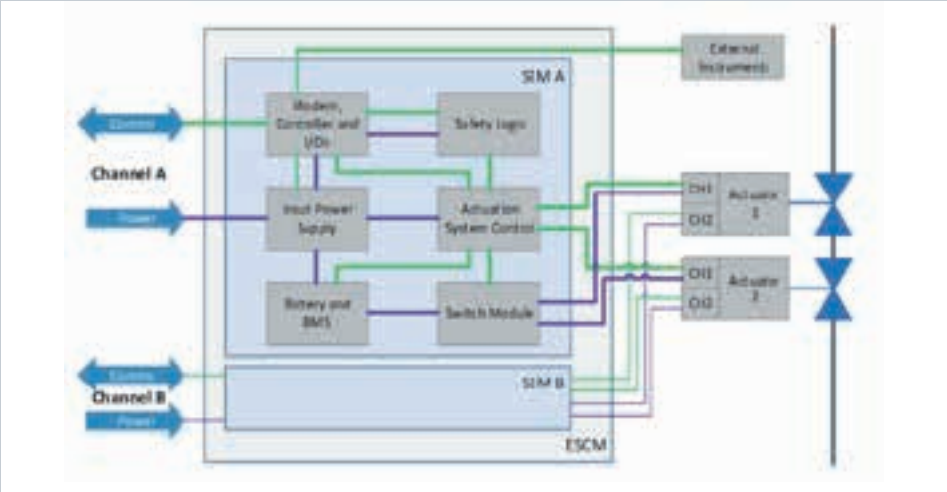


Figure 2: System Architecture of all-electric actuation system.

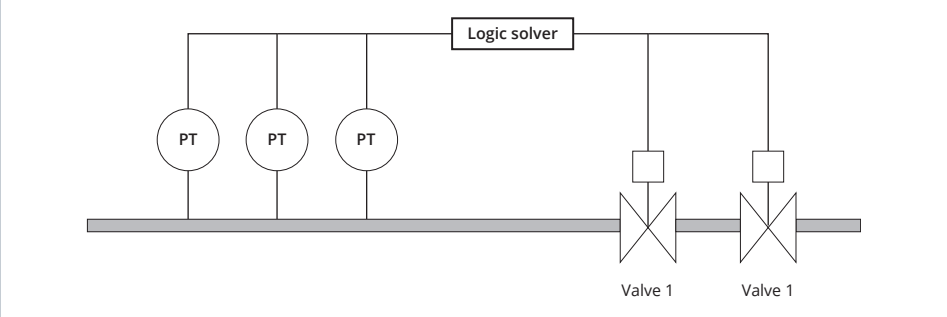


Figure 3: HIPPS with a redundancy in the safety valves.

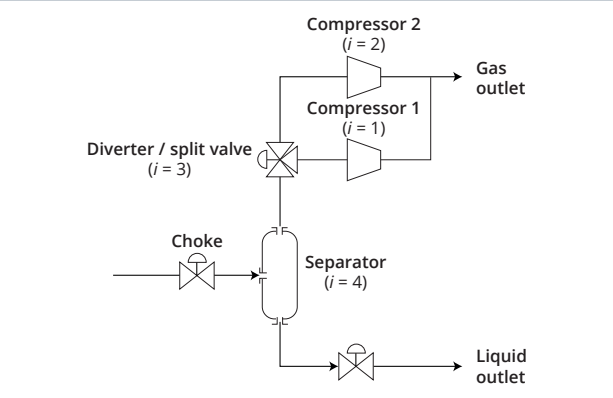


Figure 4: Illustration of subsea compressor system

- In the second research question, we extended degradation modelling techniques in the qualification of novel subsea technology. All-electric systems are the novel subsea technology that promised more reliable equipment and a safer environment. The current reliability assessment of safety valves deployed with such systems assumes perfect restoration during proof tests and no impact of degradation due to demands. We improved upon these assumptions by performing a case study on all-electric actuation systems (as shown in Figure 2). In this case study, we were able to assess more realistic safety capabilities of safety valves utilized by all-electric actuation system.

- In the third research question, we studied the testing and maintenance strategies for a redundant SIS with imperfect detection of degraded state during proof tests. This study's main purpose is to incorporate and balance system availability and life cycle costs. We performed a case study on the subsea high-integrity pressure protection system (as shown in Figure 3).

- In the fourth research question, we extended the degradation modeling techniques in the domain of subsea production systems. Subsea production systems are operated very aggressively to extract hydrocarbon quickly and as much as possible. This causes premature wearing of the systems, which increases maintenance and repair costs. There exists a trade-off between high maintenance and repair costs versus high production profits. In this study, we addressed this trade-off by developing a method that integrates the deterministic control laws to the stochastically deteriorating components. We performed a case study on the subsea compressor system in which each component undergoes stochastic degradation (as shown in Figure 4).

3. MAIN RESULTS

This main research results of this project are presented to the academic worlds through publication in international journals and proceedings of conferences with peer review processes. To industries, the results were informed under the framework of SUBPRO through bi-annual reference group meetings. The list of publication is attached herewith for the ready reference of the readers:

i. Srivastav, Himanshu; de Azevedo Vale, Guilherme; Barros, Anne; Lundteigen, Mary Ann; Pedersen, Frank Børre; Hafver, Andreas; Oliveira, Luiz F ; **Optimization of periodic inspection time of sis subject to a regular proof testing** ; Safety and Reliability – Safe Societies in a Changing World, Proceedings of ESREL 2018, June 17-21, 2018, Trondheim, Norway.

ii. Srivastav, Himanshu; Barros, Anne; Lundteigen, Mary Ann; **Modelling framework for performance analysis of SIS subject to degradation due to proof tests**; Reliability Engineering & System Safety. vol. 195 (106702).

iii. Srivastav, Himanshu; Barros, Anne; Lundteigen, Mary Ann; **Introduction of degradation modeling in qualification of the novel subsea technology**; Reliability Engineering & System Safety – under review

iv. Zhang, Aibo; Srivastav, Himanshu; Barros, Anne; Liu,Yiliu ; **Study of testing and maintenance strategies for redundant final elements in SIS with imperfect detection of degraded state** ; Reliability Engineering & System Safety

v. Verheyleweghen, Adriaen; Srivastav, Himanshu; Barros, Anne; Jäschke, Johannes; **Combined Maintenance Scheduling and Production Optimization**; Proceedings of the 29th European Safety and Reliability Conference (ESREL),22 – 26 September 2019 Hannover, Germany

vi. Verheyleweghen, Adriaen; Srivastav, Himanshu; Barros, Anne; Jäschke, Johannes; **A Unified Approach for Simultaneous Optimization of Production and Maintenance Schedules**; IEEE Transactions on Reliability

4. INNOVATION PROJECT

Post-doctoral project 3.3 c) Estimation and optimization of Remaining useful life (RUL).

5. FUTURE RESEARCH

We propose future research directions based on the understanding of the limitations of the frameworks developed in this project.

- **Inclusion of other failure modes**
  The frameworks concerning the reliability assessment of SIS mainly discuss the performance of the final element of SIS. Dangerous undetected (DU) failures are the dominant failure mode for the final elements of SIS. All analysis in this project is dedicated to the dominant failure mode. However, to make them more generic, it is required that the developed framework also includes various other failure modes (such as dangerous detected failures and safe failures) into consideration.

- **System level reliability assessment**
  The frameworks discussed in this project only perform a reliability assessment of the final elements of SIS. Generally, SIS consists of two other subsystems: the sensors subsystem and the logic solver subsystem. These frameworks need to be extended to combine the subsystem level reliability to perform the global level (system level) reliability assessment. The integration of systematic failures in the framework will be necessary to evaluate each subsystem's dependence among the various failure modes.

- **Model Verification with respect to real-time condition data**
  The frameworks developed in this project are based on identifying first a research problem with industrial interests. Then, hypothesizing about the real-time degradation phenomena that the problem is centered around, making applicable assumptions, formulating the frameworks based on these assumptions, and generate and discuss results. Twofold model validation is performed about these frameworks (i) All steps right from conceptualization of research idea to the results generated through the developed framework are discussed and presented to industry experts, (ii) All the research work carried out in the thesis is submitted and published from peer-reviewed journals and conference. However, we are yet to perform model verification concerning real-time condition data. This verification will justify the number of discrete performance levels, estimation of model parameters from the real-time condition data statistically. The unavailability of real-time data was the main reason behind no model validation.

PROFESSOR
GISLE ØYE

RESEARCH AREA
MANAGER

RESEARCH AREA

Separation – Fluid characterization

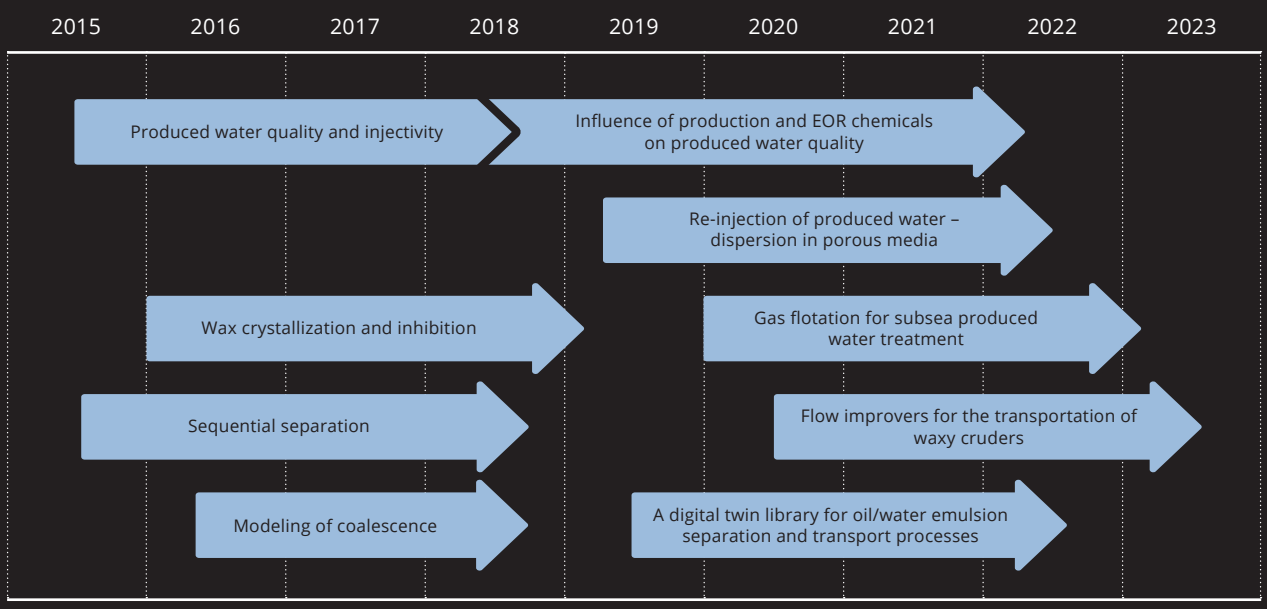
Enhancement of separation efficiency and flow assurance.

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 2020 two new projects have been started, one related to gas flotation and one related to wax precipitation mechanisms. 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, George-Claudiu and Moein.

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.
(Phd student George-Claudiu Savulescu, Professor Gisle Øye, Professor Magne Hillestad and Associate professor Brian A. Grimes were not present when the picture was taken – in early 2020).

Influence of production and EOR chemicals on produced water quality

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

Postdoctoral fellow:
Marcin Dudek

Project manager:
Professor Gisle Øye

Green shift impact: Better fundamental understanding of fluids could lead to less harmful discharges to the environment.

1. PRODUCTION CHEMICALS MAY HAVE COMPLEX EFFECTS ON OIL-WATER SEPARATION

Addition of production chemicals is an essential part of petroleum production and processing. A number of different additives is being injected in order to avoid fouling of process units and pipelines, reducing corrosion or improving separation. Many of these chemicals are surface-active and could potentially impact the separation processes, also including produced water treatment. With the increasing volumes of produced water, the unknown effect of these chemicals on these processes is undesirable and therefore requires better fundamental understanding.

2. NEW MICROFLUIDIC METHODS FOR STUDYING FUNDAMENTAL PHENOMENA

The present project uses microfluidics for studying the effect of production chemicals on the fundamental phenomena occurring during produced water treatment, such as coalescence between crude oil droplets. Microfluidics is a technique that allows observation and manipulation of fluids in small, transparent channels. Emulsion droplets are generated in a controlled manner and their interactions are recorded by high-speed imaging. In 2020, we have continued our promising work with flocculants and scale inhibitors, and also studied the effect of wax inhibitors. The methodology for studying the effect of flocculants on coalescence has been improved with additional screening options (dynamic, on-chip control of the additive concentration). Several types of wax inhibitors were tested, in collaboration with and as a follow-up to project subproject 2.2 (Prevention of wax deposition). Work on precipitation in the presence of scale inhibitors is continued from last year's research stay at ETH, but now in collaboration with a group from Heriot-Watt University (Figure).

3. COMPOSITION OF WAX INHIBITORS CAN AFFECT COALESCENCE BETWEEN OIL DROPLETS IN PRODUCED WATER

With the previously established microfluidic methodology, a series of experiments with various model wax inhibitors was performed. The oils also contained different amounts of macrocrystalline wax to probe its effect on the coalescence of droplets during simulated water treatment. In addition to these tests, the fluids were also characterized through interfacial and rheological studies, as well as the wax appearance temperature measurements. The coalescence of droplets was measured both at room and elevated temperatures. Similar components were also used in another SUBPRO project related to wax crystallization.

We have found that depending on the chemical composition of the wax inhibitor, they can also exhibit surface-active properties. For example, one additive with low molecular weight reduced the oil/water interfacial tension significantly, which could have also caused the high emulsion stability during microfluidic coalescence experiments. The behaviour of droplets containing other additives could have also been linked to their interfacial and rheological properties.

The obtained results underline the importance of more fundamental and holistic approach to the crude oil production and processing system and show that overdosing certain production chemicals on one stage of the process could lead to separation problems at the other end.

Timelapse of a microfluidic precipitation of calcium – scale inhibitor complex. Laminar flow in the channels allows for a stable water-water interface and diffusion across it, favouring controlled crystallization process.

Re-injection of produced water – dispersions in porous media

New methodology for understanding of transport and retention phenomena.

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

PhD student:
Ilgar Azizov

Project manager & main supervisor:
Professor Gisle Øye

Co-supervisor:
Postdoctoral fellow Marcin Dudek

1. BACKGROUND FOR THE PROJECT

Petroleum production is accompanied by production of water, which is the largest by-product in the industry. Produced water (PW) comprises various components, e.g. crude oil, dissolved organics, etc. Produced water re-injection (PWRI) is an environmentally attractive option as it limits the discharge of produced water into the sea. PWRI is often considered to be the base case for new fields as regulations concerning the discharge of PW become stricter. Moreover, PWRI in subsea production and processing could reduce CAPEX of field development.

The main limitation for PWRI is the injectivity decline due to pore clogging by oil droplets and particles present in PW. To date, the retention phenomenon is not completely understood, although numerous studies are reported. The main reason is the inability of experimental techniques typically (coreflooding) utilized in the literature to visualize pore-scale events. In contrast, microfluidics would allow visualization and let researchers follow fluids in single micro-channels or networks. Methods such as X-ray imaging would provide the desired result; however, they are more expensive and complex to employ.

2. A NEW MICROFLUIDICS METHOD OVERCOMING EXISTING GAPS

The literature review identified several gaps. Firstly, the effect of crude oil composition on droplet retention has not been investigated. Secondly, although the literature shows that particles affect droplet retention, the mechanisms are not clear. Moreover, PW contains production and enhanced oil recovery chemicals, which were shown to influence pore clogging. However, only a couple of studies investigated the issue. Finally, rock wettability is critical for the flow through permeable media; however, there is lack of studies examining its influence. The development of microfluidic method and addressing the gaps is the objective of the study.

The newly developed microfluidics method enables the study of droplets and particles dynamics at capillary level. In contrast to coreflooding, the method allows to register every single retention event, apply quantitative analysis on the droplet capture and draw conclusions regarding the retention directly from observations. The methodology allows to study transport of mono- and polydispersed emulsion. The figure illustrates some of the capabilities of the technique.

3. NEW INSIGHTS AND NEW TOOLS TO INCREASE EFFECTIVENESS

Understanding the factors affecting droplet capture is essential to obtain models of injectivity decline and define injection water specifications. It is expected that addressing the gaps in the knowledge will 1) help to improve the existing models and increase their effectiveness; 2) help the industry to define more effective injection water specifications. New microfluidic methodology will extend our existing toolbox and provide foundation for future studies.

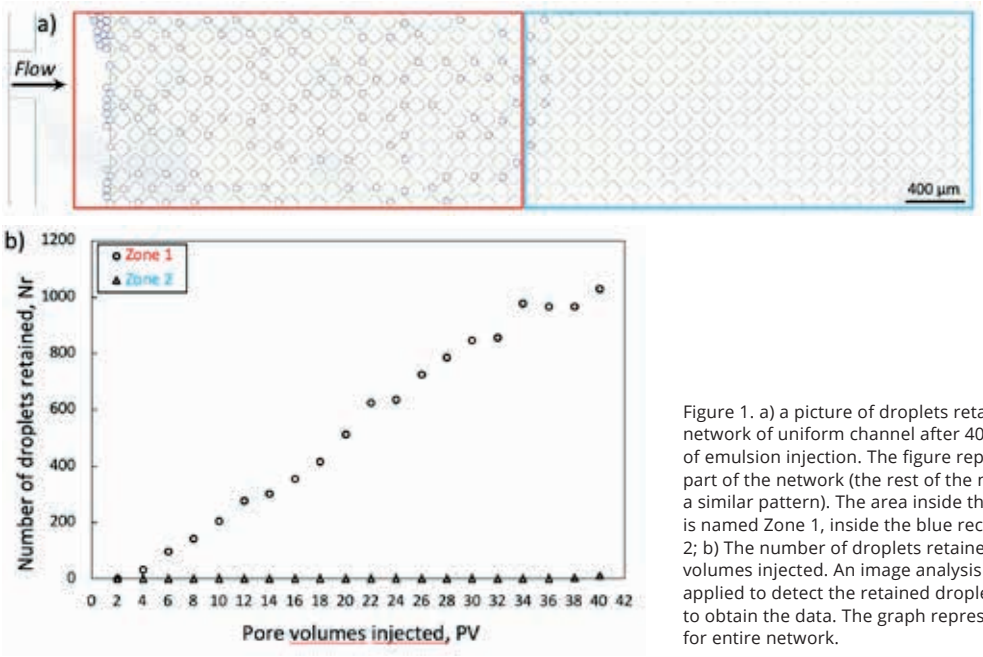


Figure 1. a) a picture of droplets retained in a network of uniform channel after 40 pore volumes of emulsion injection. The figure represents 1/9 part of the network (the rest of the network shows a similar pattern). The area inside the red rectangle is named Zone 1, inside the blue rectangle Zone 2; b) The number of droplets retained versus pore volumes injected. An image analysis technique is applied to detect the retained droplets on the image to obtain the data. The graph represents the data for entire network.

Gas flotation for subsea produced water treatment

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

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

PhD student:
Martina Piccioli

Project manager:
Professor Gisle Øye

Main supervisor:
Professor Gisle Øye

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

1. BACKGROUND OF THE PROJECT

Before discharge to the sea or reinjection into a reservoir, produced water (PW), must be treated to a certain level of purity. Gas flotation is a common and efficient technique used in the upstream petroleum processing to reduce oil and solid particles concentration in PW. 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.

Nowadays significant attention is given to subsea production and processes, and so to subsea separation. Subsea gas flotation is a strong candidate for subsea water treatment, but it is performed under considerably higher absolute pressure and various temperature conditions. These different conditions can raise the density difference between oil and water and reduce the viscosity of the fluids, that may enhance the separation performance. Anyway, there is a knowledge gap when it comes to the understanding of the microscopic phenomena and the change in the fluid properties involved in gas flotation processes at high pressure with a varying temperature.

2. AN IMPROVED HIGH-PRESSURE GAS FLOTATION SET-UP

In order to understand how different conditions of pressure and temperature influence the process, the experiments will be performed in a high-pressure gas flotation rig present at Ugelstad lab. Before starting the experiments, the set-up had to be modified in order to ensure satisfying experimental conditions. The old gas flotation rig used to give problems in controlling the pressure value, measuring the temperature and in the dispersion of gas bubbles. The adjustments that have been made consist in the installation of three pressure sensors and one temperature sensor, a new design for the base of the flotation cell, the usage of new types of spargers and a new system for the sample inlet and outlet. In the picture below (Figure 1), the old and the new set-ups are shown.

3. FUTURE EXPERIMENTAL WORK

With the renovated setup, the first step will be performing studies relating gas flotation performances and gas bubble sizes. The sizes of gas bubbles will be first studied in different conditions (salinity, pressure, dissolved components etc.). Subsequently, systematic experiments with crude oil emulsions will be performed (the crude oil samples will be provided by the SUBPRO industry partners). Gas bubbles dimensions are vital because small sizes can improve the gas flotation performances. These analyses will be carried out with a high-speed camera. An example of an image showing bubbles in the high-pressure flotation cell in Milli-Q (MQ) water, taken with the high-speed camera, is given in Figure 2. High-speed imaging will be an important part of the project, in order to study the influence of temperature and pressure on the microscopic phenomena involved during the process. Moreover, parallel experiments with the microfluidic setup present at the Ugelstad lab will be also carried out, to assess the scalability of microfluidic data and its potential to provide information about larger scale process.

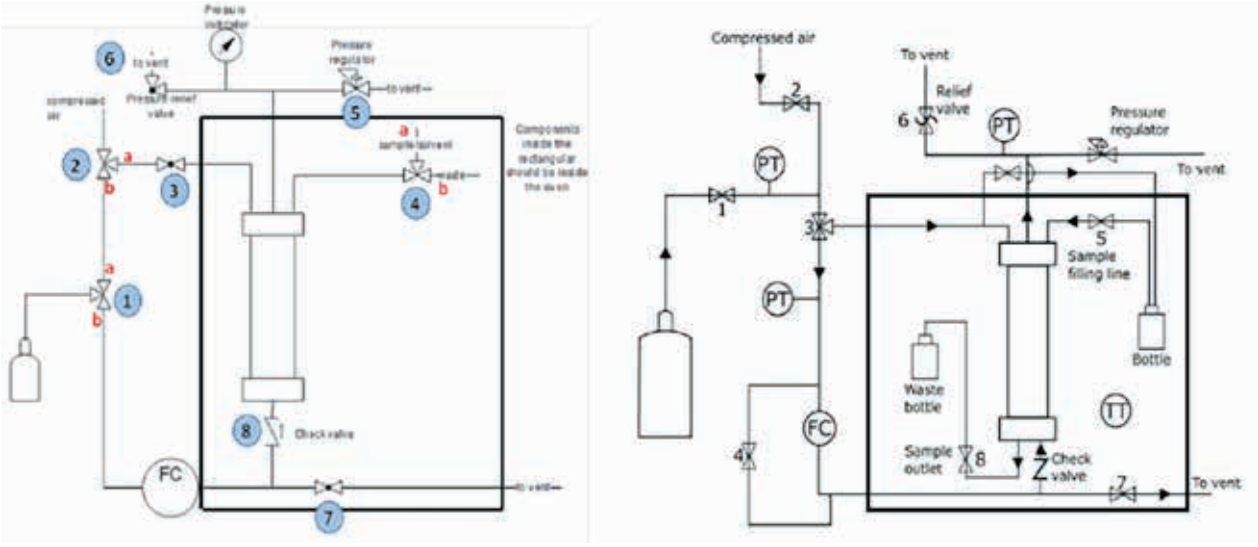


Figure 1: Old set-up (left) and modified set-up (right).

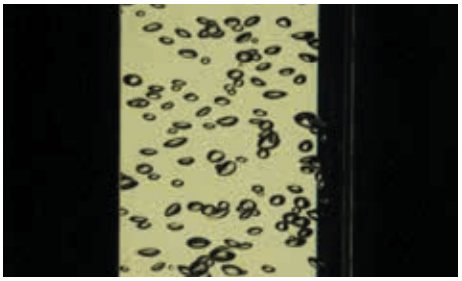


Figure 2: Image of gas bubbles in MQ water in the high-pressure gas flotation column.

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: The model library can be utilized to optimize the oily water treatment processes.

Phd student:
Moein Assar

Project manager:
Associate Professor
Brian Arthur Grimes

Supervisors:
Assoc. Prof. Brian Arthur Grimes,
Prof. Magne Hillestad,
Prof. Audun Faanes (Equinor)

1. BACKGROUND

The separation and transport of multiphase fluids, in the form of crude oil and water emulsions, is an economically and environmentally crucial process in 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 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.

2. DEVELOPMENT OF THE MODEL LIBRARY

Population balance models (PBE) provide a theoretical framework to model multiphase fluid by applying fundamental advances of coalescence and breakage modeling in form of droplet size distributions.

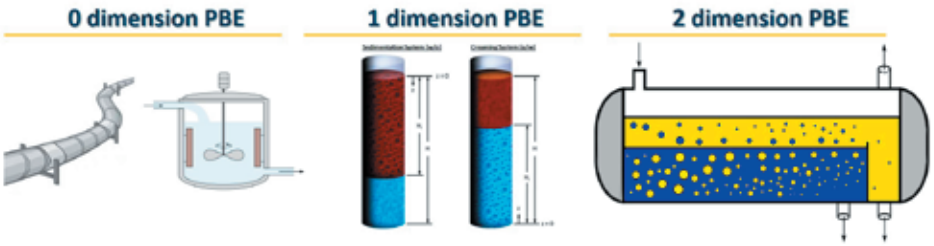
According to the level of complexity in them as well as physics involved, these models are solved for dynamic droplet size evolution in 0, 1, and 2 spatial dimensions. Consequently, library structure has been arranged according to these three modules which can cover wide applications ranging from pipe multi-phase flow to batch settler/skimmer and 3-phase separator. In this approach, these modules can be connected in different arrangements to model more complex processes providing a modular simulation capability for library users.

The computational core of the library is programmed in C++ facilitating a modular design and development using C++ powerful object-oriented features together with the its memory handling and existing numerical libraries which ensure fast calculation speeds on modern computational platforms. For instance, modules programed so far show on average around 10-15 times faster executions than previous similar MATLAB codes.

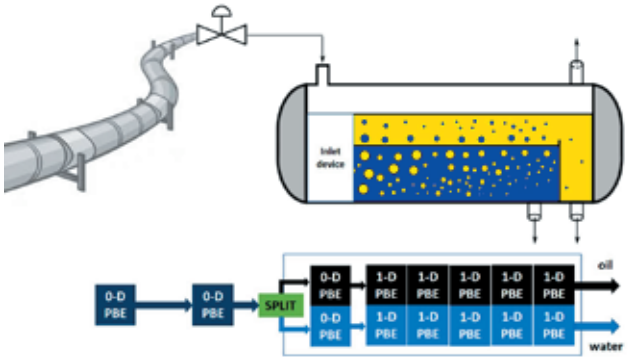
Another unique feature of this model library is the portability that has been envisaged. It will allow the PBE models to be readily incorporated into common general-purpose or specialized simulation software packages such as MATLAB, Python and HYSYS.

3. A NEW APPROACH TO SOLVE PBES

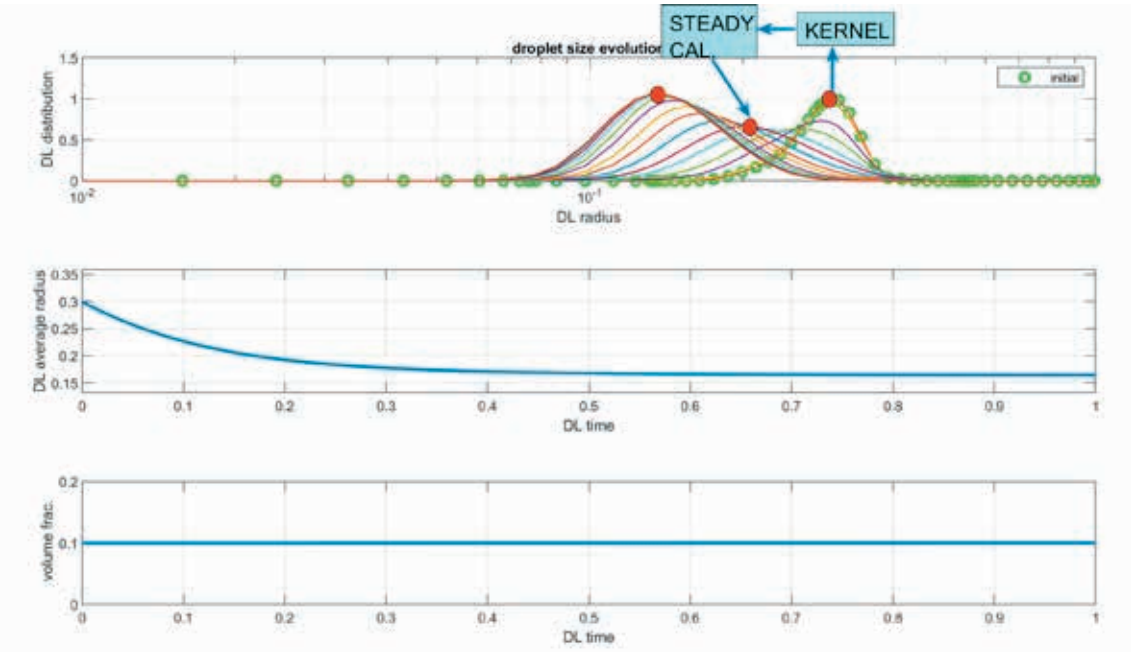
The main challenge for solving PBEs is uncertainty regarding the infinity at the bound of the integrals in the governing equations which affects accuracy of the solution as well as stiffness of the equations. The common approach requires strong reliance on the user post interpretation of the result and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



Model library modules and their applications.



Modular simulation of a more realistic multi-phase system using the model library.



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

Flow Improvers for the Transportation of Waxy Crudes

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

Phd student:
George-Claudiu Savulescu

Project manager:
Professor Gisle Øye

Supervisors:
Prof. Gisle Øye,
Dr. Sébastien Simon
and Prof. Geir Sørland

1. BACKGROUND FOR THE PROJECT

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

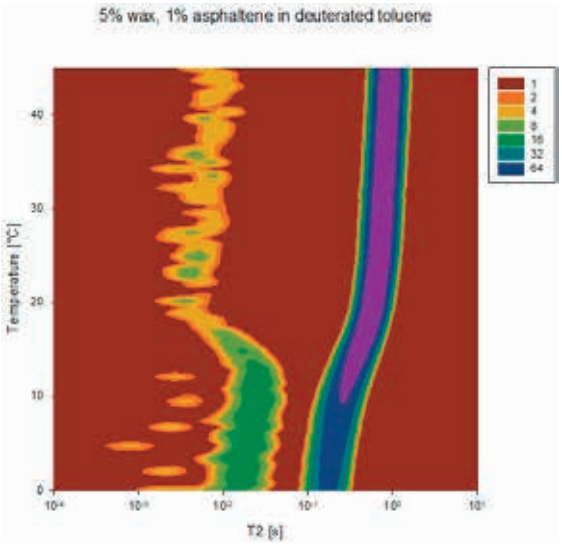


Figure 1 presents a low field NMR T2 distribution for a sample containing 1% asphaltene and 5% wax in deuterated toluene. The right side peak at T2=0.1-1 reflects the wax dissolved in liquid. It broadens and decreases in T2 as the wax starts to precipitate at temperatures below 20 degrees Celsius. The left side peak at T2=0.01 below 20 degrees Celsius reflects the steric hindrance generated by precipitated wax in dispersion. The distribution can be further processed to obtain the percentage of precipitated wax with temperature. An analysis of the wax-asphaltene molecular interactions is currently being developed based on additional experimental results.

2. EXPERIMENTAL APPROACH

The activities are divided in 3 work packages (WP):

- In WP-1, new methods will be designed to characterize and quantify the interactions between waxes and crude oil oils components as well as PPDs using model systems. The methods will be based on Atomic Force Microscopy (AFM) and Nuclear Magnetic Resonance (NMR).
- In WP-2, the interactions will be characterized in real crude oil systems using the established procedures.
- Finally, in WP-3, a special type of waxy oil behavior, in which the pour point strongly depends on sample thermal history, will be analyzed by determining the interactions in these oils.

Equinor will collaborate to the project by providing selected samples and for the co-supervision of the PhD project.

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

The methods and conclusions drawn in the project are expected to allow to design and choose more efficient wax inhibitors as well as reducing the empirical aspect of the choice of an inhibitor for a specific oil. So far, improved low field NMR methods have been developed, and once completely implemented, they will allow to determine different types of information:

- Insights about the mobility of the wax molecules with the temperature. This allows to determine the nature of wax-asphaltene interactions when wax crystals start to appear (Figure 1). In addition, the data can be processed to determine the amount of waxes precipitated with temperature
- Measurements for the specific surface of precipitated wax crystals, and consequently their compactness

The NMR procedures and codes have been developed and are currently being applied on the selected systems.

AFM is a technique that will be used intensively in the project. Contacts have been taken in 2020 with AFM manufacturer to define the set-up and procedures for the initial experiments, which are expected to begin in the first quarter of 2021.

Postdoctoral fellow Marcin Dudek engaged in a micro-fluid experiment. (Picture taken during year 2019).

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 2021; "Particle breakup, turbulence and image analysis"

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

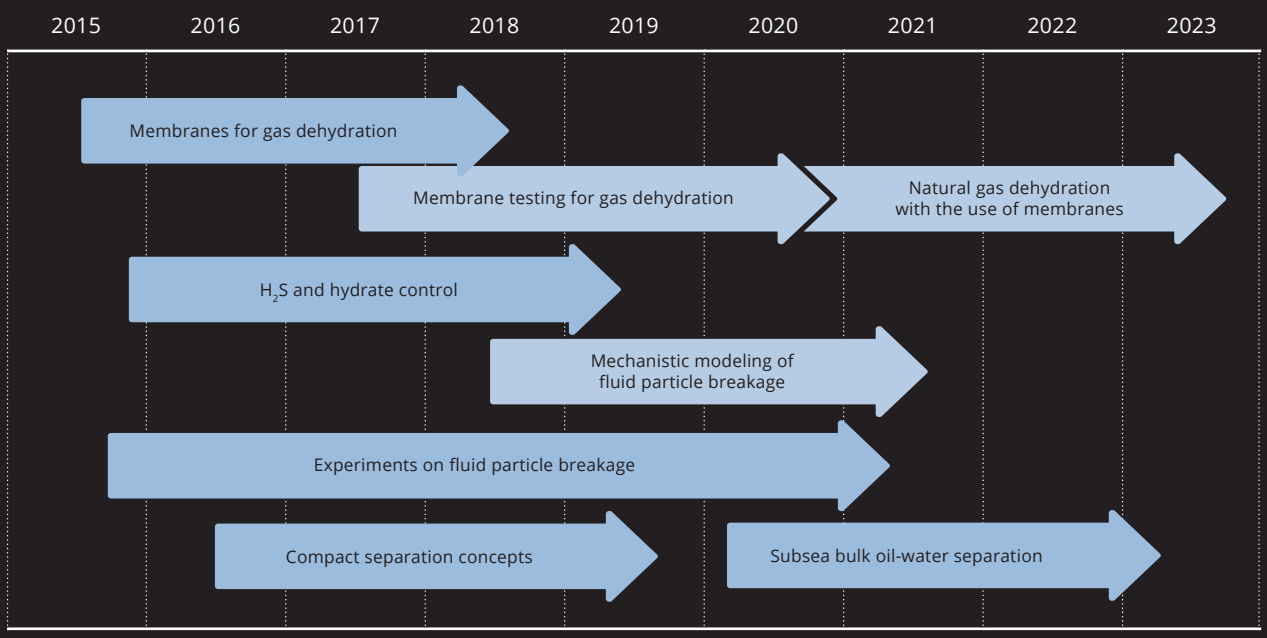
During 2019, the PhD project; "Compact separation concepts" was completed and the PhD candidate, Håvard Skjefstad, defended successfully his thesis. The project is followed up by a new PhD project "Subsea bulk oil-water separation". The PhD candidate has been selected and the project has started during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

During 2020, the PhD-student Eirini Skylogianni successfully defended her thesis in summer 2020. The work presented in the thesis "Combined hydrogen sulfide removal and hydrate control for subsea application" is also described in three peer-review papers describing the work.

During 2020, the PhD candidate Mahdi Ahmadi successfully defended his PhD thesis in November. He worked on the "membrane testing for subsea natural gas dehydration process" and evaluated different membrane technologies for efficient separation performance. The project is now continued by Mahdi, as a postdoc, and the new project (Natural gas dehydration with the use of membrane) aims to apply the experimental work to the process concept by developing models and optimize the process according to the required specifications.

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

Completed, current and planned projects



The Separation- Process concepts team
From the left: Postdoctoral fellow Mahdi Ahmadi, Postdoctoral fellow Hanieh Karbas, former PhD graduate 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 Hamidreza Asaadian was not present when the picture was taken – in early 2019).

Natural gas dehydration with the use of membranes

Subsea membrane gas dehydration technology supplies a dehydrated gas stream directly to pipelines.

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

Postdoctoral fellow:
Mahdi Ahmadi

Project manager:
Professor Magne Hillestad

Supervisor(s)/
Co-supervisor(s):
Prof. Liyuan Deng &
Dr. Dr. Eivind Johannessen
(Equinor)

1. SUBSEA DEHYDRATION PROCESS CONCEPT AND INDUSTRIAL OBJECTIVES

The main objective of this project is to design, optimize and introduce a reliable membrane-based separation process for the subsea dehydration. The process includes individual membrane systems working at different operating conditions in a closed loop, where TEG is the absorbent agent in the loop (Figure 1). This work benefits the obtained experimental data from each membrane process to optimize the process according to the required specification provided by our industry partners (i.e. Equinor). The main criteria for the process are to meet the specification by lowering the water content (dew point < -18°C at 70 bara) and TEG content (TEG emission < 0.8 liter/MSm3 gas) in the gas pipelines.

2. MEMBRANE PERFORMANCE TESTING AND EXPERIMENTS

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

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

A mathematical model describing transport properties of components will be developed in Python and then be implemented in Hysys software. Different configurations in the model (1D-1D or 1D-2D), membrane/module geometries (hollow fiber, flat sheet) and flow configurations (co- or counter current) will be evaluated to find the optimized configuration. Furthermore, to address all the gas components in the model, novel thermodynamic correlations are required to be defined. Accordingly, a multicomponent mathematical model with fast and reliable solvers will be employed for solving the equations in the simulator to optimize the required membrane area and the cost with the smallest footprint.

At the current state, 1D-1D models for water concentration and temperature profile were developed for membrane contactor in Python and the preliminary evaluation of the models show low water content in the gas outlet in the scale of laboratory membrane module and flow (Figure 2(a-c)). The model will be verified first with data obtained from laboratory and then be implemented in Hysys to predict the performance for larger membrane module with larger packing density. In a later stage, the model for thermopervaporation unit similar to membrane contactor will be extended and implemented in Python and Hysys to minimize the energy and cost for the process while enhancing the regeneration performance.

With subsea dehydration, the design will be validated and the water content in gas stream is expected to be in the rage of pipeline specification with small footprint and less complexity. The obtained water from the gas phase is expected to be pure (>99.99 %) to be discharged to the sea water safely.

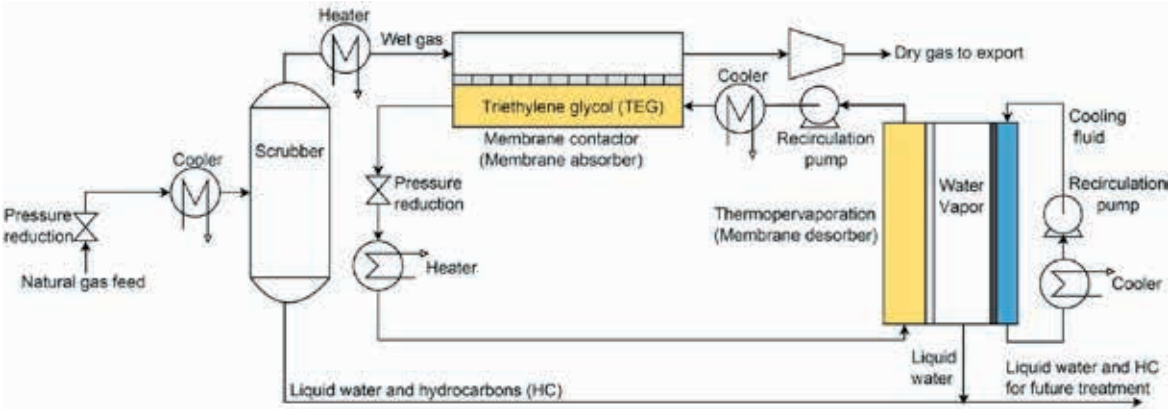


Figure 1: Subsea membrane-based natural gas dehydration process

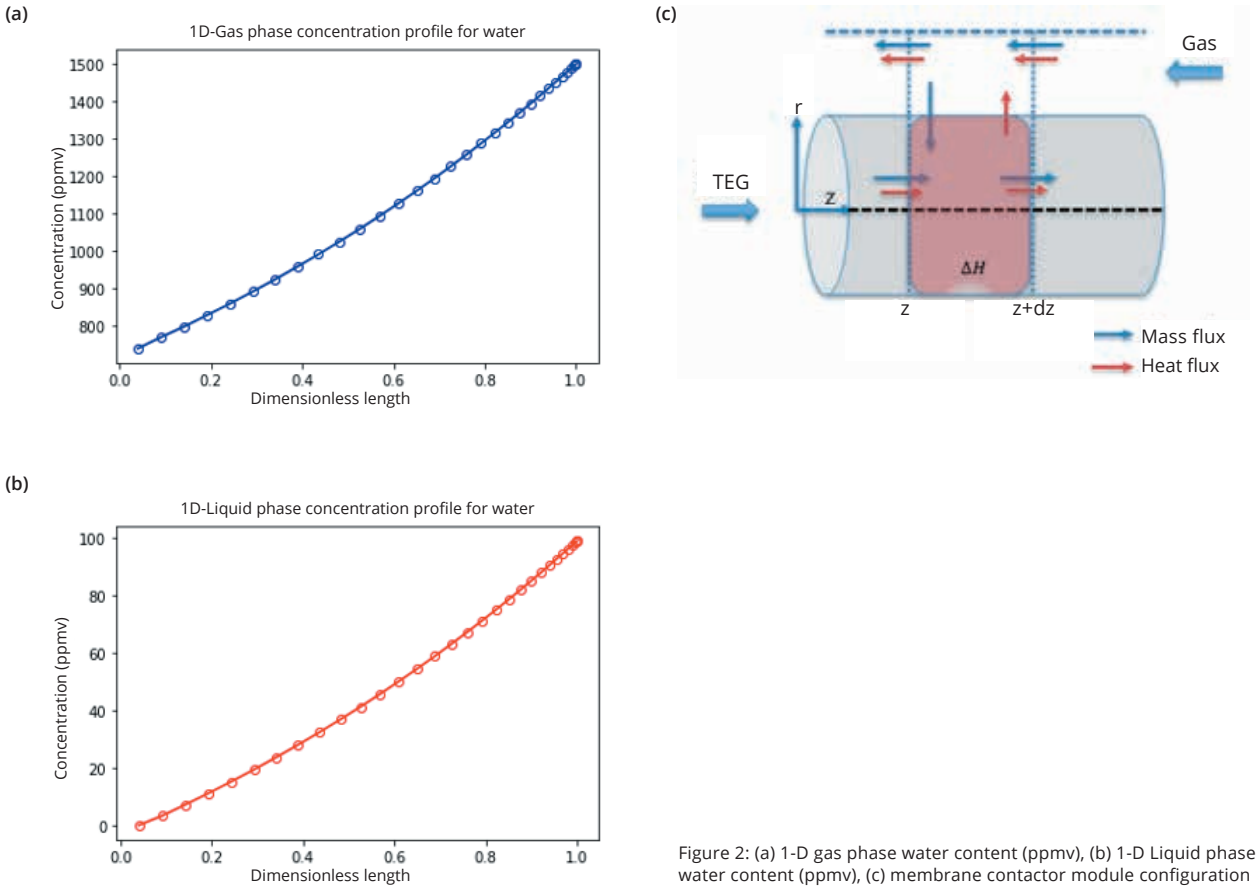


Figure 2: (a) 1-D gas phase water content (ppmv), (b) 1-D Liquid phase water content (ppmv), (c) membrane contactor module configuration

Mechanistic modeling of fluid particle breakage

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

Postdoctoral fellow:
Hanieh Karbas Foroushan

Supervisor:
Professor
Hugo Atle Jakobsen

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

Having subsea processing as one of the most effective ways for enhancement of oil and gas production, multiphase separators are recognized as the primary aid to separate the fluid components of wellbore multiphase flows for further processing. 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.

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

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.

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

3. RESEARCH ACTIVITIES AND DELIVERABLES

The current study comprises several stages:

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

- Experimental study on gas bubble breakage: According to the experiments, various patterns of breakage are recognized for bubbles, as presented in Figure 2. Figures 3 illustrate some of the selected results of the bubble breakage experiments, for a bubble with diameter of 3.17±0.23 mm, in a flow of a liquid with viscosity of 0.0018 Pa-s, Density of 977 Kg/m3, interfacial tension of 0.036 N/m, and velocity of 2 m/s. The experiments have been completed for two more velocities (1 and 1.5 m/s), representing different levels of turbulence.

4. FUTURE WORKS:

- 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

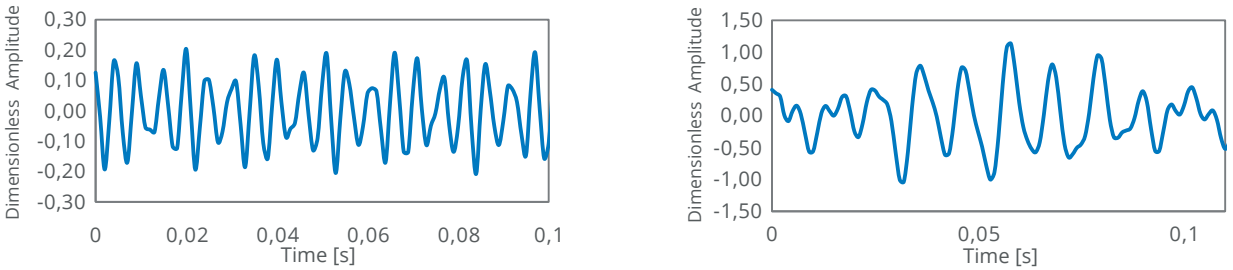


Figure 1: Subsea membrane-based natural gas dehydration process

(Binary breakage) (Multi-daughter) (High share region) (Tearing-off breakage)

Figure 2 Bubble breakage patterns

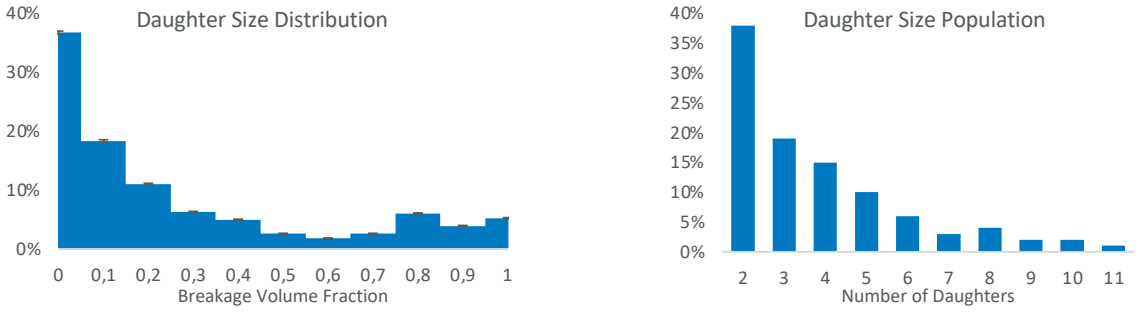


Figure 3 Selected results of bubble breakage

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 fellow:
Eirik Helno Herø

Researcher:
Nicolas La Forgia

Project manager
& supervisor:
Professor
Hugo Atle Jakobsen

1. IMPROVED UNDERSTANDING OF THE DISPERSED PHASE

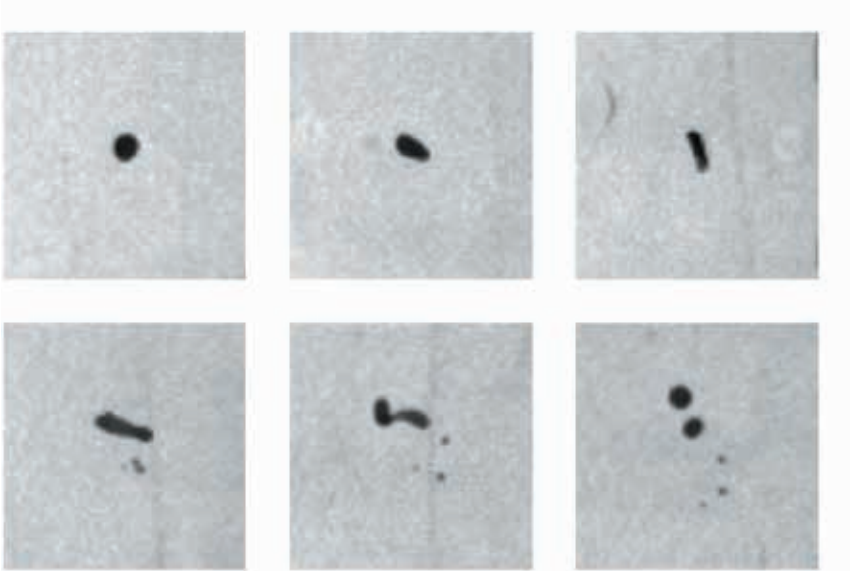
Understanding the mechanism of phase separation is key for many industrial processes, especially for subsea processing. In particular, the separation of oil and water plays a major role in the design of separators. However, a big challenge for the design of oil-water separators is accurate modelling 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.

2. 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.

Subsea bulk oil-water separation

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

Green shift impact: Subsea separation of produced water increases the recovery rates for brown field installations. Removing produced water on the seabed increases production rates, removes topside produced water bottlenecks and enables better utilization of existing topside facilities.

PhD student:
Hamidreza Asaadian

Project manager:
Associate Professor Milan Stanko

Supervisors:
Associate Prof. Milan Stanko and-
Prof. Gisle Øye

1. BACKGROUND

Management of produced water is one of the most important issues in production from mature oil fields. Subsea separation can be used to address this problem and brings additional benefits. It is therefore important to develop cost-effective subsea separator technologies, making the business case for subsea separation more attractive. The benefits of subsea separation can be outlined as three separate aspects: Subsea separation of produced water can reduce the load on topside capacity and facilities, allowing for prolonged, increased production and avoiding bottlenecking. Subsea water separation also reduces the fluid pressure losses from seabed to topside, thus enabling more energy-efficient production. Finally, separation close to the well means less mixing and agitation, reducing dispersion formation and allowing for better separation.

This project is a continuation of previous project 2.9, conducted by Håvard Skjefstad. Håvard developed a concept for bulk oil-water separation in pipe, tested it for several operational conditions and studied fundamental phenomena in oil-water separation in pipe.

2. RESEARCH ACTIVITIES AND DELIVERABLES

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

- Experimental study on the effect of small amounts of gas (air) on separation efficiency.
- Experimental study on the effect crude oil spiking on the separation efficiency and on the dispersion characteristics with or without inlet choking.
- Experimental and numerical study on the uneven flow splitting phenomenon between branches.

Some additional, tentative goals are to perform a numerical study of the fluid dynamics in the separator, to perform experimental studies on the effect of oil viscosity, refining separator design features and optimal control strategies under slugging conditions

During the last year we have worked on how to mimic the separation characteristics of real crudes-water mixtures by adding small amounts of crude to a model oil (Exxsol D60). We had technical meetings with experts from Total and Sintef to get advice and design our experimental procedures. Water-oil separation bottle tests were performed on the crude oil at high temperature and for several spiking concentrations at ambient temperature. Our results indicate that a spiking concentration of 400 ppm has similar separation characteristics than the original crude-water mixture.

We have also started to run some preliminary tests on the separator prototype.

3. FINAL IMPACT

Results of this research can be readily used by the industry to manufacture a new oil-water separator based on our technology or to improve the design of existing oil-water separators on the market. Ultimately, we hope to contribute to improve and facilitate the management of produced water and optimize oil and gas production.

Figure 1. Set-up rig modifications.

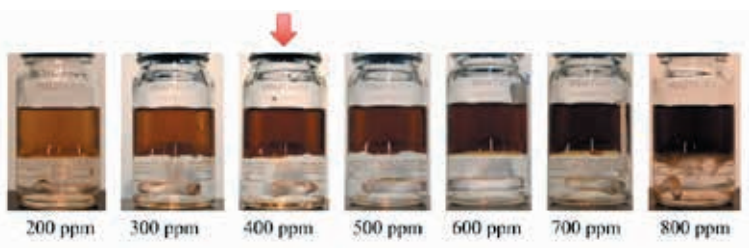


Figure 2. Optimum concentration of crude spiking.

FINAL PROJECT REPORT

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

PhD graduate:	**Mahdi Ahmadi**
Start date:	22.07.2017
Thesis defense data:	19.11.2020
Title of thesis:	Subsea Natural Gas Treatment Using Membranes: Experimental and Modeling Study
Thesis committee members:	Prof. Vladimir V. Volkov (Russian Academy of Science) Dr. Karl Anders Hoff (SINTEF, Trondheim)
Supervisors:	Prof. Liyuan Deng, Prof. Magne Hillestad

1. BACKGROUND FOR THE PROJECT

Subsea natural gas reservoirs are usually saturated with water vapor and impurities such as CO_2 and H_2S, which are the main contributors to the pipeline blockage, hydrate formation, and corrosion. Dehydration is usually the first stage in natural gas processing; a safe and reliable dehydration process close to the wellhead is desired to be installed subsea to replace the continuous chemical injection for hydrate prevention. Subsea factories for natural gas processing aim to bring down the impurity levels to meet the pipeline specifications for the direct transportation of natural gas, with no further purification onshore. Membrane-based gas separation technology offers a reliable solution for long-term unmanned subsea operation due to its low footprint (compact-sizing), high modularity, and negligible environmental impact, where the use of complicated conventional processes such as absorption is not viable. An in-house designed dehydration membrane process consisting of a membrane contactor for the dehydration of natural gas and a thermopervaporation for the regeneration of the solvent in a closed-loop has been proposed in SUBPRO through a sub-project (2014-2017).

The current work is a SUBPRO sub-project on membrane dehydration. The objective of this project is to evaluate the membrane process through experimental study and modeling.

2. WHAT I HAVE DONE

In this study, the feasibility of subsea natural gas dehydration by membrane was evaluated experimentally in a non-porous membrane contactor using a hydrophobic material (AF2400). A flat sheet membrane contactor was employed as the membrane interface, which is in contact with a glycol solvent (triethylene glycol (TEG)). A new dehydration rig and optimized membrane modules were specifically designed and installed. A structured packing turbulence promoter was used in the gas phase to improve the efficiency of the system. The water flux and outlet dew point were measured at different operating conditions (i.e., pressures, liquid and gas flow rates). A systematic modeling approach was then introduced, and the membrane permeability and overall mass transfer coefficient were estimated.

Continuous regeneration of the absorbent agent (TEG) in the closed-loop process is performed by using thermopervaporation (TPV), which is energy-efficient membrane process due to the use of free cooling energy offered by the cold subsea water. In this work, the performance of a composite membrane in thermopervaporation for TEG regeneration was investigated experimentally. Permeation characterizations of an AF2400 thin film composite (TFC) membrane were carried out in the in-house made membrane testing rig and module. The experiments were performed at various temperatures and water concentrations of the feed side. A 3D computational fluid dynamics simulation was then performed over the entire module to characterize the membrane performance.

Membrane materials suitable for natural gas processing were also studied. A mixed matrix membrane (MMM) with a metal-organic framework (MOF) was fabricated to remove water and CO_2 simultaneously from natural gas. This membrane was also found to be a good candidate for other CO_2 separation applications, such as CO_2 capture from the humid flue gas. The MMMs were tested for the humid gas streams to understand the efficiency of the MOF in the mixed matrix for CO_2 removal in the presence of water vapor. In this study, a water harvesting metal-organic framework, MOF-801, was synthesized and dispersed in Pebax matrix to fabricate MMMs. A molecular simulation (Monte Carlo and Molecular Dynamics) study was performed to reveal the potential adsorption sites in the MOF lattice and favorable interactions with gases.

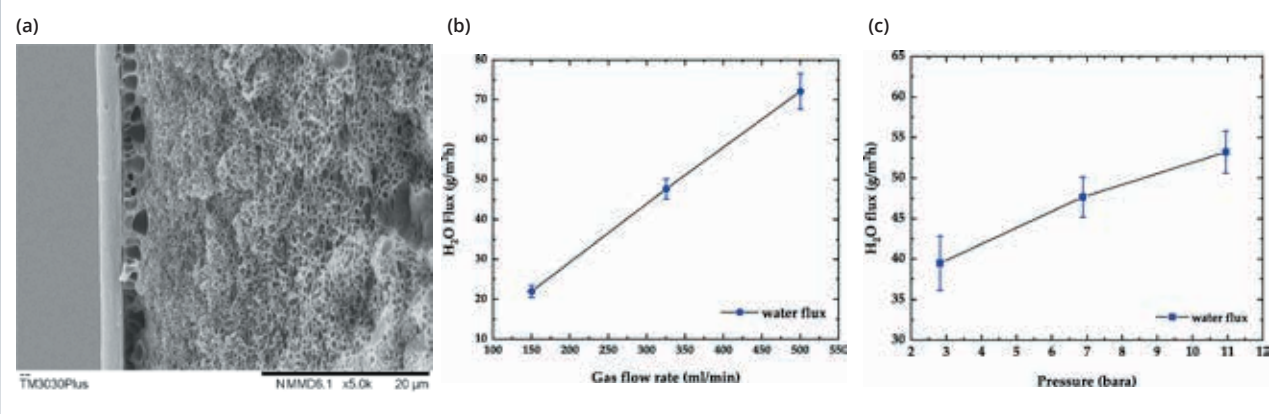


Figure 1: (a) SEM image of composite AF2400/PVDF membrane,(b) effect of gas flow rate on flux and (c) effect of pressure on water flux.

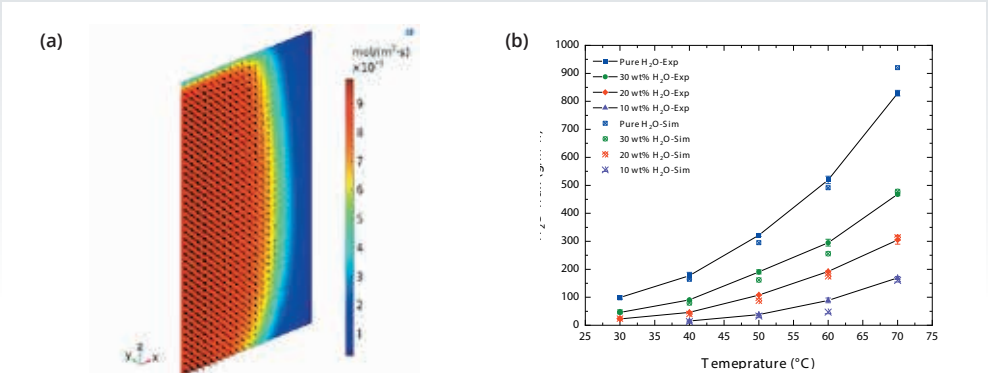


Figure 2: Total Flux (a) Simulated flux distribution and (b) total flux as a function of feed temperature and concentration.

3. MAIN RESULTS

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

Membrane contactor (membrane absorption)

- Teflon AF2400 was found a suitable membrane material for the dehydration of natural gas (Figure 1(a)).
- The effects of operating conditions on the process performance reveal that higher gas flow rate and pressure are preferred, which enhances the transmembrane water flux. However, an increase in liquid flow rate does not have a significant impact on the performance(Figure 1(b-c)).
- The simulation study using the plug flow model or dispersion-included one-dimensional model showed that water permeability of ~ 4000 Barrer and ~ 3260 Barrer were estimated at 25 °C and 35 °C, respectively. Low water concentration was measured in the outlet, and a dew point of below -20 was measured.
- The quantitative evaluation of overall resistance compared to membrane resistance shows that the dominating resistance is in the composite membrane arises from the dense selective layer of AF2400.
- The main contribution of the turbulence promoter to the membrane contactor is to increase the residence time, to enhance the backmixing, and to reduce the unfavorable concentration polarization in the gas phase.

Membrane Thermopervaporation

- Total permeate flux (g/m2h) increases with increased temperature and water loadings in the feed solution (Figure 2).
- A high separation factor was obtained for all concentrations of feed solutions at the studied operating temperatures, outperforming the VLE-based processes (Figure 3).
- A water mole fraction of above 99.98% in the permeate was obtained, which would allow discharging the removed water to the seawater.
- The temperature profile on the condensing plate facing the airgap reveals that the energy transfer from the hot fluid to the cold fluid is limited by the resistance of air in the airgap.

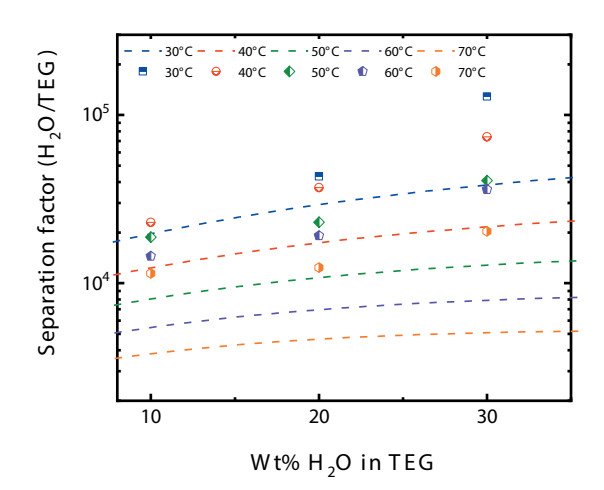


Figure 3: Separation factor in thermopervaporation process compared to VLE based separation technologies. Symbols are thermopervaporation and dash lines are VLE based lines.

Mixed Matrix Membranes for CO_2 and H_2O removal

- MOF-801 is a promising candidate for membrane dehydration, which improves the water permeability through the membrane.
- MOF-801 enhanced the CO_2 permeability for both dry and humid state. A 2.6-fold increase in CO_2 permeability was observed with respect to the neat polymer in humid conditions.
- MOF-801 shows an affinity towards CO_2 and H_2O compared to the non-polar CH_4 and N_2 confirmed by single gas adsorption isotherms.
- The transport of gas species in the MOF is governed by competitive adsorption rather than diffusion. Zirconium atom was found to be the favorable adsorption site in MOF for both CO_2 and H_2O.

4. INNOVATION AND INDUSTRY COLLABORATION

This project aims to provide experimental data for the model development and validation to be used in process design and optimization for industry. The experimental data were provided for the first time, and the models obtained in this project were useful to describe and further characterize the systems. This study proves the concept of the feasibility of the closed-loop containing membrane contactor and thermopervaporation for both subsea and onshore technology with a smaller footprint and energy-efficient technology.

5. FUTURE WORK

During the work and associated activities in the laboratory and the modeling, several interesting observations were made, reflecting ideas about the experiments, the process, and simulation. Some recommendations for future work based on these ideas are listed below:

- A broad range of hydrophobic polymers should be evaluated, and the long-term stability of membranes should be studied.
- TEG emission to the gas phase is one of the main industrial concerns for the quality of the export gas. Since the present work only considered the H_2O as the component of interest, a more sophisticated system should be installed and designed to minimize the TEG emission.
- This work includes the proof of the concept considering only a flat-sheet membrane. For a more compact design, tubular membranes can be fabricated with a selective layer in the lumen side. The permeation parameters of tubular membranes may provide information for real case applications.
- The effect of operating conditions such as flow rate, dry sweep gas as a carrier in the airgap (dry methane), and subsea temperature can be examined to find the parameters that influence the system performance.

6. MY NEW JOB

Company/Institution: SUBPRO, NTNU
Position/Area of work: Postdoctoral Researcher

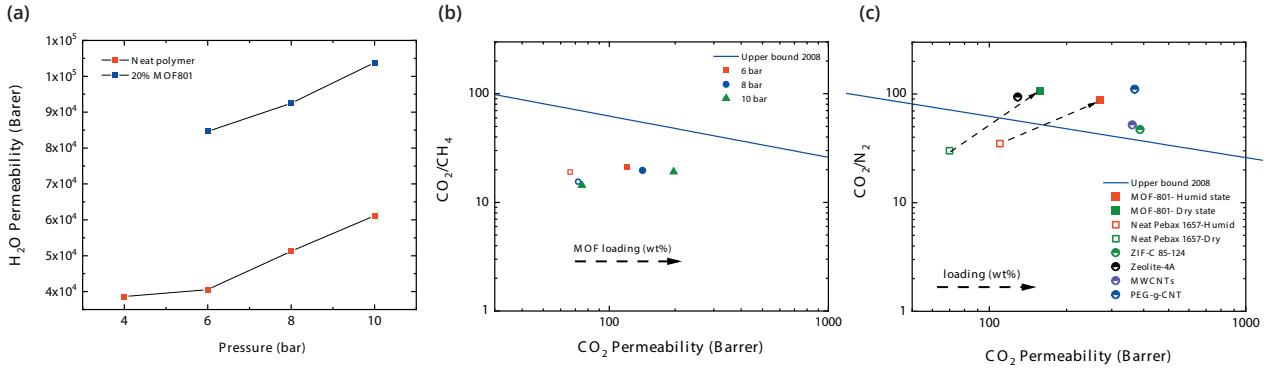
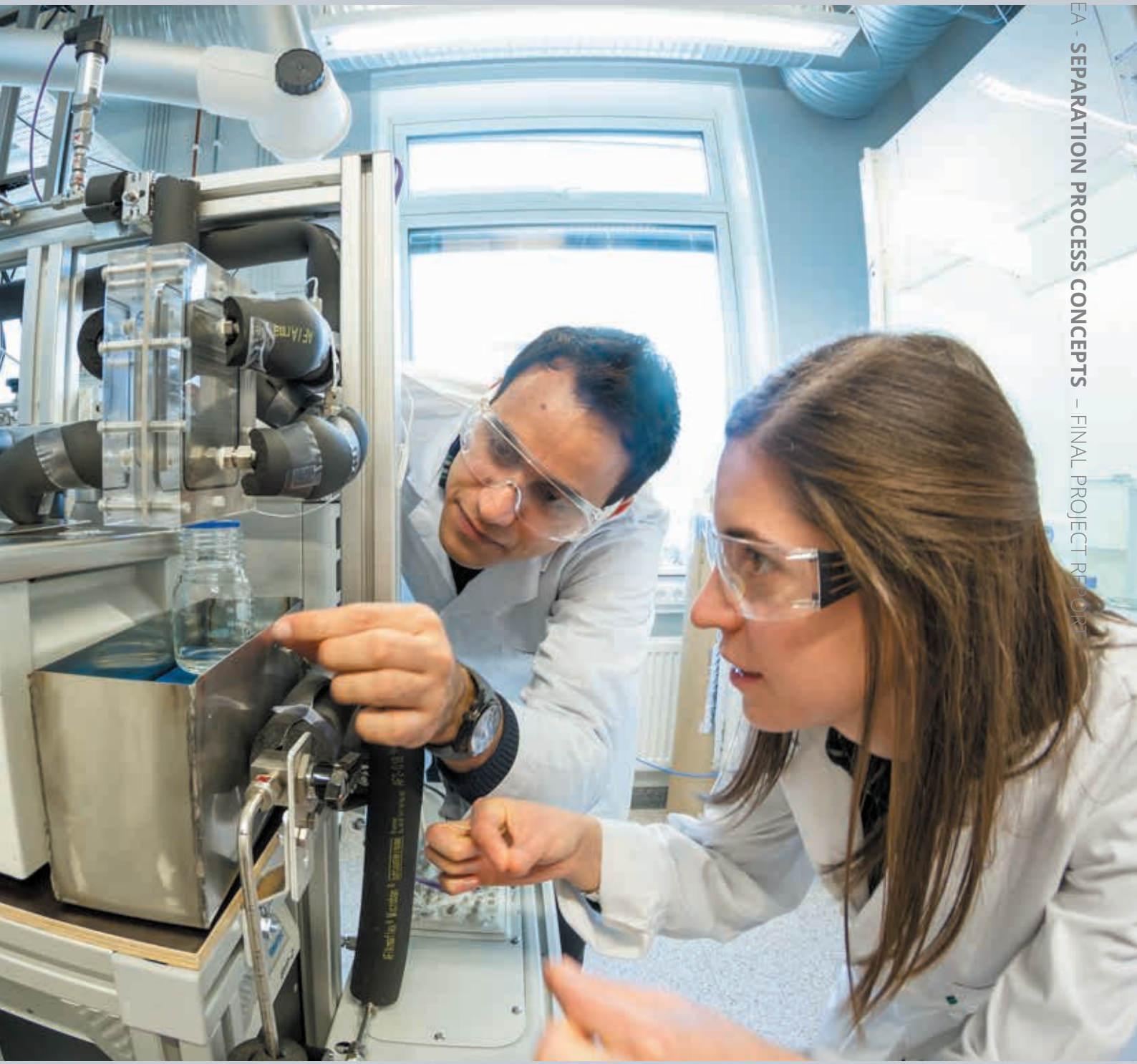


Figure 4: Caption?



From left to right: PhD graduate Mahdi Ahmadi and former PhD graduate Eirini Skylogianni working with the membrane thermopervaporation setup for gas dehydration testing. (Picture taken during year 2019).

ASSOCIATE PROFESSOR
JOHANNES JÄSCHKE

RESEARCH AREA
MANAGER

RESEARCH AREA

System control

Control systems and digital twins enable to autonomous intelligent production systems that ensure safe and optimal operation of subsea production and processing systems. This contributes to reducing the environmental footprint.

Subsea production and processing installations are not easily accessible and depend on being operated remotely. Our vision is that they should be operated autonomously, or with minimal human intervention and supervision. This means that the process should be able to regulate and monitor itself and make optimal operation decisions automatically.

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 focuses on:
- Short and medium-term production optimization of large-scale installations
- Production optimization taking equipment degradation into account
- Control algorithms for Energy-efficient production and processing
- Combining data-driven machine learning methods with first principles models to achieve optimal and autonomous system operations
- Estimation algorithms for estimating unmeasured process quantities (e.g. VFM)

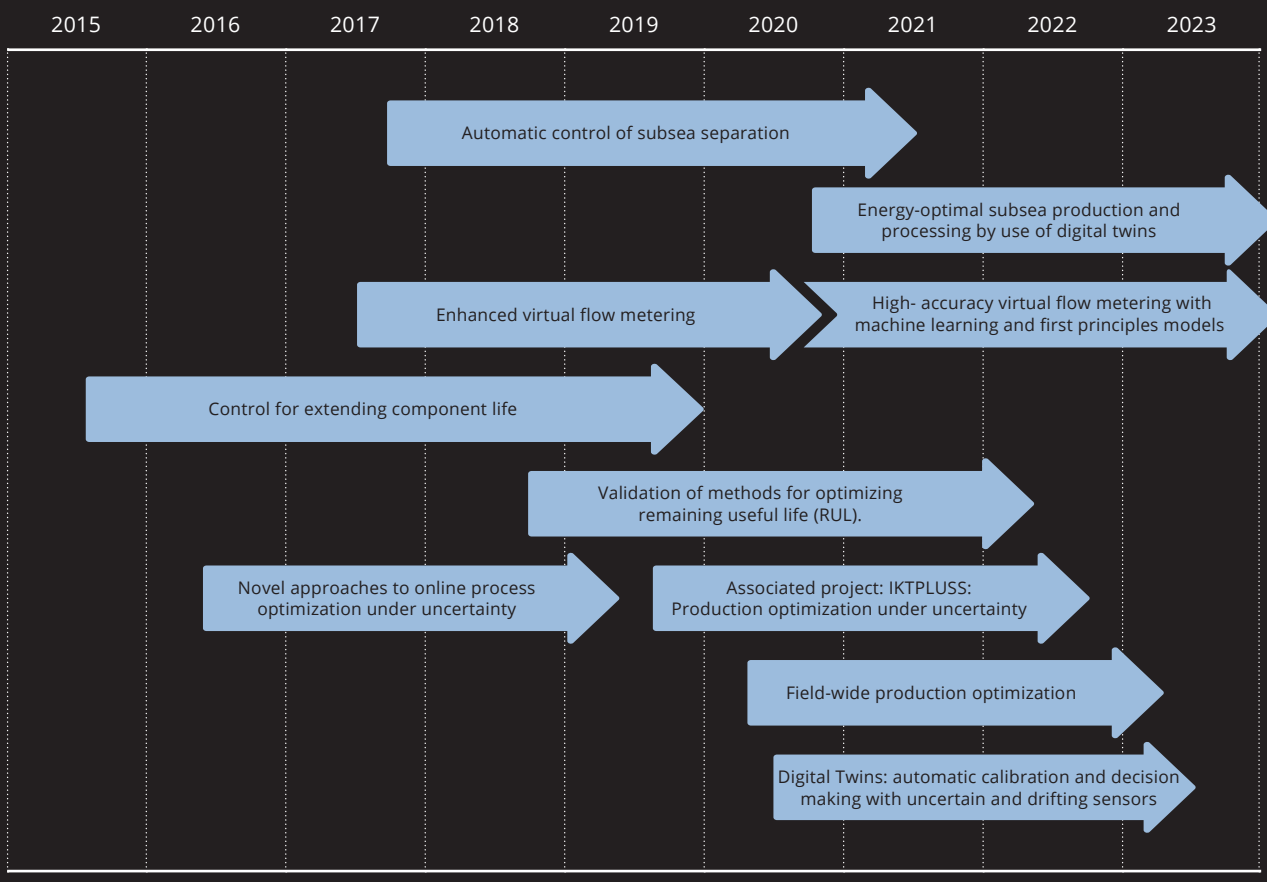
Our overall aim is to develop tools and methods that are simple and robust enough for use in industrial subsea applications, and that react optimally to changing operating conditions. The developed models are based on first-principles physics as well as data and machine learning. Controller, estimation 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.

During 2020, two PhD projects were completed; “Control Approaches for Extending Component life” (A. Verheyleweghen), and “Enhanced Virtual Flow Metering” (T. Bikmuhametov). We have started 4 new PhD projects (“Energy-optimal subsea production and processing”, Field-wide production optimization”, “ Calibration of Digital twins” and “High-Accuracy virtual flow metering with Machine learning and first principles models” .

In 2020, the activities in SUBPRO were complemented by a new spin-off project AutoPRO in collaboration with the RAMS group.

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

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 Ma tias 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.
(Phd student Asli Karacelik, Phd student Md Rizwan, Phd student Halvor Aarnes Krog, Phd graduate Timur Bikmukhametov and Phd graduate Adriaen Verheylewegen were not present when the picture was taken – in early 2020).

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

1. 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 hydrocyclones and a pump system to emulate the first stage separation.

3. Validate newly developed models, controllers, and estimators using the laboratory experiments.

2. 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. 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 consisting of pump system and hydrocyclones are fully operational. Some of the main features of the test rig are:

1. Ability to emulate the first stage gravity separator.

2. Ability to change the oil droplet distribution using a control valve.

3. Ability to vary the inlet oil concentration from 300 to 3000 PPM.

4. Oil in water sensors at the inlet and the underflow of hydrocyclones gives online measurement such as PPM, Dv50 and droplet distribution.

3. INDUSTRIAL USAGE OF THE RESULT

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

Oil in water sensor installed at the inlet and underflow outlet of hydrocyclone. The online measurement of the oil concentration can be used in the control system to improve the efficiency of hydrocyclones.

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

Energy-Optimal Subsea Production and Processing by Use of Digital Twins

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

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

PhD student:
Asli Karacelik

Project manager
and main supervisor:
Associate Professor
Christian Holden

Co-supervisors:
Prof. Dr.
Gunleiv Skofteland and
Prof. Dr.
Sigurd Skogestad

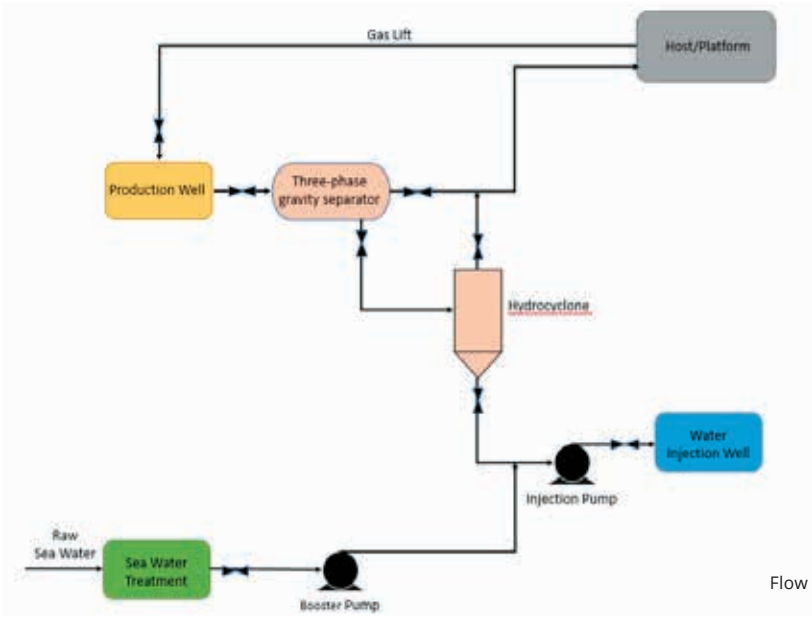
1. BACKGROUND

Energy-efficient strategies are highly demanded in traditional oil and gas plants due to high production costs and less carbon dioxide emission requirement. These strategies include reducing thermal or electrical energy consumption by changing some processing plant units, waste heat recycling, site-scale process integration, and developing control structures. Control strategies are built to maximize the production rate by effective use of the process conditions and reducing the response time of the control structure.

The whole system is modeled for an energy-efficient subsea processing plant in this study. Energy-efficient control structures of sub-systems are implemented using the relative gain array (RGA) and the relative exergy array (REA) methods. Balancing steady-state and transient operations is necessary to optimize the whole system. Software models are used for each component to understand the trade-offs of these balancing effects. These systems mutually interact in complex ways, and being optimal only for one sub-system might result in high costs in another. Consequently, optimal control of the whole system will be attained for an energy-efficient subsea processing plant.

2. RESEARCH ACTIVITIES

The mathematical model of the whole system was studied in the specified process design. Different configurations of this system will be considered for further improvements in the design. The current process design contains a gas lift, three-phase gravity separator, hydrocyclone, injection pump, and a booster pump. An injection pump is used to inject wastewater into an empty reservoir. Using an empty reservoir increases the energy consumption within the system. Therefore, we will consider injecting the wastewater into the production well having convenient well pressure in the next step. Seawater treatment containing sand cyclone, hydrocyclone, and water de-gassing drum will be investigated. Moreover, a gas compression system including a wet gas compressor, heat exchanger, scrubber, and possibly distillation will be considered. Nonlinear model predictive control (NMPC) with moving horizon estimation will be implemented to the current system design. Additionally, model predictive control (MPC) will be used for the same system, and the difference between the results will be analyzed. MPC uses linear system models whereas NMPC uses nonlinear system models. NMPC is widely used in the industry due to highly nonlinear systems, although it has an iterative solution that induces difficulties in numerical solutions and stability. Nevertheless, NMPC is a successful method dealing with the problems having nonlinear dynamics and constraints.



Flow diagram of subsea processing plant.

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

To develop methods that combine machine learning and first principles models for accurate and inexpensive multiphase flowrate measurements. Furthermore, the plan is to use these developed models to optimize overall production systems.

Green Shift: Cheap and accurate virtual flow metering has a great potential as it enables oil and gas industry to reduce environmental footprint, achieve higher safety and improve efficiency.

PhD student:
Md Rizwan

Project manager and main supervisor: Associate Professor Christian Holden.

Co-supervisor(s): Assoc. Prof Johannes Jäschke, and Assoc. Prof. Milan Stanko

1. BACKGROUND

Multi-phase flow metering is challenging, expensive, requires regular calibration, and often employs sensors that are costly. In virtual flow metering, physical flow meters are replaced by cheaper, more accurate sensors (such as pressure or temperature) and a mathematical model of the process that allows the flow rate to be calculated rather than measured. These new possibilities to model complex systems are also facilitated with the recent availability of computing power and advances in machine learning algorithms.

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

2. RESEARCH ACTIVITIES

A traditional way of doing multi-phase flow metering is to separate the fluid stream, send the different fluids through single-phase flowmeters, and then mix the fluids again. A compact solution that may do away with the majority of flowmeters is to combine separation and virtual flow metering, thus increasing accuracy while reducing both size and cost of equipment. The combined expertise and laboratory facilities brought to bear on this project are uniquely positioned to do investigate this possibility.

We are planning to combine machine learning and first principles modelling to describe whole production systems, including several wells and their topside facilities. A special focus will be put on finding methods that can give good results, also when limited data is available to train the machine learning algorithm. Here, we believe that simplified first principles models can play an important role. The supervisory team for the project consists of the supervisors from 3 departments with expertise in flow, separation, soft sensors, and machine learning, as well as experimental proficiency.

We will perform a literature search on methods for combining first principles and machine learning (ML). One approach that we will consider is to combine static local models with dynamic models that capture the behavior of the system on a larger scale: Local machine learning models may be used to model certain parts of the system, for example a choke. These local models are then used in an overall first principles mass balance, that describes the system on a slower scale. This model is then used for estimation of unmeasured variables, or for production optimization. This is visualized in Figure 1, but we will investigate other promising approaches, too.

The ability to use existing and obtain new data from laboratory experiments will be crucial to the proposed project. This will be accomplished by using the existing laboratory facilities developed and being developed as part of SUBPRO. In the final part of this project, we will investigate to how to systematically develop hybrid models which are able to quantify estimation uncertainties for further production optimization and back-allocation problems. This approach seems promising for obtaining integrated models of large systems, including topside facilities.

3. INNOVATION POTENTIAL

The research in this project is driven by industrial needs to operate the existing assets as economically as possible. The methods developed can be applied to industrial field data, and the prototype software can be distributed and applied to our industrial partners. We propose a 2-months industrial placement at the end of the PhD, where the results can be implemented and tested in practice.

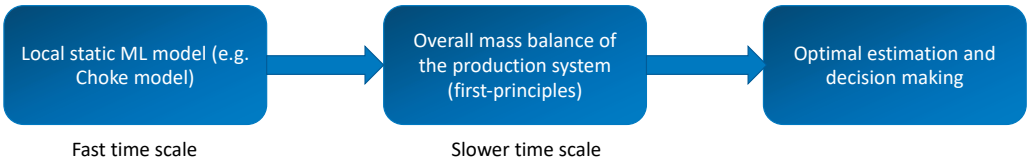


Figure 1. A possible way of combining first-principles models with data-driven machine learning (ML) models.

Validation of Methods for Optimizing Remaining Useful Life (RUL)

Using real-time data to support accurate decision-making on optimization and maintenance.

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

Postdoctoral fellow:
Jose Otavio Assumpcao Matias

Project manager and supervisor:
Associate professor Johannes Jäschke

1. HEATH-AWARE CONTROLLER: COMBINING PROCESS OPTIMIZATION AND EQUIPMENT HEALTH MONITORING

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

In order to avoid equipment wear, process engineers and operators often adopt conservative production strategies, leading to sub-optimal operation and potential profit loss. By proposing a **health-aware controller** that incorporates equipment degradation in its formulation, we want to automate this decision. A block diagram of the method is shown in Figure 1.

2. WHY DOES THE INDUSTRY NEED A HEALTH-AWARE CONTROLLER? WHAT ARE ITS BENEFITS?

The health-aware controller can help engineers and plant personal with:

- **Extend equipment life and reduce unplanned downtime**: Since the controller monitors critical equipment condition, its decisions take equipment health into account. Meaning the whole system can run for longer before the equipment needs replacing.
- **System maintenance**: The diagnosis step of the controller provides equipment health information, which can also be used offline. For instance, operators can check the health of specific assets in real-time and schedule maintenance stops if necessary.
- **Increase productivity**: the health aware controller increases productivity by improving the economic performance while allowing the operation to move away from time-based maintenance to condition-based maintenance.

3. SETTING UP AN EXPERIMENTAL RIG TO VALIDATE THE HEALTH-AWARE CONTROLLER.

So far, the health-aware controller has been implemented only in simulations. Thus, we built an experimental rig to verify it in a more realistic environment. The rig emulates a 3-well network where a mixture of water and air flows through a probe, which is placed inside an “erosion box”. The probe was designed to erode fast, in less than 1 hour. Since its degradation is not only a function of time but also the flowrates of liquid and gas, we want to use our health-aware controller to maximize the liquid throughput, while avoiding that the probe erosion reaches a given threshold.

In the first implementation stage, we developed reliable diagnostics models for indicating the remaining useful life of the probes. The models are based on machine-learning technique such as regression trees, support vector regression and neural networks. The next step concerns the testing of our control strategy in this system. The goal is to further study the health-aware controller benefits and its potential implementational risks.

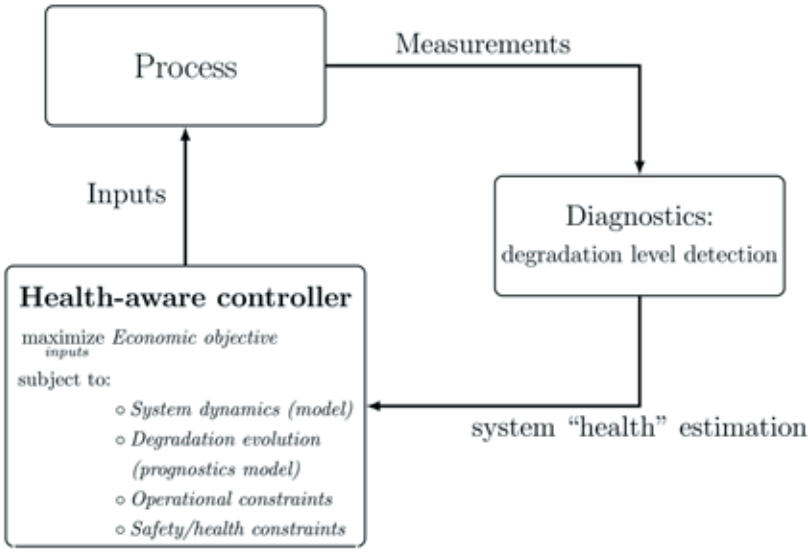


Figure 1: Health-aware controller block diagram.

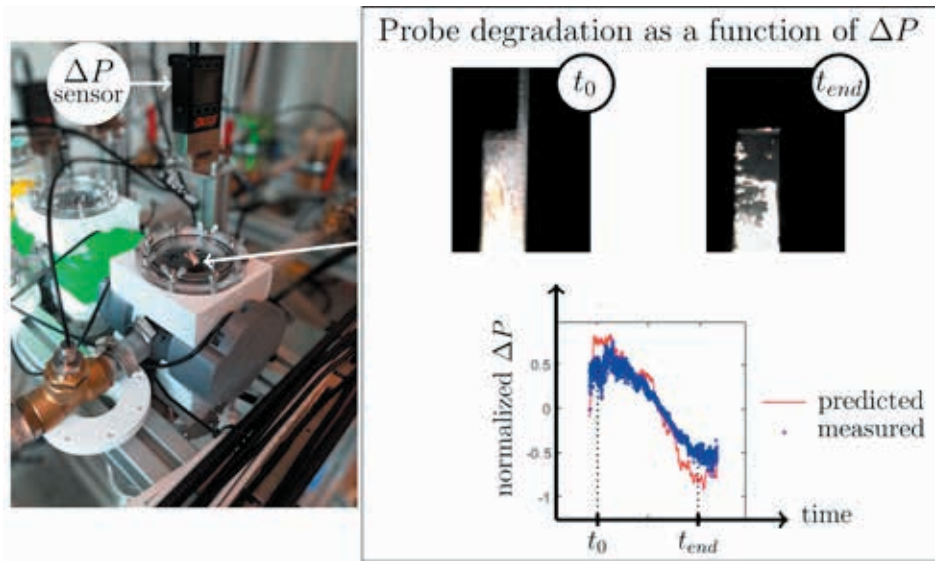


Figure 2: The left figure shows the "erosion box" of one the wells. The probe is placed inside this box, which also contains a set of cameras for monitoring the erosion of the probes. The initial (t_0) and final (t_end) probe images are also shown. The white part of the image is the probe surface that is impeding the liquid flow path. As the probe degrades, the cross-sectional area of the flow increases. Consequently, the delta pressure (ΔP) along the "erosion box" decreases. Since the ΔP is directly correlated to the equipment remaining useful like, we can use it as an indicator of the system "health". We, then, apply machine learning methods to predict the pressure difference evolution as a function of the flowrate and time.

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

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

With increasing energy demands, stringent emission regulations, and the 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 as well as optimize resource allocation (e.g., lift-gas, fuel-gas, power, instrument gas) on a day-to-day basis. The production optimization requires a detailed model of the system to determine the optimal operation of the field. However, as the complexity of the systems increases, the models used may not be enough to capture the real production system accurately. This may lead to a sub-optimal operation.

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

In this project, we develop different methods in order to optimize production, given a large and/or complex oil and gas production system. One way to deal with this model is to construct the model partially (subsystem model). Consequently, the subsystem model may have coupled variables such as shared resources to deal with, in order to obtain optimal operation for the entire production system. Another way is to construct a surrogate model or optimizer, that require data, where machine learning tools can be useful. In this activity, we are currently using upstream oil and gas production and processing facilities developed in K-Spice, a process simulation software developed by Kongsberg Digital. The last option is by combining both the simplified first-principle model and data, where data can be used to improve or update the simplified model. It results in what is called a grey-box model. Such a model is more flexible and has the potential for further savings. In summary, this project focuses on developing and implementing (if possible) simple tools where real-time data can be utilized to make optimal decisions, given a large and/or complex production system.

3. WHAT WE HAVE DONE

Result so far,

- A distributed simple feedback real-time optimization can achieve optimal operation among different subsystems, that have coupled variables such as shared resource in this case. This method can be model-free and can obtain optimal operation for the entire production system with the assistance of a central coordinator.
- A consensus-based decentralized distributed real-time optimization can also achieve optimal operation among different subsystems, that have coupled variables such as shared resources in this case. This method can obtain optimal operation for the entire production system without a central coordinator.
- Analysis and development of surrogate model and surrogate optimizer using machine learning tools for an oil production system.
- Analysis of upstream oil and gas production and processing facilities developed in a high-fidelity simulator.
- Simplified model integration of gas-lifted well, riser, separator, and pump for testing algorithms.

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 safer, environmental-friendly, and in better-optimized production.

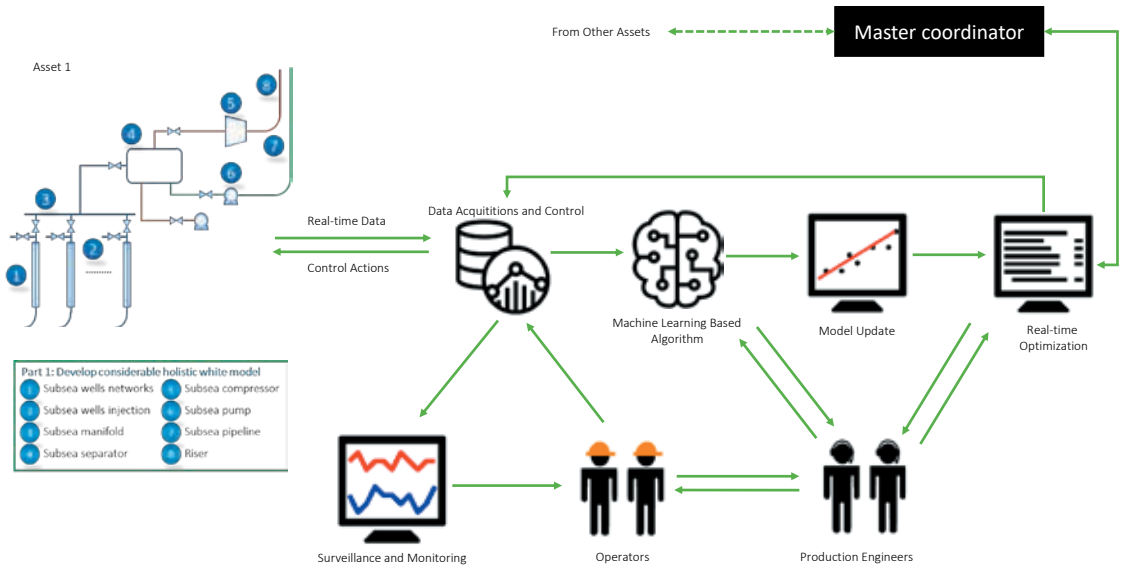


Illustration of the field-wide production optimization systems.

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

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

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

PhD Student:
Halvor Aarnes Krog

Project manager and supervisor:
Associated Professor Johannes Jäschke

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

All sensors drift over time. For example, meaning that regardless if a temperature sensor would be accurately calibrated when installed, it would still report that the temperature of the fluid is 100,1°C while the real value would be 100,0°C. After some years of operation, the true value would be unchanged at 100,0°C but the sensor would drift and consequently would report a value of 103,0°C instead. Despite of the measurements used to calibrate the process model, it would still result into a mismatch between the model and the true plant. And therefore, any optimization done on the model may result in sub-optimal plant performance.

In this project, the aim is to incorporate information about the sensor drift into the modelling phase. Furthermore, automatic model calibration and model selection routines which take sensor drift into account will also be investigated. This project aims to

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

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

2. STATISTICAL METHODS FOR QUANTIFYING THE SENSOR DRIFT

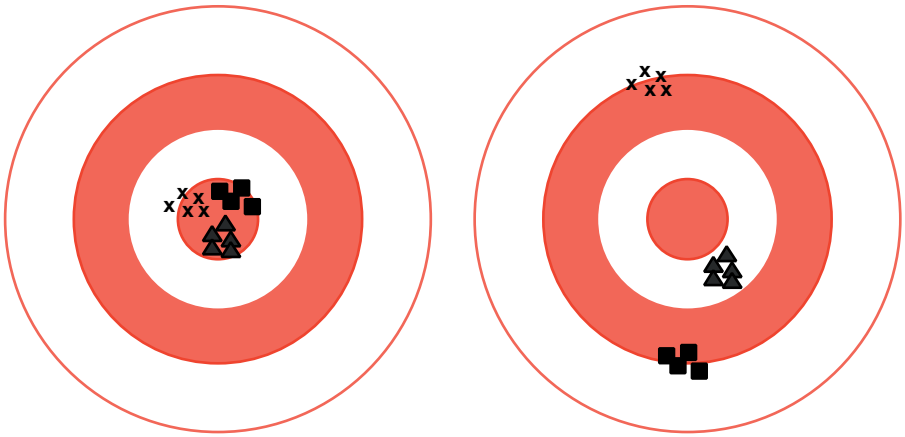
This project will be based on data from our industry partners. An initial case study on a subsea booster pump with field data is planned. The subsea system is a good case

study, as there is a redundancy of sensors. Due to the sensor redundancy, it is possible to apply a statistical analysis, and to attempt to estimate the true process variables.

Once a good method for the booster pump case study has been found, the framework will be tested on other case studies. Possible case studies include a network of booster pumps and compressor.

3. POTENTIAL INDUSTRIAL APPLICATIONS

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



The left figure shows the accuracy of three sensors (x, ▲ and ■) measuring the same property when installed and accurately calibrated. The right figure shows the accuracy of the same sensors after some years of operation. The sensors have drifted from the real value.

Production optimization under uncertainty

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

Post-doc (20%):
Dinesh Krishnamoorthy

Project manager
and main supervisor:
Professor
Sigurd Skogestad

1. INDUSTRIAL CHALLENGE

In order to stay sustainable and 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 facilities. Such mutually beneficial exchange of materials and resources between different organization is known as Industrial symbiosis. 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 cost information 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 resource sharing in an industrial symbiotic setting.

2. HOW CAN WE SOLVE IT

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 total 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.

3. RESULTS SO FAR:

- Distributed feedback-based RTO framework for optimal resource sharing without tht need to solve numerical optimization problems (Published in the Journal of Process Control)
- Distributed steady-state RTO framework using transient measurements with limited information sharing. (Proceeding of 2020 American Control Conference)
- Multi-scenario Design Optimization using ADMM (accepted for publication in Computer-aided Chemical Engineering)

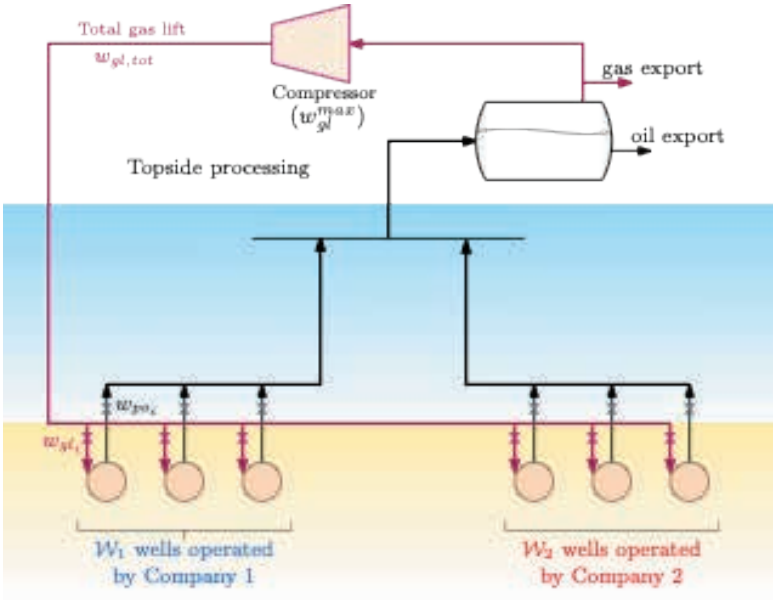


Figure 1: Industrial symbiosis in subsea oil and gas production. Illustration of the subsea wells operated by different companies, sharing the same processing facility.

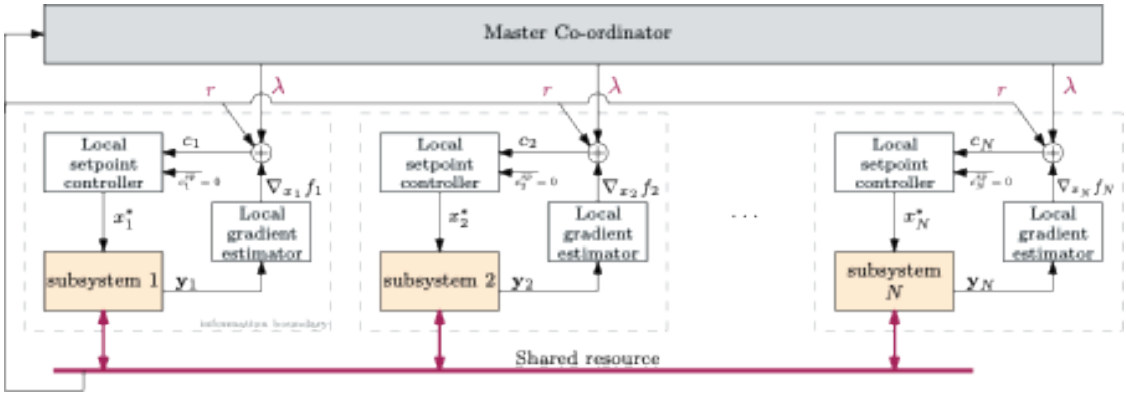


Figure 2 : Feedback based distributed optimization framework for optimal resource sharing.

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

A SUBPRO spin-off project.

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

Yiliu Liu
(RAMS Systems Control,
PhD supervisor)

Edmary Altamiranda
(Aker BP,
Industrial PhD supervisor)

The fruitful collaboration between SUBPRO and the industry partners has led to a new spin-off research project funded by the Norwegian Research Council, which stared in autumn 2020. The ropject involves the Department of Chemical Engineering and the RAMS group from Department of Mechanical and Industrial Engineering, and is a collaboration project between NTNU SUBPRO, Aker BP and 3 Chinese Universities: China Univ. of Petroleum (E. China), Ocean University of China, and Beihang University. On the Chinese side, the industrial partners are Yantai Jereh and the Chinese National Offshore Oil Cooperation (CNOOC)

The primary research question that we seek to answer is:

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

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

There are three PhD projects at NTNU in AutoPRO, that are associated to the Systems Control Group and the RAMS group in SUBPRO.

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

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

3. Autonomous production optimization with degrading equipment
(Sandeep Prakash –
Systems Control)

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

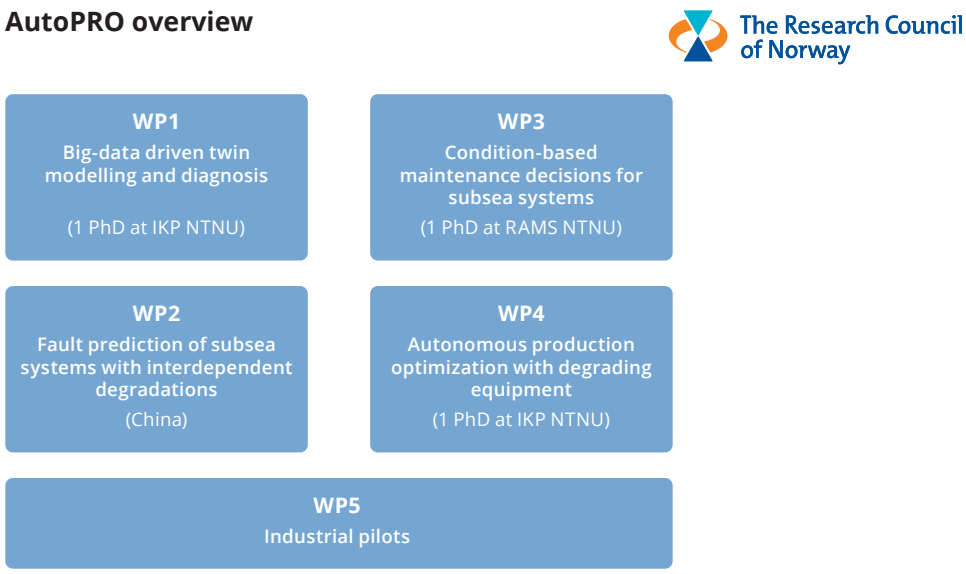


Figure 1: AutoPRO Project organization

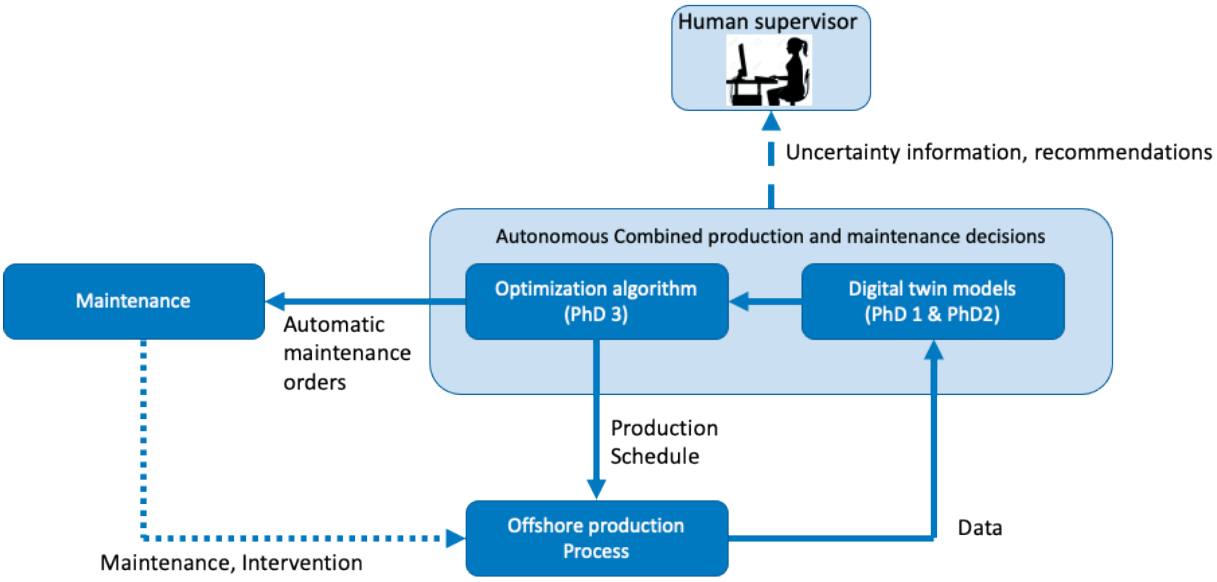


Figure 2: AutoPRO conept for realizing autonomous Production, including automatic matinenance ordering. Only high-level information is passed to the human supervisor.

FINAL PROJECT REPORT

Enhanced Virtual Flow Metering

PhD graduate:	**Timur Bikmukhametov**
Start date:	13.08.2017
Defense date:	18.12.2020
Title of the thesis:	Machine Learning and First Principles Modeling Applied to Multiphase Flow Estimation (with a focus on the oil and gas industry)
Thesis committee members:	Francisco Corona, Gunnar Staff, Christian Holden
Supervisor:	Associate Professor Johannes Jäschke

1. BACKGROUND FOR THE PROJECT

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 is dedicated to improving the understanding of this technology and development 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.

2. WHAT I HAVE DONE

- **Comprehensive literature review** on the topic of Virtual Flow Metering using first principles and machine learning models. Based on this review, I identified main directions for future research and development. The review received a great feedback in the oil and gas industrial and research communities.

- **Proposals and comprehensive comparison of several methods** of combining machine learning models with multiphase flow physics in order to construct accurate and more explainable Virtual Flow Metering solutions. The concepts can further be extended to modeling of other oil and gas production systems.

- **Framework for combining Bayesian machine learning framework with physical models** that is able to tune first principles models to the data at hand and quantify uncertainty of the resulted hybrid models of a physical system. The framework is applied to a developed simple yet accurate pipe multiphase flow model that can be used for modeling steady state multiphase flows in wells and pipelines with various geometry setups.

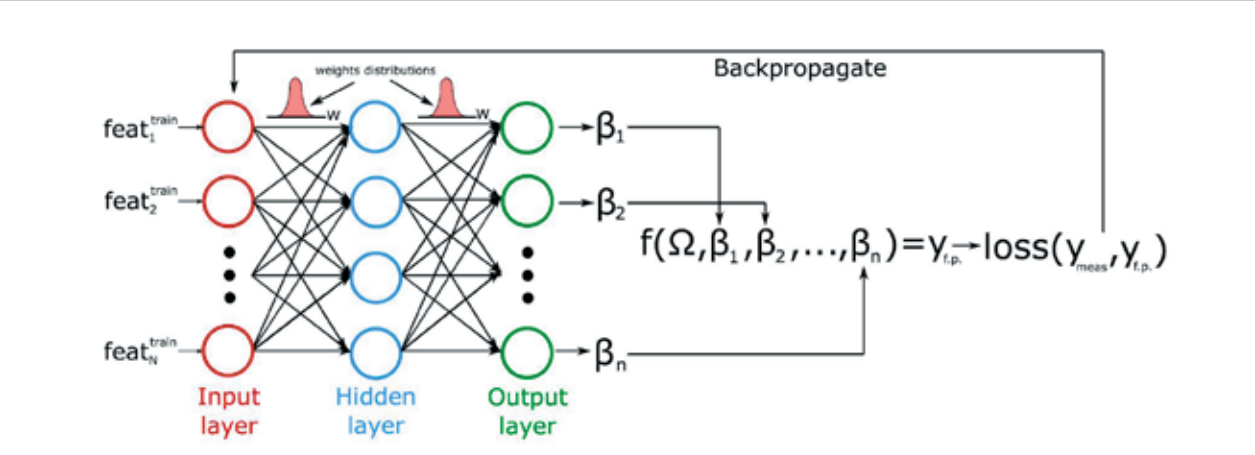
3. MAIN RESULTS

In my work, I got several main results and conclusions.

1. The literature review showed that currently first principles-based approaches for multiphase flowrate estimation take the leading role, however, machine learning methods have a big potential to enhance, be combined or even replace them depending on the data availability. The general trend of the multiphase flowrate estimation methods development is positive and such approaches have the potential to replace physical multiphase flow meters in the near future. Currently, they can be successfully applied as a back-up system to hardware installations.

2. Based on the obtained results on combining first principles and machine learning models for multiphase flow estimation purposes I found that even simple physical models introduced to machine learning models might enhance accuracy and explainability of the resulting data-driven solutions. Meta-modeling which combines different hybrid machine learning models creates the most accurate results among other combinations of machine learning models in case of multiphase flowrate estimation systems.

3. I considered different approaches on uncertainty estimation of hybrid machine learning models with the purpose of multiphase flow estimation and I found that accuracy of first principles multiphase flowrate estimation tools are very sensitive to measurement drift and relatively sensitive to measurement noise, while some simplifications can be made during the modeling process, for instance, in the thermodynamic part. As such, robust re-tuning process has to be performed regularly when measurement drift exists in the production system measurements. Bayesian Neural Networks are good tools for tuning first principles multiphase flow models to different process conditions and able to estimate uncertainties correctly depending on the historical distribution and the size of the data. Bayesian Neural Networks can



Schematic representation of developed hybrid machine learning and first principles models that can be applied for multiphase flow estimation or other type of process engineering problems

be successfully used under changing process conditions of engineering systems in order to understand when there is a need to recalibrate the model or when there is a need to perform condition maintenance of the system.

4. INNOVATION AND INDUSTRY COLLABORATION

The developed methods for multiphase flow estimation using hybrid approaches utilizing machine learning with multiphase flow physics and Bayesian learning framework formulate a great basis for further improvements of accuracy and robustness of multiphase flow estimation solutions that are currently not well-developed in the industry, but have a rising trend in the research and development. I believe that the proposed methods will put light on how to fully uncover the potential of machine learning algorithms and available production data in order to form reliable multiphase flow metering solutions at an affordable cost. The produced work was always focused on industrial applicability, so the industry partners can effectively start using proposed concepts for improving their soft-sensing solutions not only for multiphase flow estimation problems, but for other process engineering systems of interest without going very deep into theoretical details and implementation challenges.

5. FURTHER WORK

Based on the conducted research work and the current research activity in the community of process and petroleum engineering, the following research directions can extend the conducted research work:

- Considering dynamic Bayesian recurrent neural networks together with dynamic multiphase flow models. With this approach, it is potentially possible to accurately describe dynamic multiphase flow behavior using unsteady production data. This will allow to get valuable insights on how to operate the field in challenging dynamic conditions and estimate uncertainties of the resulting predictions.
- Extending the work conducted on Bayesian Neural Networks for tuning multiphase flow pipe models to the entire production system and investigate formal criteria under which model recalibration is required or when non-observable process conditions change and there is a need for condition maintenance.
- Extending the work on combining non-Bayesian machine learning methods and physics of process engineering systems and investigate how these models can be used under limited data criteria and how to perform transfer learning in such regression problems, such that the model from one well can be applied to another well with minimal model re-training.

6. MY NEW JOB

Company: Zyfra (Moscow, Russia)
Position: Lead Data Scientist
(Industrial Machine Learning Applications)

FINAL PROJECT REPORT

Control for extending component life

A new method for safe and economical operation.

PhD graduate:	**Adriaen Verheylewegen**
Start date:	August 2015
Defense date:	12.06.2020
Title of thesis:	"Control Degrees of Freedom for Optimal Operation and Extending Remaining Useful Life – Application to subsea production and processing"
Thesis committee members:	Professor John Bagterp Jørgensen (DTU), Doctor Olav Slupphaug (ABB) and Professor Magne Hillestad (NT
Supervisor:	Associate Professor Johannes Jäschke

1. BACKGROUND FOR THE PROJECT

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.

2. WHAT I HAVE DONE

My 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. To achieve this, I have developed a method which uses model predictive control to find the optimal input trajectory, given a mathematical description of the system behavior and its degradation.

Most of my work has been focused on developing these new methods and applying them to industrially relevant simulation studies. Experimental work has not been performed, although other students have further developed my work, and tested the methods experimentally (see section 5 – Further work).

3. MAIN RESULTS

The main results of this subproject are several new tools and methods:

- 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. This work was nominated for the "Best paper" award at the OOGP conference in Esbjerg in 2018.
- Methods for systematic handling of model uncertainty in the optimization framework, either by considering a worst-case scenario for the uncertainty realization, or by optimizing an ensemble of representative scenarios simultaneously.
- A systematic method for optimal scheduling of production and maintenance

The main take-aways from this project are the following:

- Systematic inclusion of the system degradation in the control- and planning domain is useful and provides economic benefit by reducing the expected downtime and maintenance costs.
- Developing accurate models of the system degradation as a function of its usage is crucial for success, although it can be difficult due to the lack of clear health indicators.

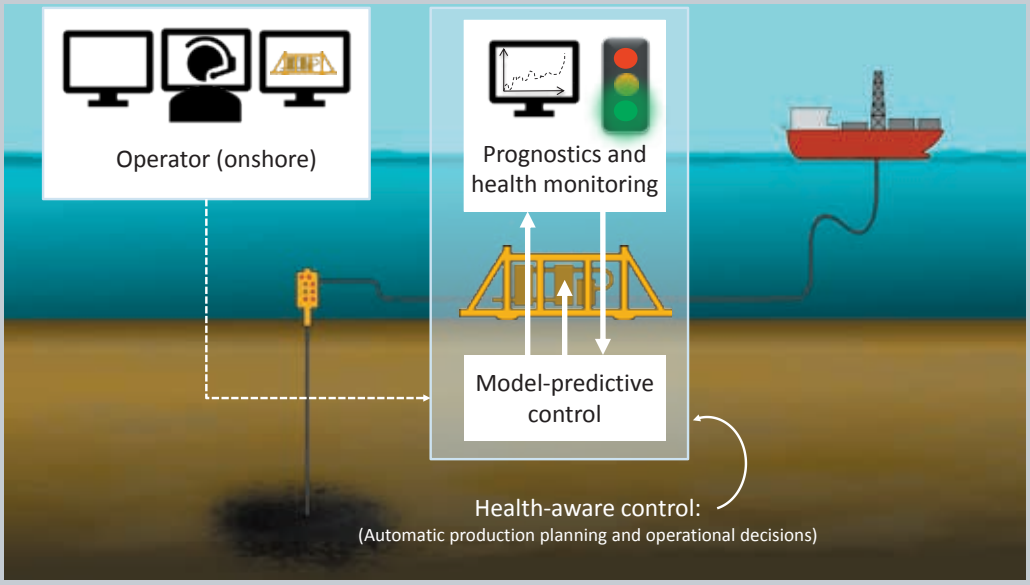


Figure 1: Illustration of the proposed health-aware control method for subsea production and processing.

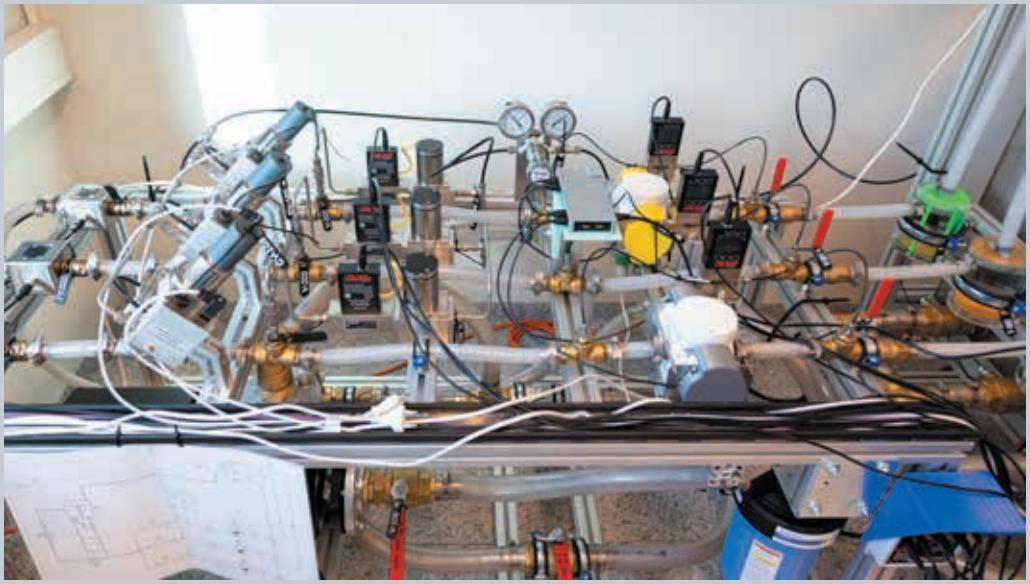


Figure 2: Experimental rig for testing degradation models and for verifying the control methods.

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

a. Gas compressors / rotating machinery

b. System-wide production and maintenance optimization

c. Scheduling of gas turbine washing

d. Test frequency for safety critical valves (see the project "Reliability and availability assessment in subsea design")

5. FURTHER WORK
Future work should focus on developing better prognostic degradation models for subsea equipment. Very little data exists for how equipment degrades under varying operating conditions, as would be the case for a process with active control. If such models can be developed, the uncertainty of the models will be reduced, leading to less conservative operation.

The method for combined optimization of production and maintenance scheduling should also be improved. The multi-start approach used to ensure near-global optimality is somewhat crude in its implementation, and calculation times can be sped up significantly by using a more advanced method. More sophisticated algorithms for solving complementarity-constrained NLPs should also be used, e.g. branch and bound algorithms or evolutionary algorithms.

The methods developed in my project are to be tested experimentally and further developed in project 3.8b by post. doc. José Matias. In that subproject, the aim is to develop an experimental rig for testing degradation models and for verifying the control methods. The rig consists of a water-oil-particle slurry which is sent through three parallel flow lines (see figure 2). Erosion is measured optically in a purpose-designed erosion element. By varying the operating conditions and the allocation of water-oil-particle slurry to the flow lines, erosion can be controlled to stay below an acceptable threshold.

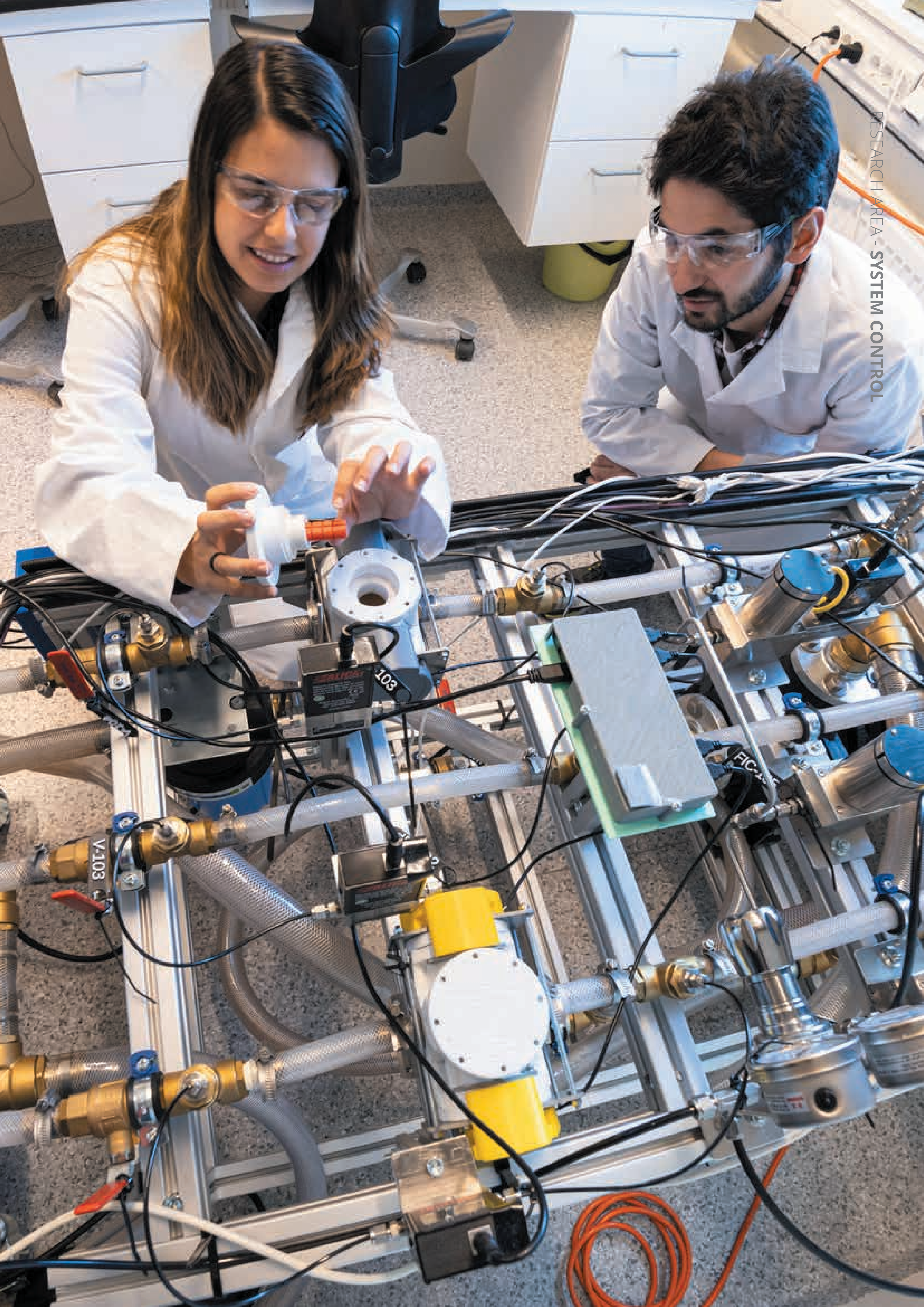
The rig has been designed and fully assembled. Experimental work is currently being performed, and results are looking promising (Figure 2).

6. MY NEW JOB
Company/institution: Cybernetica AS
Position/area of work: Senior Control Engineer

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 several O&G projects where my background from SUBPRO is very useful.

"During 2019, We have built the experimental rig for verifying the methods proposed by the SUBPRO project -Control for extending component life- by PhD student Adriaen Verheyleweghen. 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 – year 2020.

From left to right: associate PhD student Allyne dos Santos (Faculty of Natural Sciences NTNU) and Postdoctoral fellow Jose Otavio Assumpcao Matias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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 Brazilian-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.- February 2020.

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

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 2020, 20 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 2020, SUBPRO offered (4) 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 2020 and the Master thesis during the spring of 2021, 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 for 2020 summer internships, were the followings:

1 Performance monitoring of hydrocyclones for different oil droplet distribution

2 Influence of thermal history on oil properties

3 Implementing a model predictive controller (MPC) in a lab rig

4 Modeling of fluid particle coalescence phenomena

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

COVID-19 has taken its toll on social activities at SUBPRO during 2020. Nevertheless, and right before the pandemic hits Norway a second common trip with fellows from BRU21 project took place with the aim of strengthening internal and external collaboration. All other social events kept going while being converted from live to digital episodes.

SUBPRO AND BRU21 SECOND COMMON TRIP TO RØROS: FROM 6TH TO THE 7TH MARCH 2020

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.

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

Arrival to Røros after a visit at Equinor Stjørdal (Simulator center and subsea department). The 6th March 2020.

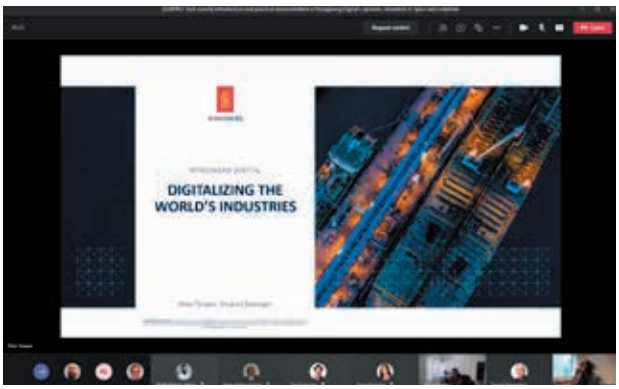
The SUBPRO/BRU21 technical session at Røros Hotel, followed by a dinner and a quiz- The 6th March 2020. The next day was fully dedicated for skiing and snow activities on Røros slopes.

Photo taken on the 22nMarch 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.

SUBPRO TECH-LUNCH

Due to COVID-19 restrictions, most of the tech-lunch sessions at SUBPRO during 2020/2021 took place on a digital platform. Despite the physical distancing, PHD students and postdocs at SUBPRO were able to meet on regular intervals; in an informal context combining social interaction and multi- discipline collaboration possibilities through knowledge sharing.

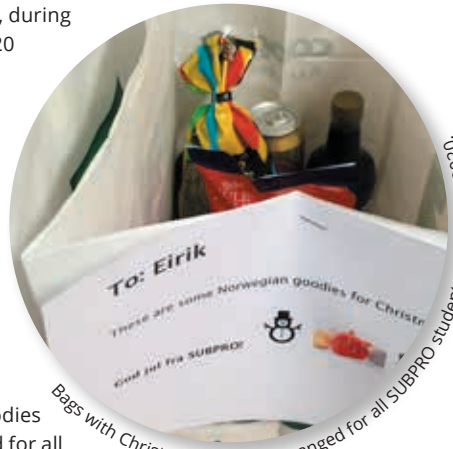
A technical presentation was included in each event – where topics and presenters were elected based on recommendations from the students themselves.



From the technical presentation held by one of SUBPRO industry partners: Kongsberg Digital about: "Introduction and practical demonstration of Kongsberg Digital's dynamic simulators K-Spice and LedaFlow". Digital SUBPRO tech-lunch on March 2021.

CHRISTMAS 2020 AT SUBPRO

Unfortunately, during December 2020 members of the SUBPRO family could not gather around a "Julebord" like in former years prior COVID-19. Nevertheless, personalized Christmas goodies were arranged for all SUBPRO students that they were able to pick up themselves from the administration office.



Bags with Christmas goodies, arranged for all SUBPRO students- December 2020.

A digital meeting was followed by right after new year, gathering all SUBPRO members, wishing a "Happy New Year" to everyone and announcing plans of the coming year.

International Collaboration

Despite travel restrictions in year 2020 due to COVID-19,, international collaboration at SUBPRO continued, but as almost all travel activities have stopped, there has been less direct contact than for example in 2019 and less cooperation through conferences etc. Nevertheless:

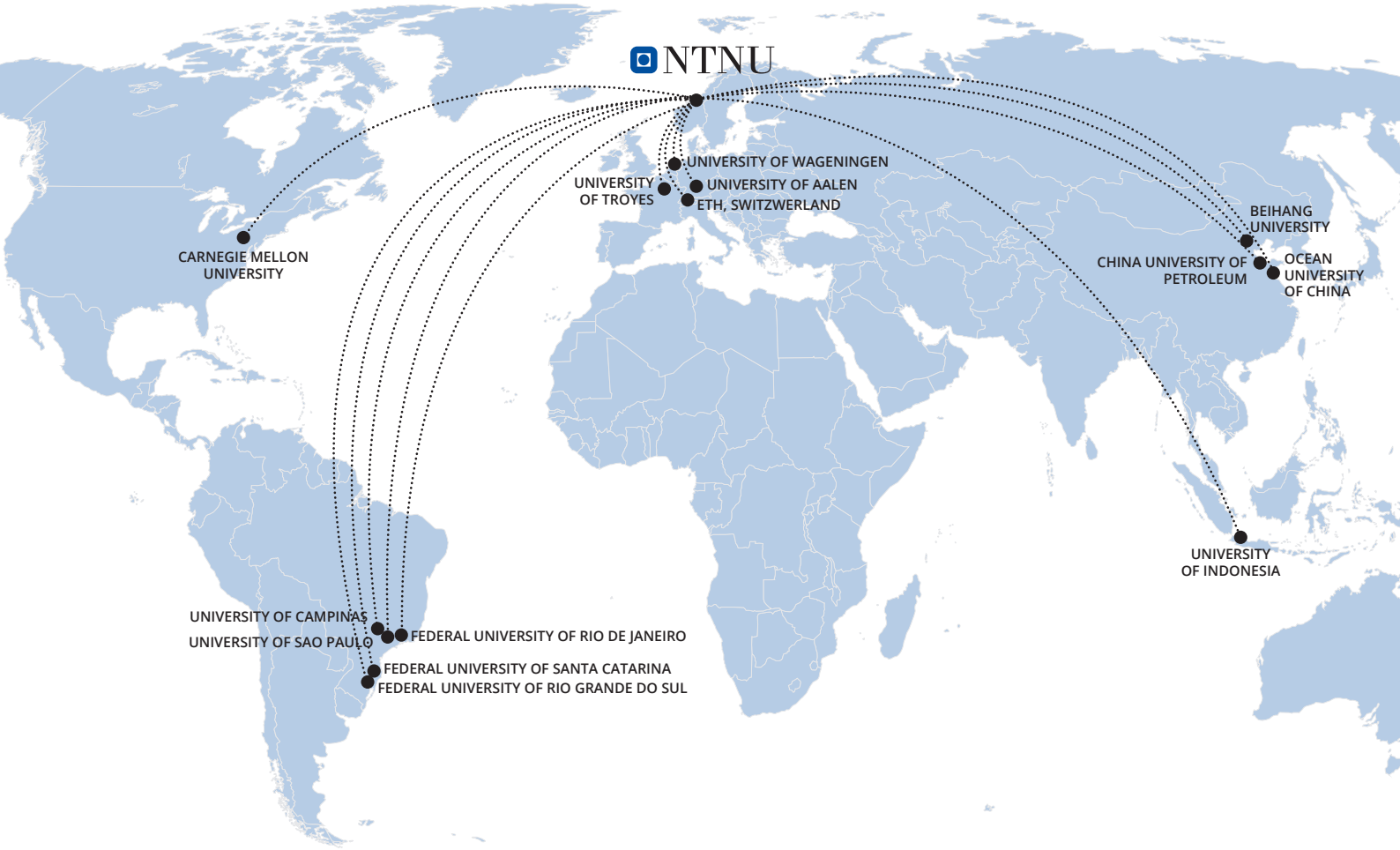
- SUBPRO received international guests, and one of our PhDs was on a research stay in University of Aalen, Germany during October 2020.

- Cooperation with (3) Chinese universities has been inaugurated through AutoPRO project (referred to in page 74)
  - o China University of Petroleum (E. China)
  - o Ocean University of China
  - o Beihang University

- We kept good cooperation and exchange with several universities in Brazil through INTPART:
  - ➢ Visits / exchange stays from Intpart PhD candidates within several research areas in SUBPRO.
  - ➢ Several researchers from Brazil have visited / workshops at SUBPRO in the spring of 2020.
  - ➢ The Research Council's INTPART calls.
    - o Federal University of Rio de Janeiro/COPPE
    - o Federal University of Santa Catarina
    - o University of Sao Paulo
    - o University of Campinas

- Brazil-Norway Subsea Operations Consortium (BN-SOC) - ended June 2020. Received a new award in the summer of 2020, and the project will continue again from January 2021.

- In addition to Germany, China and Brazil, SUBPRO also cooperated with researchers from Denmark, Indonesia and the United States of America during year 2020.

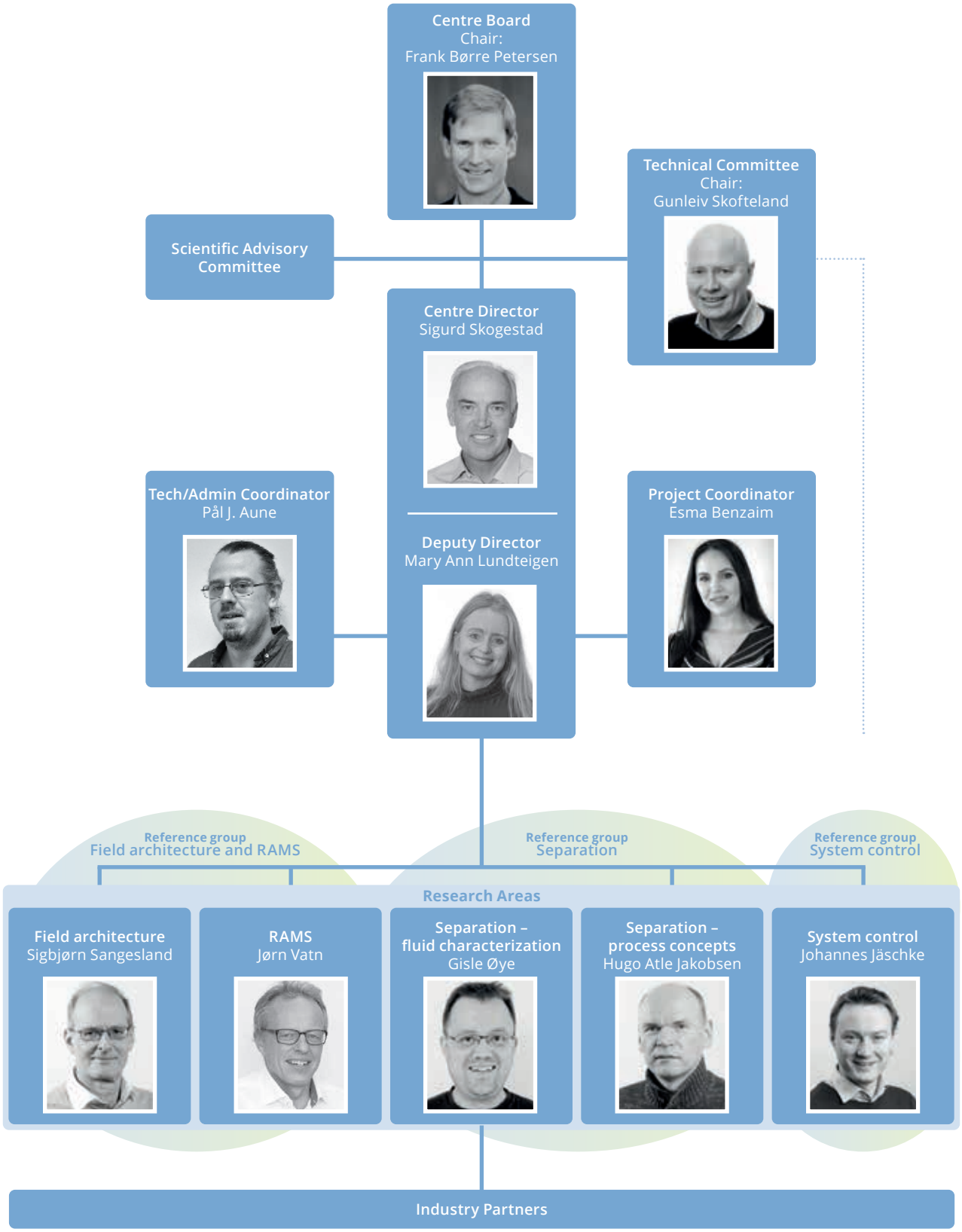


"A compact separation test-rig for produced-water treatment -using hydrocyclones- were built to test novel automatic control methods and advanced soft sensor technologies. These new control schemes can improve and maintain the efficiency of hydrocyclones. The lab is equipped with state-of-the-art online oil in water analysers which can directly give the efficiency of hydrocyclones. Currently, we are running experiments to verify the new control schemes. Also shown in the picture is the oil-in-water analyser placed at the water reject of the hydrocyclones".

PhD student Mishiga Vallabhan- March 2020.

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 yearly meeting held in the month of October, 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 pro¬jects through industrial cases, field data, technical knowledge transfer through advice and co-supervision of SUBPRO 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 to enable implementation of project results in the industry.

Postdoc Jose Matias has started a six-month Innovation Project in February/2021. The project goal is to validate experimentally the new control approaches for gas-lift optimization that were proposed in previous and ongoing SUBPRO projects (Dinesh Krishnamorthy: *"Production optimization under uncertainty"* and Risvan Dirza's project: *"Filed-wide Production optimization"*). Since the benefits of these approaches were verified only in simulations, this innovation project aims at studying their applicability in a more realistic setting in order to move them towards a higher TRL and closer to implementation in industry. (More information about this innovation project on page 68-69).

CENTRE BOARD 2020-2021


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 Widerøe
Lundin Norway


Lars-Erik Svabø
Kongsberg Digital


Jostein Kolbu
Aker Solutions


Lachlan McKenzie
TechnipFMC


Kristin Moe Elgsaas
Aker BP
(from 01.01.2021)


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 2020, two HSE related incidents have been reported to SUBPRO:

1- The first incident occurred during the SUBPRO and BRU21's common social trip to Røros in March 2020, where two of the participants sustained injuries while doing winter activities. One of them required surgery at the hospital in Tynset.

The incident was followed-up and injuries were registered. A reinforced risk assessment will be made before social activities in the future.

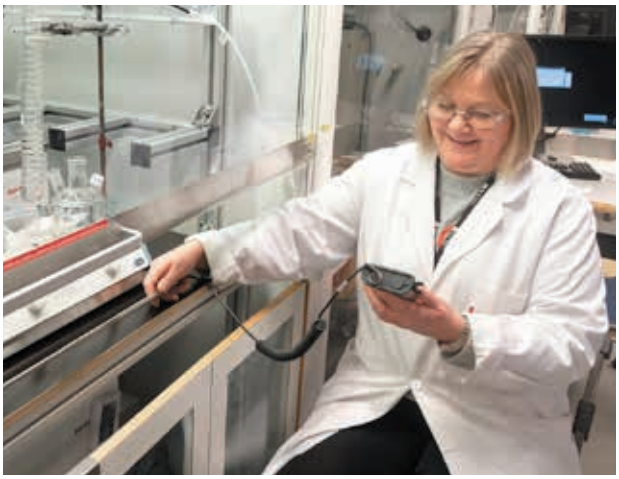
2- For the second incident, SUBPRO staff have reported strong smells in laboratories twice, but these were not caused by SUBPRO Staff. There were no personnel injuries or damage to equipment. Strong smell has been a reoccurring problem in the PFI-building. Risk assessment will be done, and tests will be run at night.

All incidents have been systematically followed up with a post-event analysis and preventive mitigations.

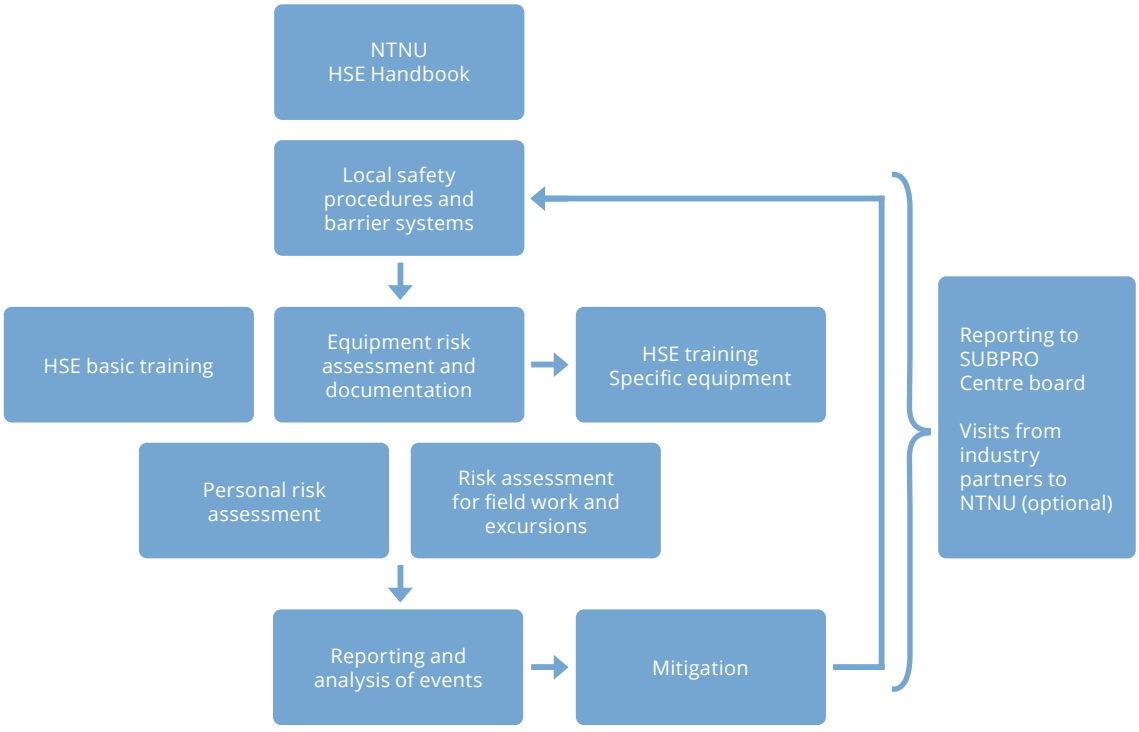
All PhD students, postdoctoral fellows and Master students who work in laboratory projects in SUBPRO receive a two-level safety training; basic HSE training and HSE training for specific equipment.

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.



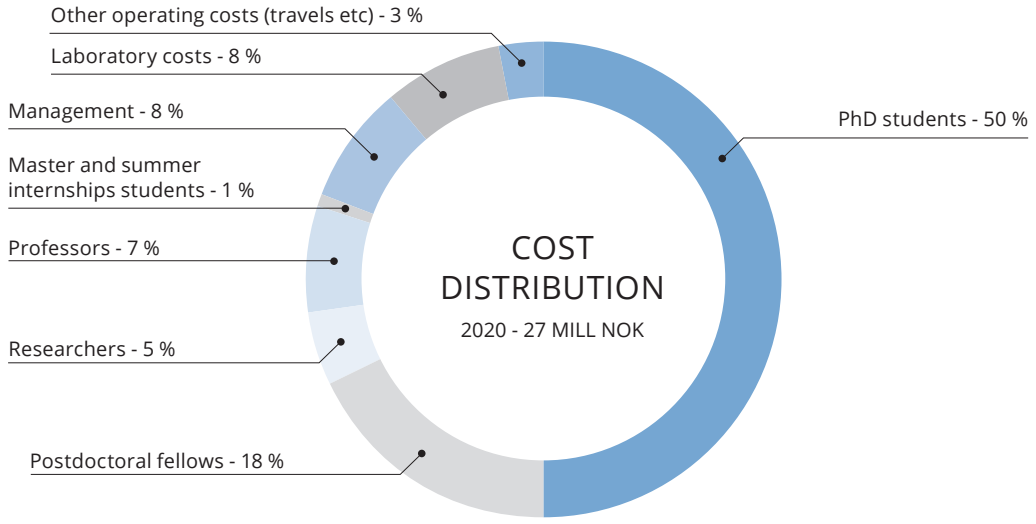
NTNU/SUBPRO HSE system

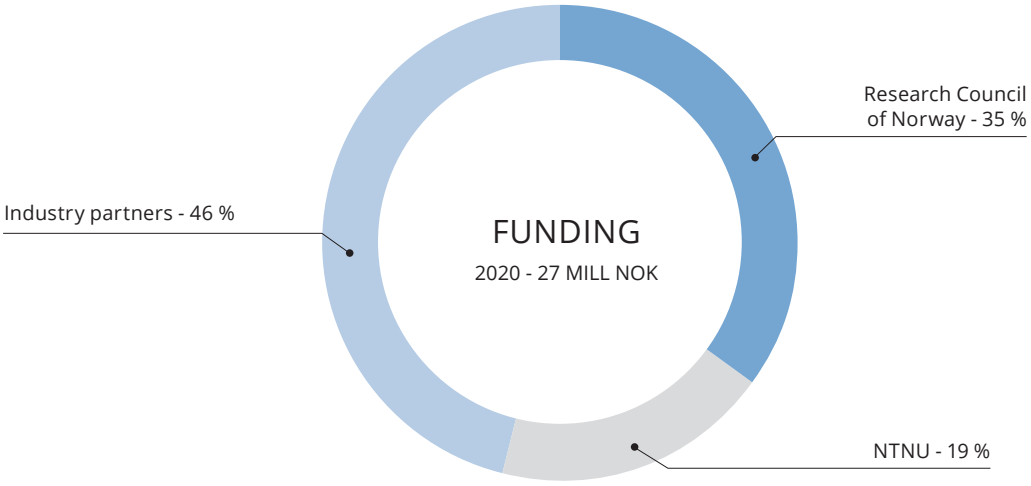
Key figures 2020

PROJECT DURATION	AUGUST 2015 – AUGUST 2023*		
Total annual budget (annual average, 2015-2023)	32 mill. NOK		
Personnel	Planned 2015-2023	Currently engaged 2020	Female percentage
PhD students	34[1]	19	24 %
Postdoctoral scholars	9[1]	7	29 %
Researchers (full or part time)	7[1]	5	20 %
Professors	22	22	23 %
MSc students (per year)	25	20	30 %

[1] Accumulated over 8 years

PUBLICATION 2020	
Journal and conference papers	22





Publications

Journal papers and conference papers published in 2020

RELIABILITY, AVAILABILITY, MAINTENANCE AND SAFETY

Kim, Hyungju; Lundteigen, Mary Ann; Hafver, Andreas; Pedersen, Frank Børre.
"Utilization of risk priority number to systems-theoretic process analysis: A practical solution to manage a large number of unsafe control actions and loss scenarios. Proceedings of the Institution of Mechanical Engineers".
Part O, Journal of risk and reliability (2020); Vol 235.-1- s.92-107.

SEPARATION – FLUID CHARACTERIZATION

Dudek, Marcin; Azizov, Ilgar; Edøy, Karoline; Saadat, Marzieh; Ullaland, Hanne Skudal; Wehrle, Amandine; Øye, Gisle.
"Introducing Microfluidic Methods to Evaluate the Performance of Oil Field Chemicals".
Oil Field Chemistry Symposium; (2020-09-23 - 2020-09-24).

Dudek, Marcin; Fernandes, Diana; Herø, Eirik Helno; Øye, Gisle.
"Microfluidic method for determining drop-drop coalescence and contact times in flow".
Colloids and Surfaces A: Physicochemical and Engineering Aspects (2020); Vol 586.

Dudek, Marcin; Ullaland, Hanne Skudal; Wehrle, Amandine; Øye, Gisle.
"Microfluidic testing of flocculants for produced water treatment: Comparison with other methodologies".
Water Research X (2020); Vol 9. s.1-11.

Dudek, Marcin; Vik, Eilen Arctander; Aanesen, Svein Viggo; Øye, Gisle.
"Colloid chemistry and experimental techniques for understanding fundamental behaviour of produced water in oil and gas production".
Advances in Colloid and Interface Science (2020); Vol 276. -102105- s.1-20

Piccioli, Martina; Aanesen, Svein Viggo; Zhao, He; Dudek, Marcin; Øye, Gisle.
"Gas Flotation of Petroleum Produced Water: A Review on Status, Fundamental Aspects, and Perspectives".
Energy & Fuels (2020); Vol 34.-12- s.15579-15592.

Simon, Sebastien Charles; Ruwoldt, Jost; Sjøblom, Johan.
"A critical update of experimental techniques of bulk and interfacial components for fluid characterization with relevance to well fluid processing and transport".
Advances in Colloid and Interface Science (2020); Vol 277. s.1-21

Skjefstad, Håvard Slettahjell; Dudek, Marcin; Øye, Gisle; Stanko, Milan.
"The effect of upstream inlet choking and surfactant addition on the performance of a novel parallel pipe oil-water separator".
Journal of Petroleum Science and Engineering (2020); Vol 189.

SEPARATION – PROCESS CONCEPTS

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

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

Herø, Eirik Helno; La Forgia, Nicolas; Solsvik, Jannike; Jakobsen, Hugo Atle.
"Single Drop Breakage in Turbulent Flow: Statistical Data Analysis".
Chemical Engineering Science: X (2020); Vol 8.

Karbas Foroushan, Hanieh; Jakobsen, Hugo Atle.
"On the dynamics of fluid particle breakage induced by hydrodynamic instabilities: A review of modelling approaches".
Chemical Engineering Science (CES) (2020); Vol 219. s.1-20.

Karbas Foroushan, Hanieh; Jakobsen, Hugo Atle.
"On the Instability of Fluid Particle Interface and Shape Oscillations".
International Journal of Multiphase Flow (2020); Vol 136. s.1-32

Skylogianni, Eirini; Mundal, Ingvild; Pinto, Diego Di Domenico; Coquelet, Christophe; Knuutila, Hanna K.
"Hydrogen Sulfide Solubility in 50 wt.% and 70 wt.% Aqueous Methyldiethanolamine at Temperatures from 283 to 393 K and Total Pressures from 500 to 10000 kPa".
Fluid Phase Equilibria (2020); Vol 511.

Skylogianni, Eirini; Perinu, Cristina; Cervantes Gameros, Blanca Y; Knuutila, Hanna K.
"Carbon dioxide solubility in mixtures of methyldiethanolamine with monoethylene glycol, monoethylene glycol–water, water and triethylene glycol".
Journal of Chemical Thermodynamics (2020); Vol 151. s.1-19.

SYSTEM CONTROL

Assumpcao Matias, Jose Otavio; Jäschke, Johannes.
"Online Model Maintenance in Real-time Optimization Methods".
Computers and Chemical Engineering (2020); Vol 145. s.1-17.

Assumpcao Matias, Jose Otavio; Ågotnes, Joachim Alexander Hauge; Jäschke, Johannes.
"Health-aware advanced control applied to a gas-lifted oil well network".
IFAC-PapersOnLine (2020); Vol 53. -3- s.301-306.

Backi, Christoph Josef; Gravdahl, Jan Tommy; Skogestad, Sigurd.
"Combined state and parameter estimation for not fully observable dynamic systems".
IFAC Journal of Systems and Control (2020); Vol 13.

Bikmukhametov, Timur; Jäschke, Johannes.
"Combining machine learning and process engineering physics towards enhanced accuracy and explainability of data-driven models".
Computers and Chemical Engineering (2020); Vol 138. s.1-27.

Krishnamoorthy, Dinesh; Biegler, Lorenz T.; Jäschke, Johannes.
"Adaptive horizon economic nonlinear model predictive control".
Journal of Process Control (2020); Vol 92. s.100-118

Krishnamoorthy, Dinesh; Valli, Carlo; Skogestad, Sigurd.
"Real-time Optimal Resource Allocation in an Industrial Symbiotic Network using Transient Measurements".
Proceedings of the (2020) American Control Conference,p. 3541-3546.

Kulangarakalam Gayathrivallabh, Mishiga Vallabhan; Holden, Christian.
"Non-linear control algorithms for de-oiling hydrocyclones".
I: (2020) 28th Mediterranean Conference on Control and Automation (MED) proceedings. IEEE (2020) ISBN 978-1-7281-5742-9.

Kulangarakalam Gayathrivallabh, Mishiga Vallabhan; Holden, Christian; Skogestad, Sigurd.
"A First-Principles Approach for Control-Oriented Modeling of De-oiling Hydrocyclones".
Industrial & Engineering Chemistry Research (2020); Vol 59. s.18937-18950.

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Fluid characteristics

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models

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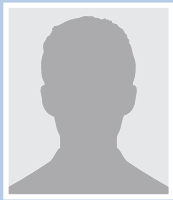

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Chair of the
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Tore Myhrvold
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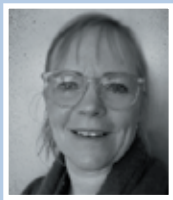

Trine Boyer
Total E&P Norge

Subsea factory – Courtesy of Equinor

SUBPRO

SUBSEA PRODUCTION AND PROCESSING

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SUBPRO team at NTNU,
in front of a Subsea Distribution Unit
from the Njord field, Equinor.- year 2018

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