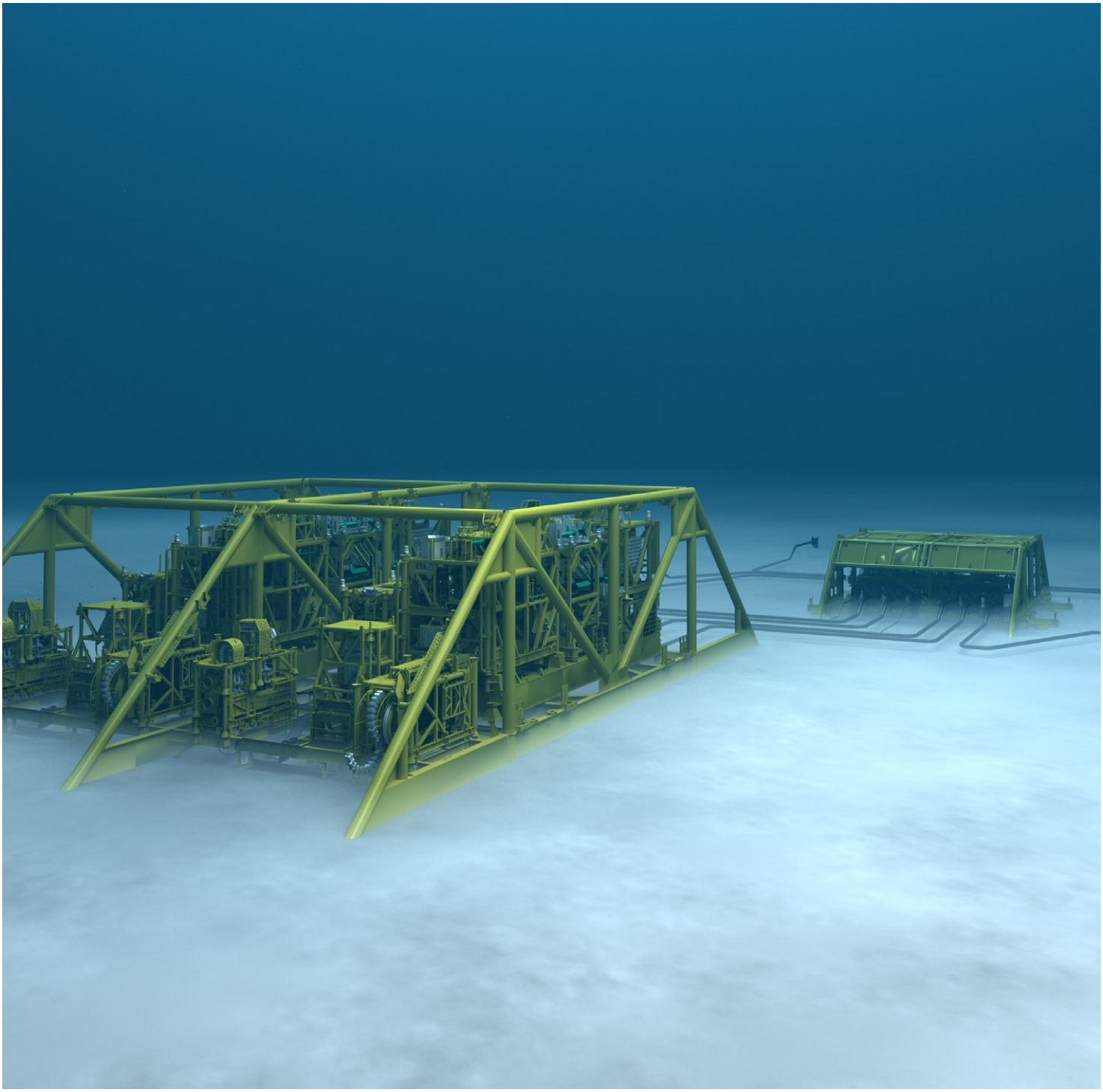
SUBPRO

SUBSEA PRODUCTION AND PROCESSING

Annual Report

2017

2018



sfi Centre for Research-based Innovation

Established by the Research Council of Norway

NTNU

Norwegian University of Science and Technology

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

Why Supro?

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: Åsgard subsea compression system Courtesy of Equinor - Asle Haugland 2016.

Content

Chairman of the Board

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

Subsea technology out of Norway has a strong international position in the oil and gas industry. It is difficult to pin-point what has been the most influential factors for this success; natural conditions or a very high emphasis on Research and Development within subsea production on The Norwegian Continental Shelf (NCS). What we know for fact is that Norway quite early in the 1970s and 1980s was targeted within subsea R&D due to its favourable oil and gas taxation system. And it paid off! The Norwegian Continental Shelf became an innovative arena for development, testing, qualification and implementation of new technology. Today the Norwegian subsea cluster industries are a significant exporter of high technology goods and services to subsea field developments in Brazil, West Africa, Malaysia and the Gulf of Mexico, i.e. all deep water oil and gas exploitation areas around the world.

If we want this industry to prosper and continue its development, we need to continue and even strengthen our efforts into R&D. The NCS initiative for a Centre for Research-based Innovation (SFI) within Subsea Production and Processing technology (SUBPRO) has been taken to accelerate the level of innovation within the subsea oil and gas industry. Demands are steadily becoming more challenging as we take on more benign conditions; cold climates, longer step-outs and tie-back distances, deeper waters in combination with reservoirs of higher temperatures and pressure, and reservoirs which are harder to reach. In order to be successful with our efforts in SUBPRO we need to combine academia, research institutions, suppliers and the end user of the needed technologies in an efficient manner. SUBPRO shall serve the industry's need for long term research and innovation by organising relevant resources within the process industries, and combining this effort with highly recognised research at the university environment at NTNU, which successfully has served the NCS for many decades already.

Stig Lyder Støme, Lundin Norway
Chairman of the SUBPRO Centre Board

Centre director

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

Our SFI started up at the worst possible time in terms of oil prices, and we think that the industry has proven their interest in our work by continuing their support.

We have got two new industrial partners (VNG Norge from 2017 and Aker BP from 2018) and we thank Shell and ABB for their participation up to 2017.

We have managed to develop a centre model with strong structures and mechanisms for collaboration between industry partners and academia and across the projects. It is very important for us to have a good collaboration with active industry partners. The Technical committee and reference groups form the backbone for our industry-academia collaboration. Here engineers from the industry partners and NTNU researchers meet to discuss project results, applications and further work. Particular emphasis is now put on industrial applications, as the first generation of PhD students are entering their final year.

Most of the research work is done at NTNU, where SUBPRO is presently funding 25 fulltime PhD students and Postdoctoral fellows. In addition, 20 professors and 10 researchers contribute to the projects. During 2017 the work has resulted in 46 journal and conference papers and 6 industrial conference presentations

NTNU/SUBPRO educated 22 Master students in the spring of 2017, who specialised in various fields of subsea technology. We also organised an "Experts in teamwork" village and had 8 summer internships at NTNU during 2017.

The Norwegian oil and gas sector, including subsea technology, has proven over the years to be very innovative, and the goal of SUBPRO is to further contribute to this by strengthening the knowledge basis and providing new talent for the industry.

SUBPRO has several projects in the area of "digitalization", which is a hot topic in the subsea industry at the moment.

SUBPRO is the most comprehensive academic research program 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 fulfill them.

Professor Sigurd Skogestad
SUBPRO Centre Director

Partners

FRANK BØRRE PEDERSEN
PROGRAMME DIRECTOR, DNV GL

What is the goal for DNV GL's membership in SUBPRO?
'Subsea will be increasingly important going forward. DNV GL sees SUBPRO as a key enabler for future subsea technologies and novel production and maintenance strategies. Being part of this development and building knowledge for the future together with the leading academic and industry actors is the main objective of our membership.'

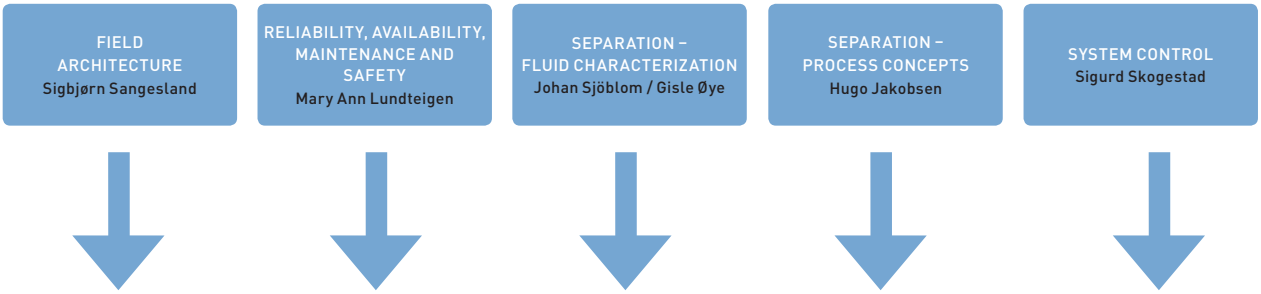
How has DNV GL benefitted from the collaboration with SUBPRO?
'SUBPRO has provided DNV GL with new insights and knowledge into novel subsea technologies. This will allow us to improve our standards, guidelines and services. Furthermore, based on work in SUBPRO we have been able to create a spin-off project with several industry partners and funding from the Norwegian Research Council. This would not have happened without DNV GL being part of the SUBPRO collaboration.'

CAMILLA LEON
VP TECHNOLOGY & DIGITALIZATION
PROJECTS AKER BP

What is the main motivation for Aker BP to join SUBPRO?
'Aker BP continues to pursue research and development (R&D) activities within topics related to expanded subsea facilities. As part of this work, the Company works together with alliance partners, independent suppliers and research centres. SUBPRO is an exciting opportunity for us, where we want to bring our field experience to the work undertaken by SUBPRO and also for us to utilise the competence in SUBPRO to increase our internal competence on subsea production and processing technology.'

Project structure

RESEARCH AREAS



PROJECTS

SUBSEA GATE BOX	NEW SAFETY AND CONTROL PHILOSOPHY FOR SUBSEA SYSTEMS	PRODUCED WATER QUALITY AND INJECTIVITY	MEMBRANES FOR GAS DEHYDRATION	DYNAMIC SIMULATION MODEL LIBRARY
FIELD DEVELOPMENT CONCEPTS	RELIABILITY AND AVAILABILITY IN SUBSEA SYSTEM DESIGN	INFLUENCE OF CHEMICALS ON PRODUCED WATER QUALITY	MEMBRANE TESTING FOR GAS DEHYDRATION	MODELLING AND MULTI-VARIABLE CONTROL OF SUBSEA SYSTEMS
MULTIPHASE BOOSTER MODELS	PROGNOSTICS AND CONDITION BASED MAINTENANCE	WAX CRYSTALLIZATION AND WAX INHIBITION MECHANISMS	H_2S AND HYDRATE CONTROL	AUTOMATIC CONTROL OF SUBSEA SEPARATION
	OPTIMIZING CONDITION MONITORING	SEQUENTIAL SEPARATION	CHARACTERIZATION OF PARTICLE BREAKUP IN TURBULENT FLOW	ADAPTIVE CONTROL OF SUBSEA PROCESSES
		MODELING OF COALESCENCE	COMPACT SEPARATION CONCEPTS	ESTIMATION OF UN-MEASURED VARIABLES
				ENHANCED VIRTUAL FLOW METERING
				CONTROL FOR EXTENDING COMPONENT LIFE
				PRODUCTION OPTIMIZATION UNDER UN-CERTAINTY

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 integrated subsea production systems. 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, reduces the transport costs or prolongs the economic life of the field.
- Cost effective strategies for depleting remote offshore reservoirs with low pressure and low temperature in harsh environments. Such strategies include two scenarios; long distance tie-ins and near field receiving facilities.

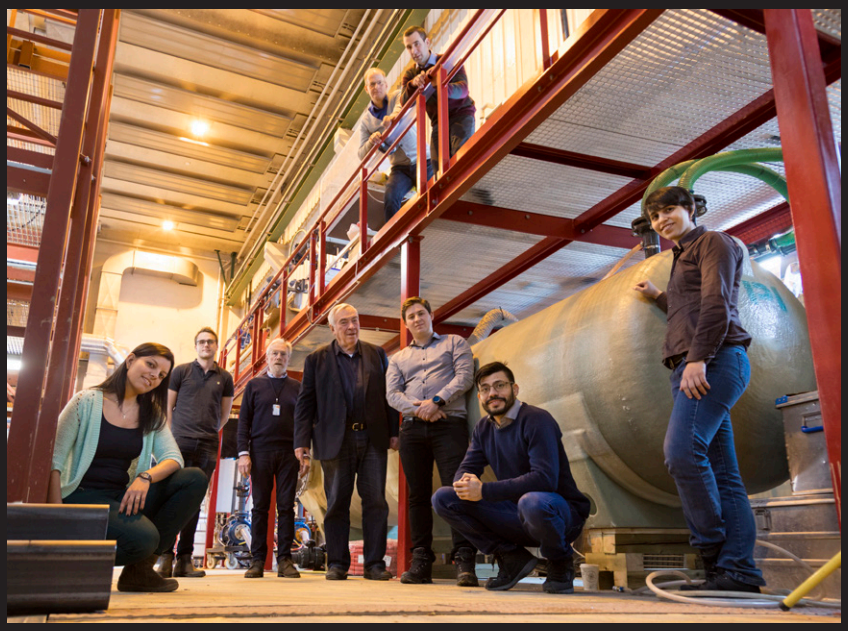
Three business cases with relevant data and information are formulated to guide and narrow the scope of the R&D work. They represent reference oil and gas fields with current gaps and challenges to subsea production and processing:
Case 1: Gas field with low Gas Oil Ratio (GOR)
Case 2: Remote, low energy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

SUB-PROJECTS OF FIELD ARCHITECTURE

The following three sub-projects are ongoing as a part of the research area Field architecture:

- Subsea Gate Box
- Field development concepts
- Multiphase booster models

Prof. Sigbjørn Sangesland
Research area manager



The Field architecture team, gathered in the laboratory of Department of Geoscience and Petroleum.
From left, lower row: Mariana Diaz, Håvard S. Skjefstad, Tor Berge Gjersvik, Michael Golan, Jesus de Andrade, Gilberto Nunez, Diana Gonzales.
From left, upper row: Sigbjørn Sangesland, Milan Stanko.

Subsea gate box

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

POSTDOC: MARIANA DIAZ

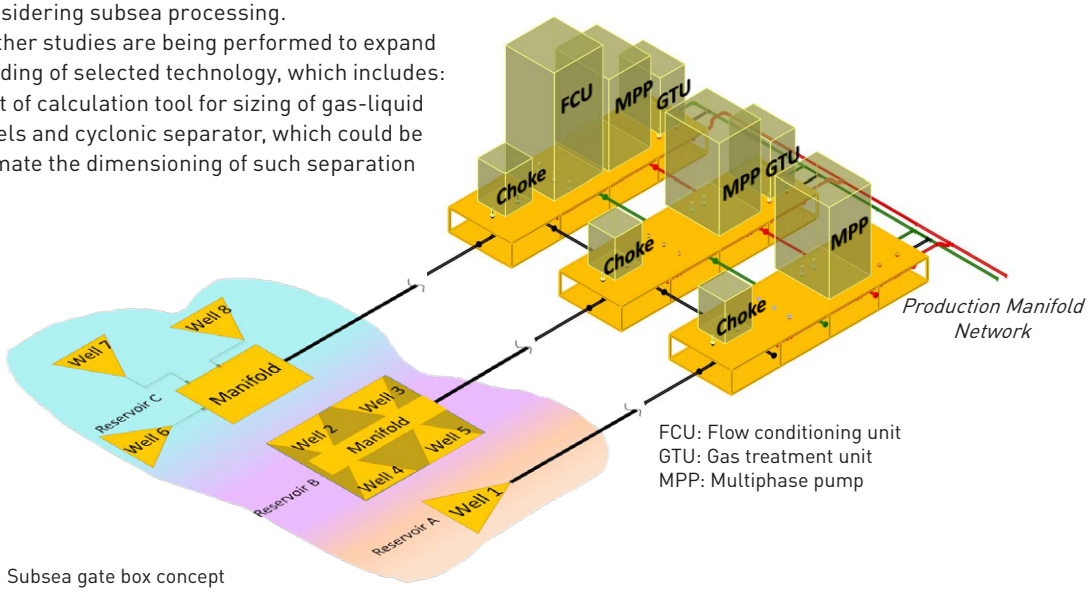
PROJECT MANAGER:
PROFESSOR SIGBJØRN SANGESLAND

CO-SUPERVISORS:
ASSOCIATE PROFESSOR MILAN STANKO
PROFESSOR EMERITUS MICHAEL GOLAN

The subsea gate box (SGB) 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. In standard field architectures, it is common to comingle the production streams of the individual wells into manifolds prior to its transport to topside for processing. This creates a strong interdependence of the flow rates and production pressures of the individual wells. Such strategy might lead to a sub-optimal use of the naturally available reservoir energy as the "weakest" well determines the maximum commingled flow rate. Some of the project results include:

- Performance evaluation. Simulations of a new integrated production model has demonstrated the possibility to increase production of a target well by more than 20% when comparing the SGB with a typical central boosting station.
- Technology evaluation. Technical information and development status of subsea processing solutions are summarised in a technical report. It is shown how recognized service providers have presented novel solutions such as the *PowerJump*, skid mounted electrical submerged pump (ESP) and the contra-rotating pump, which are in line with the subsea gate box concept. The technology report can be used as a support document in the concept screening process for evaluating and comparing available technology when considering subsea processing.
- Moreover, further studies are being performed to expand the understanding of selected technology, which includes:
  - Development of calculation tool for sizing of gas-liquid gravity vessels and cyclonic separator, which could be used to estimate the dimensioning of such separation modules.
  - CFD analysis of pipe-based separator for gas-liquid flow. The model will give the opportunity to estimate the performance of such separators and generate performance maps that could be used in production simulations.
- Preliminary conceptualisation. A preliminary proposal of the subsea gate box is illustrated below. The SGB is configured for different well configurations (satellite, clusters or template). Each module of the SGB will offer the opportunity to adapt the process train to the specific operating conditions of an individual well or group of wells over the lifetime of the field. Thus, a train could contain units for separation, liquid boosting and gas treatment, while another train could contain a multiphase booster only and leave some free slots for future needs. Furthermore, the trains could be interconnected to allow bypassing production from one train to other; this as a means to increase redundancy or increase operational flexibility during maintenance.

The trade-off between operational flexibility and the increased complexity is being analysed in terms of flexibility value, reliability and cost impact. CAPEX comparison and the value of the flexibility over the time is an ongoing activity and part of the future work of this project, while the reliability and availability analysis have been studied by the sub-project "Reliability and availability assessment in subsea design". Moreover, the SGB project will be included in a new research project oriented to optimise subsea field architecture in terms of the development life-cycle cost where the interdependencies of relevant cost factors will be modelled.



Subsea gate box concept

Field development concepts

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

PHD STUDENT: DIANA GONZALES

PROJECT MANAGER AND MAIN SUPERVISOR:
ASSOCIATE PROFESSOR MILAN STANKO

CO-SUPERVISORS:
PROFESSOR SIGBJØRN SANGESLAND
PROFESSOR EMERITUS MICHAEL GOLAN

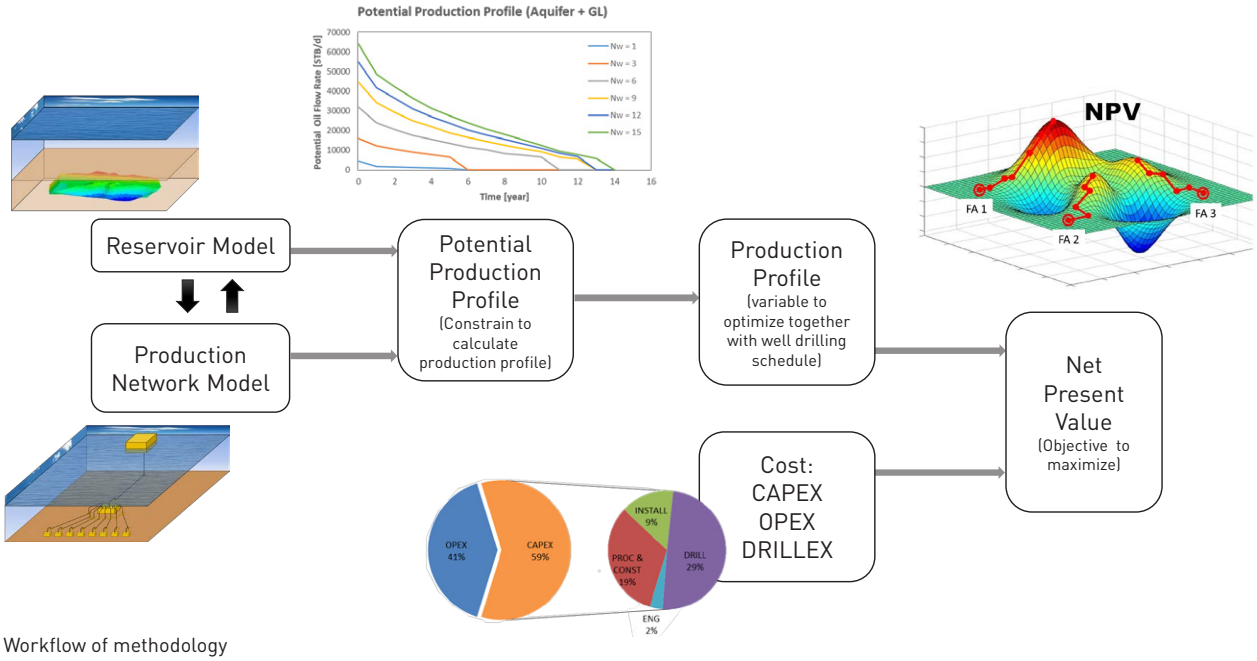
The objective of this project is to create better methods to determine and evaluate cost effective strategies to develop remote offshore oil reservoirs with low pressure and temperature. Additionally, some cost effective solutions were studied that allow wax-free subsea hydrocarbon transportation in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

The main objective of this project has been addressed by two activities. A first activity consists of developing an automated methodology based on mathematical optimization for decision support in field planning. The aim is to use optimization to find the best production strategy (production profile over the life of a field) and well drilling schedules that give maximum project profitability (net present value - NPV). Some development scenarios considered are: gas-lifted wells, water injection, multiphase boosting, production to platform, FPSO or tie-back. In the methodology, the production profile is constrained by the maximum production the system reservoir-network can physically deliver. The effect of uncertainties in the cost figures, oil price and reservoir characteristics is also considered.

Two Excel-based tools have been developed to perform this analysis that could potentially be customized for other cases or fields. Preliminary results seem to indicate that variations in the oil price and cost figures do not affect significantly the optimum production and drilling schedule computed.

The second activity consists of studying the influence of using coupled models (reservoir + network) in the field planning when computing the production profile instead of standalone reservoir models (traditional approach). Both approaches and their influence in the NPV are compared through an uncertainty analysis study. Preliminary results seem to indicate, for the particular case studied, that the NPV of the project can be significantly overpredicted if only the reservoir model is used to compute the production profile.

The results from this project could be useful to provide better decision support during early phases of the field design process where there is limited information available about the reservoir, and the uncertainty is high. The ultimate goal is to improve current field design practices by developing and testing automated methodologies and enable cost-effective production from remote, low pressure and temperature offshore oil fields.



Workflow of methodology for optimization of field design.

Multiphase booster models

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

PHD STUDENT: GILBERTO NUNEZ

MAIN SUPERVISOR:
PROF. SIGBJØRN SANGESLAND

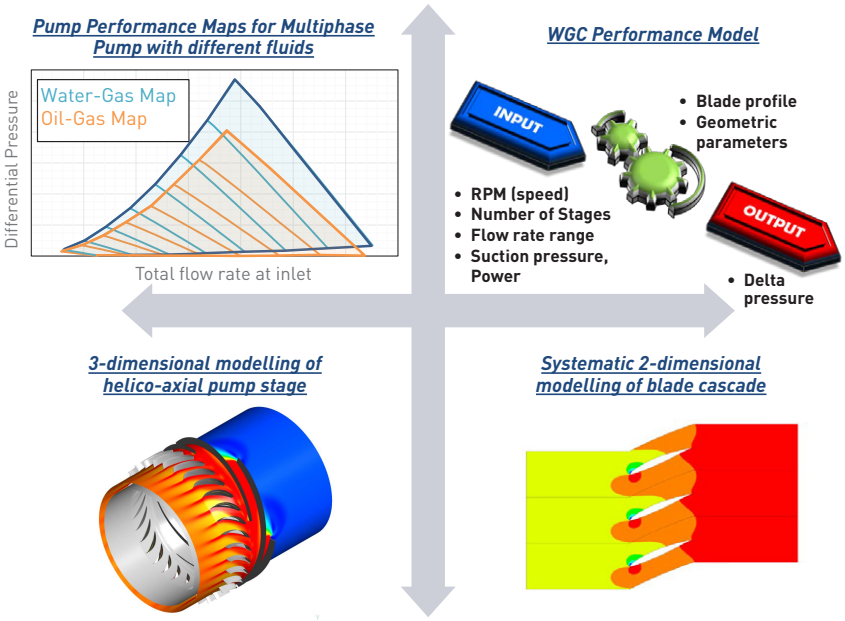
PROJECT MANAGER AND CO-SUPERVISOR:
POSTDOCTORAL FELLOW JESUS DE ANDRADE

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

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

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

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



Development of models for predicting booster performance.

Gilberto Nunez

AGE 34
FROM MARACAY, VENEZUELA

TAKING A PHD IN
FIELD ARCHITECTURE

‘An offer you can’t refuse’

That was what went through Gilberto Nunez’s mind when he was given an opportunity to take a PhD degree through SUBPRO.

Back home in Venezuela, he had a good job at a water purification company in Caracas. He also taught at the Simon Bolivar University, where he had taken both his bachelor’s and master’s degrees a few years back.

‘But then, in 2015, the opportunity arose to take a PhD through the SUBPRO project. It looked very attractive to me based on my academic background, and I applied. The interview took place via Skype, and here I am. After all, it was an offer I couldn’t refuse!’

He had visited Norway earlier on a trip to Trondheim and NTNU, which has an exchange agreement with the Simon Bolivar University in Caracas. He met Professor Curtis Whitson and Professor Michael Golan from NTNU in Caracas, when they were visiting the university. This resulted in a three-month exchange with NTNU in 2014 as a guest lecturer/researcher at the department he is now affiliated to as a PhD student.

‘I was very impressed by the fact that you can meet some of the best professors in the world here at NTNU, practically at the lunch table. This made me think that I had to come back here. So when SUBPRO came along, I applied, of course. Although I was in a good situation in Venezuela, it’s important to see how other people do things in this industry, which, after all, is so important to Venezuela.’

CHALLENGING SITUATION

Back in Venezuela, his mother and two brothers live in the cities of Maracay and Caracas.

The past five years, the situation in Venezuela has been very unstable, and many people struggle to find both food and work. Gilberto’s family is also affected.

‘But it’s probably worst in the capital. The food shortage is not as bad where my family lives, for example. And since I have a job in Norway, I can help them out with money, among other things. So in that respect, it’s OK to be here, although I think about them a lot. After all, we are very family-oriented in Venezuela, and when we get together, everyone comes along. The extended family includes cousins, aunts and uncles. I miss that sometimes.’

Trondheim has gradually come to be home to quite a few students from Venezuela, thanks to exchange agreements with the university in Caracas. ‘We support each other and are like a family here. We come from the same cultural background, and that’s important. We understand each other.’

A LOT AT STAKE

He has been home a few times since moving to Norway, but flying to Venezuela is expensive.

A lot is at stake for him now: he is submitting his doctoral thesis and he is also about to become a father!

‘I can’t move from Norway, you know.’ He smiles. His girlfriend Tatiana is pregnant, and the baby is due in autumn.

It was clear early on that Gilberto was to become an engineer.

‘I loved mathematics and mastered numbers already as a child. I loved learning new things. My father was an engineer, and when I realised that mechanical engineering can be used to solve so many problems with turbines, pump mechanisms and compressors, I was so excited. And you can do almost anything!’

UPS AND DOWNS

Now, his PhD is due. His time at SUBPRO has been characterised by both ups and downs, which is often the case in processes like this.

‘It has been different and more challenging than I thought, and quite an emotional time. Right now, I think that what I’m doing has potential, or at least that it’s not a waste of time. Apart from the thesis itself, it’s been very valuable to be part of SUBPRO. We are well taken care of, and the academic aspects are followed up. We have study groups and meetings with reference groups. They are an important part of learning and a chance to meet the industry. In the oil and gas industry, it’s important to have an idea what others are doing.’

What the future has in store after the PhD degree is difficult to say. First fatherhood, then the rest will follow.

‘But I enjoyed teaching in Venezuela, so an academic career is a possibility. It also depends on where we choose to live. It may be in Oslo because of my family there. But nothing is certain at this point.’

LANGUAGE AND FOOTBALL

What is certain, on the other hand, is that he will be battling with the Norwegian language twice a week, attending a course and submitting assignments.

‘You have so many sounds that all sound the same to me, and I struggle with that,’ he says, and has a go at pronouncing the letters e, æ, ø and å. ‘The grammar is not too difficult, though. Spanish is more demanding in that respect. Still, it takes time. Sometimes I think I’ve got the hang of it, and then I hear someone speaking in dialect and I’m completely at a loss,’ he says, laughing. But he is making progress.

‘Trondheim is a very likeable city,’ says Gilberto. ‘It’s safe here, the university is good, it’s close to nature, and, not least, I can ride my bicycle everywhere, all year round. It’s quite brilliant!’

Apart from studies and his girlfriend, football is one of his passions. NTNU’s company sports team now has a dedicated manager.

‘Well, my job is to make sure people come to practice and wash their uniforms. So calling me the manager might be a bit exaggerated! By the way, you wouldn’t happen to know a goalie, would you? We’re always on the lookout for goalies!’ The grin is back on his face.

RESEARCH AREA

Reliability, Availability, Maintenance and Safety

Cost efficient solutions without compromising safety and environment.

Subsea oil and gas industry often requires innovative solutions to make forecasted field developments economically feasible. At the same time, it is more important than ever to reduce environmental footprint and enhance safety. Some current initiatives rely on new design philosophies (e.g. transfer to all electric solutions and increased use of subsea boosting and separation). Innovative solutions sometimes also introduce new concepts for operation; including process control, safety, monitoring and maintenance planning. The research area of reliability, availability, maintenance, and safety (RAMS) is looking into solving challenges related to these aspects. Our contributions during the first three years of the center have been:

- Predictive and prognostic models for maintenance planning, utilizing the benefits from more digitalized solutions for data collection and analysis.
- Development and testing of new methods for identifying hazards in subsea control and safety systems
- New framework to make reliability evaluation of early design concepts more efficient

In 2017 we also started a new research activity where the focus is on optimizing the way subsea systems are monitored and digitalized, considering the cost-benefit and value of investments made at the design stage (e.g. instrumentation level) and during operation (e.g. use of regular inspections and testing).

In all of our activities, we have collaborated closely with the SUBPRO industry partners, particularly DNV-GL and Equinor, and the results have been shared with all partners in the project.

Professor Mary Ann Lundteigen
Research area manager

The Reliability, Availability, Maintenance and Safety team.
From 1 o'clock: Himanshu Srivastav, Yiliu Liu, Anne Barros, Yun Zhang, Mary Ann Lundteigen, HyungJu Kim, Juntao Zhang.

New safety and control philosophy for subsea systems

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

POSTDOCTORAL FELLOW:
HYUNGJU KIM

PROJECT MANAGER:
PROFESSOR MARY ANN LUNDTEIGEN

CO-SUPERVISOR:
ASSOCIATE PROFESSOR CHRISTIAN HOLDEN

WE NEED NEW SAFETY PHILOSOPHIES FOR SUBSEA SYSTEMS

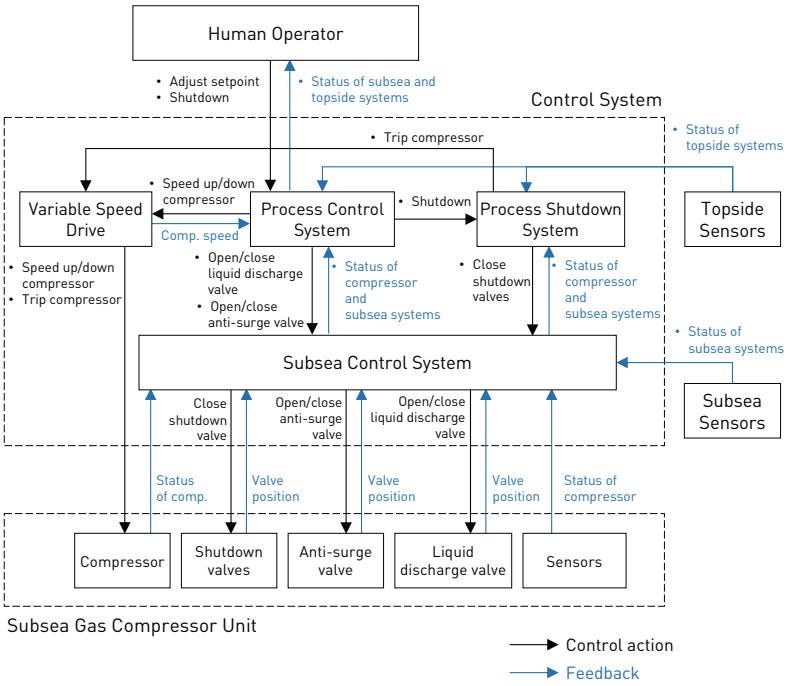
Today, the current philosophies for the design of subsea production and processing systems build on experience from topside systems. Unfortunately, it is not straightforward to apply the same philosophies for subsea systems, due to different technical design constraints, different operation conditions,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

A NEW ACCIDENT CAUSATION THEORY IS USED TO DEVELOP THE NEW SAFETY PHILOSOPHIES

We have applied the new Systems-Theoretic Accident Model and Process (STAMP) theory to subsea systems. The main idea of STAMP theory is that major accidents in today's complex, software-intensive, and sociotechnical systems are mainly caused by complex unintended interactions between the system components, rather than a single failure of physical component or chains of failure events. Systems-Theoretic Process Analysis (STPA) is a hazard identification technique that was developed based on the STAMP theory. STPA has already been adopted in many different sectors and domains, but has not yet been tested for subsea processing systems. We have conducted two case studies that applied STPA to subsea systems (subsea gas compression system and isolation of subsea wells). The conclusion of these studies is that the STPA method is well suited for the analyses of subsea systems in principle, but a couple of challenges were identified when applying STPA to subsea systems. We will focus on these challenges and try to provide solutions this year.

WE CAN ALSO LEARN FROM OTHER INDUSTRIES

In 2018, we will also learn lessons from other industries. The conflict between outdated safety philosophies and novel technologies is not an issue just for subsea systems. In maritime industries, for instance, novel solutions that are beyond the regulations can be approved under the condition that the equivalent functionality and safety have been proved. This is called "Alternative Design", and this concept can be used to develop the new safety philosophies of subsea systems. Similar issues in other industries will be investigated this year.



Hazard identification for a Subsea Gas Compression System by use of Systems-Theoretic Process Analysis (STPA).

A NEW ASSOCIATED PROJECT

Safety 4.0 – Demonstrating safety of novel subsea technologies

TORE MYHRVOLD, DNV GL
PROJECT MANAGER

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". The new joint-industry research project is headed by DNV GL and involves NTNU, University of Stavanger, and eight industry partners, of which four are current members of SUBPRO. The project will be funded by the Petromaks 2 program and the partners. The R&D project has been awarded by the Research Council of Norway and it is expected that the contract between the consortium partners will be signed in the second quarter of 2018.

The Petroleum Safety Authority will take the important role as observer throughout the whole project.

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

The main outcome of the project is a new framework to support demonstration of safety for novel subsea technologies. Elements of the new framework will be tested throughout the project period using 3-4 use cases from the industry, and the intermediate results are expected to be of direct support to the partners decision-making and concept selection.

A PhD (at NTNU) and a postdoc position (at UiS) will also be funded by the project.

Reliability and availability assessment in subsea system design

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

PHD STUDENT: JUNTAO ZHANG

PROJECT MANAGER AND
MAIN SUPERVISOR:
PROFESSOR MARY ANN LUNDTEIGEN

CO-SUPERVISOR:
ASSOCIATE PROFESSOR YILIU LIU

WHY THIS PROJECT:
New technologies and concepts introduced to subsea environment must be properly evaluated at an early stage. Reliability and availability are two important aspects of such evaluations, expressing the level of confidence to the system performance in its future operating environment. Most manufacturers include reliability and availability analyses in their qualification programs for new products. Unfortunately, existing methods/models are not well suited for handling complexity issues of subsea operation, in form of interaction of subsea functions, their proneness to external and internal exposures, and strategies to operate with optimum efficiency in a long run subsea operation.

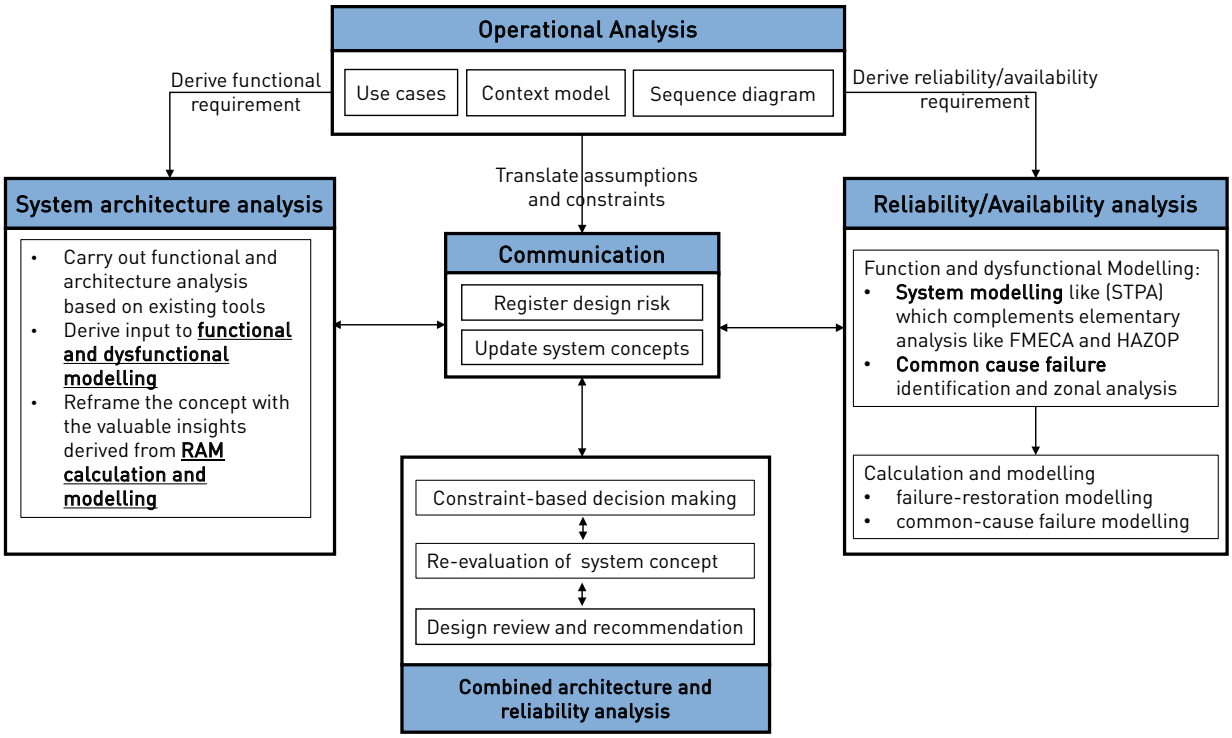
WHAT ARE WE DOING:
The focus of this project is to propose a new framework for conducting reliability and availability analysis in a systematic manner, which is capable of addressing complexity issues as stated above.

The first contribution to this framework is a conceptual procedure to obtain a close interaction between a system architecture analysis elaborated in the system design process and the existing techniques of reliability engineering. With our proposal, reliability and availability analysis (e.g. dysfunctional analysis, common case failure evaluation, dynamic simulation and modelling) will benefit from the analysis of system architecture (e.g. operational, functional and physical analysis) under the responsibility of design teams (with multiple disciplines including chemical, mechanical and electronic engineering). The application of this proposal has been demonstrated with a design case provided by Equinor, i.e. subsea fiscal flow metering system.

The second contribution focuses on the detailed steps to integrate system thinking in the existing reliability analysis process. One emerging method named Systems Theoretical Process Analysis (STPA) is selected. This systematic approach is promising to uncover the

safety issues of software-intensive system, but not for reliability and availability problems. Therefore, in this project the focus is placed on exploring the necessary adaptations and extensions of STPA to actively support reliability and availability analysis. The work on this topic has an active collaboration with project "New philosophy for safety and control of subsea systems", in form of experience exchanged and joint publication. The results and some reflections are communicated with DNV-GL through internal seminars and workshops.

HOW COULD THE RESULTS BE USED:
The proposed method and framework is tested in SUBPRO, in close collaboration with the project "Subsea Gate Box" (SGB). The proposal is applied to derive some insights about reliability and availability challenges faced in the conceptual design of SGB. For example, the decisions made related to the redundancy level of isolation valves on SGB, maintenance needs and operating strategies, considering pump performance of SGB. The proposal can be implemented in existing industry practices. For example, to give new insights on reliability techniques adopted in technology qualification programs, e.g. DNV-RP-A203.



The framework of integrating systems engineering activities in a reliability analysis process and bridging this process with system architecture analysis.

Prognostics and condition based maintenance

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

PHD STUDENT: YUN ZHANG

PROJECT MANAGER AND
MAIN SUPERVISOR:
PROFESSOR ANNE BARROS

CO-SUPERVISOR:
ASSOCIATE PROFESSOR ANTOINE RAUZY

WHY THIS PROJECT

Subsea systems must be highly reliable for both environmental and economic reasons. Among available means to achieve improved reliability performance, maintenance is one of the solutions. However, maintenance cannot always compensate low availability. The risk and cost of maintenance including onshore testing, vessel costs, spare parts, personnel and production loss (due to planned shutdown), could be as prohibitively high as the production loss and risks induced by degradations and failures.

In order to find a balance between high reliability and low maintenance induced costs, maintenance activities need to be planned based on the holistic condition of the subsea system instead of on each unit independently.

To this end, quite a few issues need to be considered: For instance, the degradation of each components in the system, the integration at the system level of the results obtained for parts and the computational complexity of calculation of relevant key process indicators. If such problem is well mastered for calendar- or time-based maintenance policies, it gets much harder for condition-based maintenance policies.

WHAT ARE WE DOING

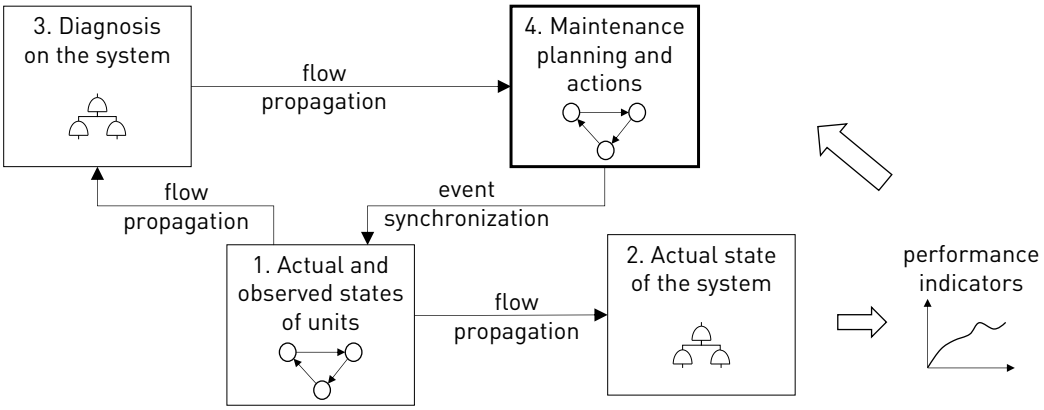
This project is thus producing models to assess and optimize the maintenance policies for subsea systems in the arising context of digitalization. Optimization concerns the design phase (e.g. the number and locations of spare units) and the operation phase (e.g. the number and the frequency of maintenance operations, the maintenance/reconfiguration decisions made during these operations given health indicators at hand).

The core research activity relies on a model-based assessment approach applied to subsea systems, which evolves two key phases: system model and assessment of the performance. There are joint use of i) stochastic processes as a basis for degradation modelling and ii) high level language modelling AltaRica 3.0 for system modelling, calculation and decision making.

HOW COULD THE RESULTS BE USED

We provide a generic modelling framework (see illustration) together with a series of basic patterns, which are adaptable to the developing knowledge of subsea systems. This can be used to select maintenance policy, and to hit an optimum distribution between preventive, corrective and condition based maintenance schedules allocated to specific types of equipment and degradation mechanisms and types of failure.

It can also be used to support operational decisions regarding maintenance planning and execution in the operations phase.



Architecture of model for optimizing maintenance policies for subsea systems
Currently, a set of system models are ready for High-integrity Pressure Protection Systems (HIPPS) (downtime assessment) and a gas compressor (production assessment).

Optimizing condition monitoring

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

PHD STUDENT: HIMANSHU SRIVASTAV

PROJECT MANAGER AND
MAIN SUPERVISOR:
PROFESSOR ANNE BARROS

WHY THIS PROJECT

Condition based maintenance is a 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, that is to say on inspection and condition monitoring. Currently, there is a lack of knowledge and methods for optimizing monitoring schedules and efficient use of available condition data in subsea systems.

WHAT WE ARE DOING

The research questions we propose to address are:

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

In the initial phase the project has focused on a case study of Safety Instrumented Systems (SIS) in low demand mode. Such systems are submitted to periodic inspections (proof testing), that can degrade the condition of system components (a mild type of destructive testing). The goal for the case study is to find the optimum testing frequency, which balances the added value of frequent testing versus the negative effect on wear caused by the testing.

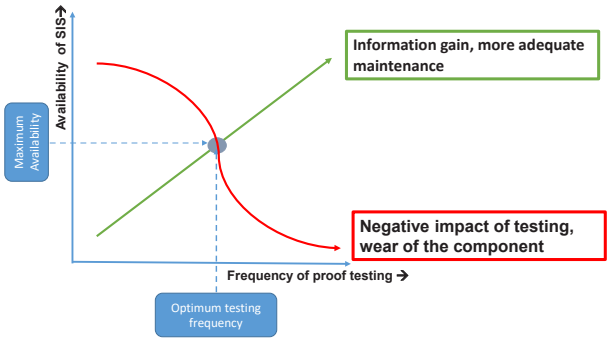
HOW THE RESULTS COULD BE USED

The result of the case study on Safety Instrumented Systems (SIS) can be used to optimize testing strategies for safety critical systems.

Further work will focus on prediction models and tools that integrate different levels and quality of monitoring information. This can be used to optimise systems for instrumentation, data collection and analysis/prediction.

EMERGENCY SHUTOFF VALVE

A typical example of a Safety Instrumented System: An emergency shutoff valve.



Trade-off between added condition information and increased wear, as a function of proof testing frequency.

Yun Zhang

AGE 29
FROM SHANGHAI, CHINA

TAKING A PHD IN RELIABILITY, AVAILABILITY, MAINTENANCE AND SAFETY (RAMS)

From the metropolis of Shanghai to little Trondheim

With a special ability to challenge herself and an 'I can do better' attitude, Yun Zhang arrived in Norway as a master's degree student. She is now in the final stages of her PhD degree.

'But I never imagined I'd be sitting here,' she says, looking around her office. The temperature outside is almost minus 20 degrees, and you would be hard pressed to find a stronger contrast to Shanghai's warm and humid climate.

'It was my own choice to take higher education and go abroad for my master's degree. Neither of my parents have an academic education. My mother is an accountant and my father is a driver. So I didn't inherit my academic interests from them.'

DREAMT OF BECOMING AN ARTIST

At the age of five she picked up the interest for drawing. In upper secondary school in Shanghai, she learnt to play the piano and doing art. 'I dreamt of becoming an artist or musician. I never thought I would go to Norway or take a PhD.' So, what happened?

Her eyes widen: 'I'm not sure, but I'm very conscientious about everything I do. And in upper secondary school, I discovered that I was good at engineering subjects, so I thought that this was a talent I should pursue.' She therefore continued to the university in Shanghai and a three-year bachelor's degree.

Her initial plan was to become a textile engineer, but she switched to mechanical engineering after a year.

'I found textile engineering a bit too easy. I wanted to challenge myself, which meant I had to have another goal to reach for. That's why I switched.' And Yun's ability to challenge herself and avoid the easiest solutions eventually took her all the way to Norway.

NOT AN EASILY MADE CHOICE

She was accepted by many top universities around the world, and the choice was not easy. But finally she chose Norway and Trondheim. 'NTNU is very invested in creating the best technological solutions for the future. That triggered me to apply here.'

There is a yoga mat in the corner. Her office chair is covered by a flowery blue fabric. Orchids decorate her desk and other green plants have been placed around on the shelves. 'The orchids are from my supervisors, while the others are from colleagues who ask me to take care of their plants when they leave the office for short trips, and I like plants'. She smiles.

NATURAL TRANSITION

In summer 2013, Yun arrived in Trondheim and embarked on a two-year master's degree in reliability engineering. After the two years, she made an almost seamless transition to the PhD level. 'I'm very happy about the things I learnt in the course of my master's degree studies. It gives me a basis for doing the PhD project.'

She has now started the final year of her doctorate. It is time to produce some results.

'In short, the objective of my project is to optimise maintenance procedures in relation to subsea systems, as the focus on digitalisation increases. Although subsea systems are built to be maintenance-free and flawless, we need framework and concept models to simulate system errors and behaviour. Through my research, I hope I can help to make smarter decisions about maintenance, based on condition monitoring. I think I have managed to attract the industry's attention with this project.'

Yun's parents were not too pleased to see their only daughter moving so far away, but after visiting Norway for three months last year, they were reassured. 'They can see that I am happy, and that I have a great working environment and nice colleagues.' says Yun. 'Living here is very comfortable and very peaceful compared to everyday life in Shanghai.'

LACK OF HIERARCHY

The working conditions and the way people socialise were perhaps what surprised her the most when she first came to Norway. Here, students, supervisors and professors socialise as friends.

'We can sit together in the canteen and talk about all sorts of things, not just work or studies. And my two supervisors have become almost like my Norwegian family. The academic staff spend lots of time on their students here, which is not that common in China. The professors there are in a whole other league. And there are much more master and PhD students per professor, so it's rather difficult to set aside much time for each student. Here, I also work with people from different countries and fields, and I'm really learning a lot from that.'

Do you think you will go back to Shanghai to live and work?

'I'm not sure. As for work, I'm keeping an open mind and considering all interesting opportunities. I have an expertise that will be important in the time ahead, and I can use it in either research or the industry. As for my way of life, I have become quite European. I live independently of my parents here. That's not common in China, where you live with your parents until you get married and start your own family. I appreciate the European way of life. Here, people become independent as quickly as possible and have faith in themselves. I'm learning to solve problems and face challenges alone – and I am proud of myself for doing that'.

'My plans for the summer are to finish my PhD thesis, and perhaps take a little drive up to Lofoten.' She will be taking her driving test soon. 'I hope I manage it!'

RESEARCH AREA

Separation - Fluid characterization

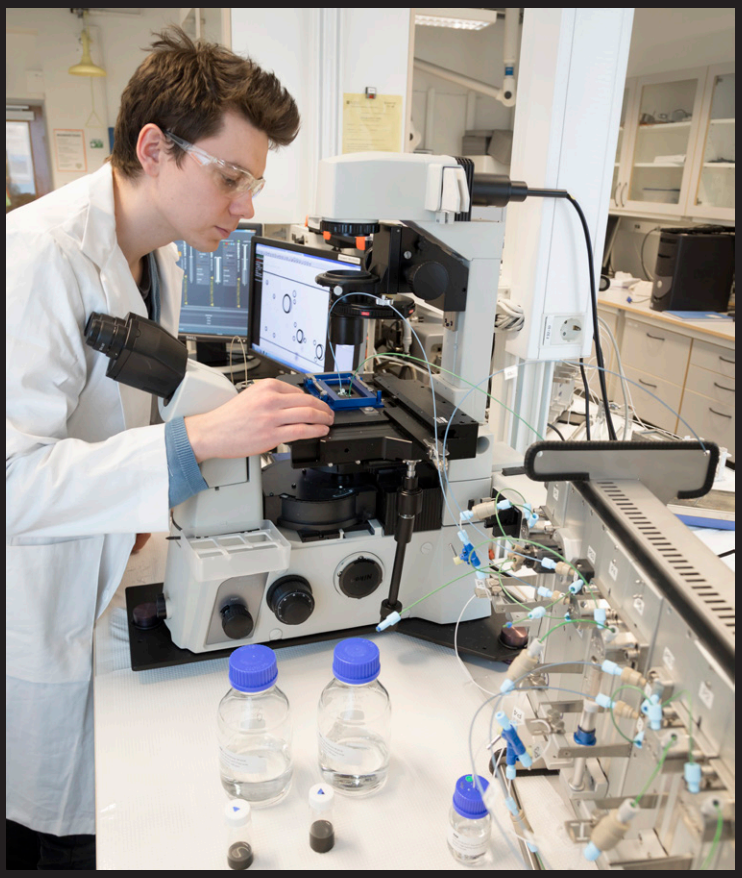
Enhancement of separation efficiency and flow assurance.

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. The following topics are currently focused on:

- Development of new methods for studying oil drop and gas bubble interactions at elevated temperature and pressure. This will facilitate design of subsea water treatment systems.
- Investigation of mechanisms that can inhibit wax formation.
- Investigation of the produced water quality at different separation stages. This will facilitate design of subsea separation systems and explore a sequential separation concept.
- Development of a new coalescence model roughly linked to the chemical composition of a crude oil.

Professor Johan Sjöblom
Research area manager

Professor Gisle Øye
Research area co-manager



PhD student Marcin Dudek engaged in a micro-fluidic experiment.

Produced water quality and injectivity

Development and application of microfluidic tools to study the fundamental aspects of produced water treatment processes in subsea conditions.

PHD STUDENT: MARCIN DUDEK

PROJECT MANAGER AND
MAIN SUPERVISOR:
PROFESSOR GISLE ØYE

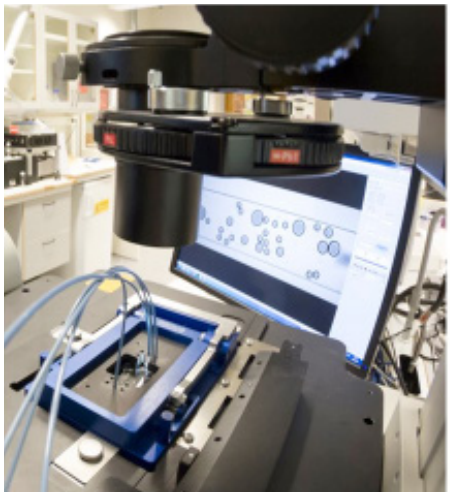
The increased production of water is often bottlenecking the offshore petroleum production process. Separation and treatment of the produced water closer to the well (i.e. on the seabed) can void the issue by reducing the volume of fluids pumped to the platform. Moreover, the separation of the produced fluids should be easier in the high pressure and temperature conditions. After treatment, the produced water can be re-injected back to the reservoir for pressure support and to increase the recovery of remaining hydrocarbons.

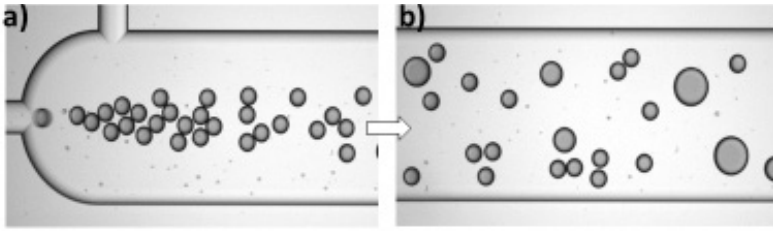
The efficiency of many produced water treatment processes can be traced down to very fundamental interactions between microscale particles. For instance, in a gravity separator, the rate of coalescence (merging of drops) and size of droplets will determine their rising velocity, while in a gas flotation unit the drop size will have an impact on the attachment to and successful removal by gas bubbles. Furthermore, the role of crude oil chemistry in these processes cannot be neglected. All this, together with the unknown effect of the subsea conditions, was the motivation for this project.

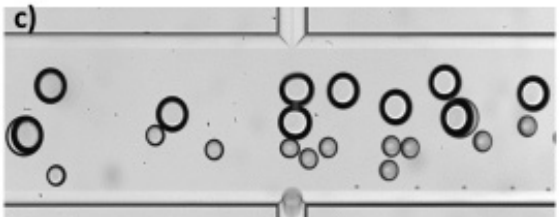
The newly developed microfluidic platform enables us to precisely control the flow of various fluids through microfluidic chips with small channels, and simulate the flow of dispersed oil droplets and gas bubbles in the water phase. All experiments are followed with a high-speed camera and later processed with image analysis tools. As a result, we are able to determine the effect of different parameters, such as water composition, droplet size or pressure, on the coalescence process and the interactions between gas bubbles and oil drops in water.

The microfluidic methodology, developed and used in this project, can give a more fundamental insight into the separation processes occurring during produced water treatment. With a better understanding of the role of crude oil chemistry and process conditions, the produced water can be treated more efficiently. This project will be followed by a postdoc project, which will focus on the influence of production chemicals on the treatment processes. In addition, the newly established microfluidic platform will be used in other projects related to produced water.

Left picture shows an experiment under progress: the chip holder, placed in the microscope, serves as an interface between a microfluidic chip and the rest of the setup.
Pictures a) and b) show the initial and final size distributions of oil droplets flowing in water, respectively.
Picture c) depicts a 'microfluidic gas flotation' experiment with smaller, darker crude oil droplets and bigger nitrogen bubbles.







Influence of Production and EOR Chemicals on Produced Water Quality

POSTDOCTORAL FELLOW:
MARCIN DUDEK
(FROM JUNE 2018)

PROJECT MANAGER:
PROFESSOR GISLE ØYE

During crude oil extraction, various production chemicals are added in order to mitigate or prevent certain process issues, such as wax deposition, asphaltene precipitation or scale formation. While the concentration of these chemicals in crude oil is relatively low, their influence on the separation processes, occurring in the later stage of crude oil processing and produced water treatment, is unknown. What is more, the fluids injected during the enhanced oil recovery (EOR) stages can also partly return, together with the produced crude oil and water. The EOR chemicals often consist of surfactants or polymers that aid in extracting oil trapped in the reservoir pores, but also negatively affect the separation of the dispersed oil from the produced water.

This project will utilize the newly developed microfluidic methodology from the project "Produced Water Quality and Injectivity", and apply it for studying the effect of the production chemicals on the fundamentals of the produced water treatment. Moreover, the project will focus on improving the screening abilities of the techniques, for instance through actively changing the concentration of given chemical in the oil phase or the pH of the water phase, inside the chip. In addition, based on the conversation with the industrial partners, new methodology that is relevant for the produced water research, can be proposed and investigated. As a result, it is expected that this subproject, building on the experience and work from the previous one, will deliver more precise information on the effect of production and EOR chemicals on the produced water treatment and contribute to a better understanding of underlying fundamental mechanisms, governing the separation processes in the crude oil production processes.

Wax crystallization and wax inhibition mechanisms

Improved characterization of inhibitor wax interactions may help development of better chemical additives.

PHD STUDENT: JOST RUWOLDT

PROJECT MANAGER AND MAIN SUPERVISOR:
PROFESSOR JOHAN SJÖBLOM

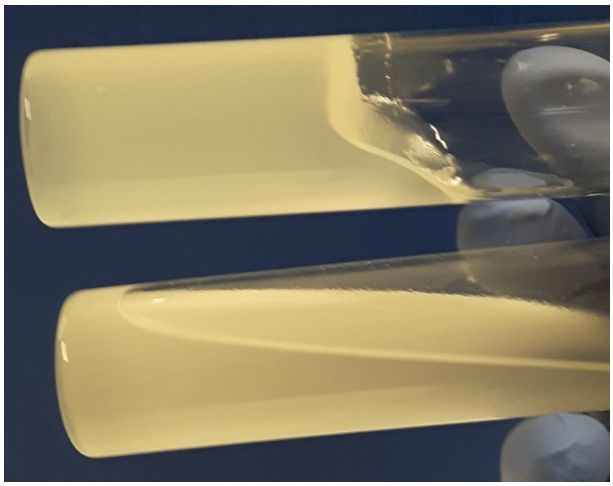
CO-SUPERVISORS:
PROFESSOR II HANS-JÖRG OSCHMANN
ASS. PROFESSOR KRISTOFFER GUNNAR PASO

Current trends in the oil and gas industry are to explore deeper and harsher environments, often involving transportation of crude oil at low temperatures on the sea floor. Challenges can emerge due to paraffin wax in the crude oil, as cold temperatures induce wax crystallization. This can further lead to decreased productivity, issues during pipeline restart, and even pipeline blockage. Wax prevention and remediation therefore plays an important role in flow assurance. Chemical additives such as polymeric wax inhibitors are most common in wax prevention. The inhibitor's action reduces the size and shape of occurring wax crystals. This keeps the oil's viscosity low and prevents gelling, even after a considerable amount of wax has crystallized. Much is known about the effect of wax inhibitors, however, the working mechanisms are still largely unknown. Inhibitor performance can vary a lot for different crude oils. Moreover, some crude oils show no response to wax inhibitors.

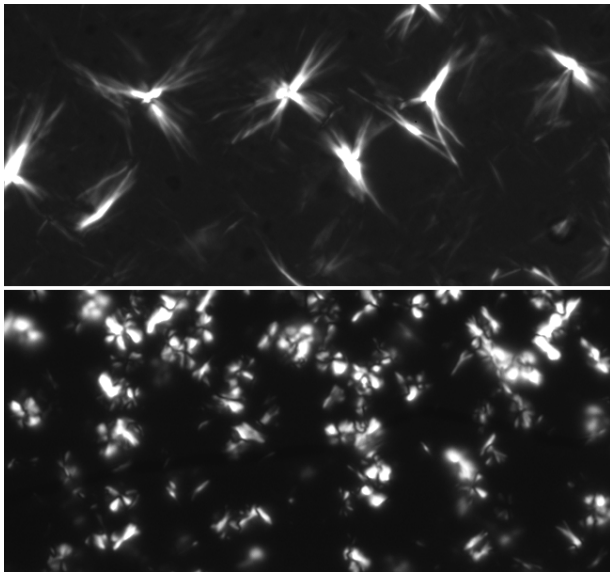
Activities in this project are therefore dedicated to improve both the understanding of wax crystallization, and the reaction mechanisms of wax inhibitors. The gained insights will help the management and prevention of wax related issues. Additionally, the development of better and more efficient wax inhibitors will be facilitated.

To achieve these goals, inhibitor wax interactions have been investigated via thermal, rheological, nuclear magnetic resonance, and microscopy techniques. New investigation techniques were introduced to the study of wax inhibitors, such as isothermal titration calorimetry. In addition to mitigating waxy gelation, inhibitors can also lower the temperature at which wax crystallizes. Still, interactions with crystalline wax were found to be 150 times stronger than interactions with dissolved wax. The dominant mechanism is therefore co crystallization of inhibitor on wax crystals. This process is influenced by various parameters, which include the inhibitor's molecular weight and abundance of functional groups, but also inhibitor concentration, and natural crude oil constituents. Moreover, work on improving predictive methods for wax crystallization and waxy gelation is done.

The research results from this project can facilitate improvements in flow assurance. These can make crude oil production more efficient and reliable – all at potentially reduced costs.



Model waxy oil without wax inhibitor (top) and with wax inhibitor (bottom).



Cross polarized microscopy showing the effect of the inhibitor on crystal structure: Large wax crystals (top) are changed to more round and compact structures (bottom). As a result, the inhibitor depresses waxy gelation and the fluid remains free flowing.

Sequential Separation

Study of crude oil resins for predictability of separation efficiency and produced water quality in subsea processing facilities.

PHD STUDENT: ARE BERTHEUSSEN

PROJECT MANAGER AND MAIN SUPERVISOR: PROFESSOR JOHAN SJÖBLOM

CO-SUPERVISOR: DR. SÉBASTIEN SIMON

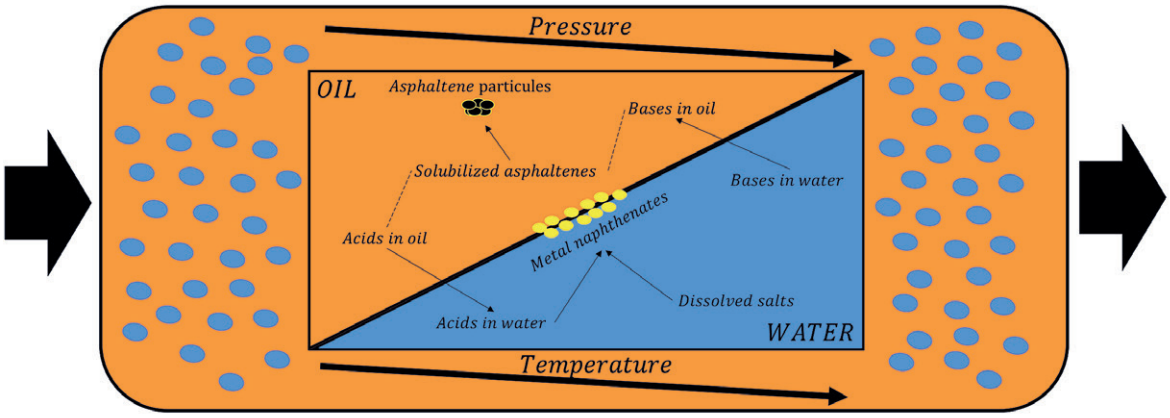
Water is co-produced with crude oil from the reservoir. Crude oils contain different amounts of resins (organic acids and bases) which distribute themselves between the oil and water phase. Resins dissolved in the water phase affect the efficiency of the separation process through stabilizing oil and water continuous emulsions, it may clog process equipment through formation of metal naphthenates or soaps and alter injection water properties adversely.

The project is studying such mechanisms and characteristics of resins in the water phase for various system conditions.

Current subsea oil-water separators installed at fields like Marlim (Petrobras), Troll and Tordis (Equinor) are designed to produce water which meets injection criteria, at the expense of a high water-cut in the oil outlet. As with topside operations, attaining the pure oil and water subsea, as envisioned in the subsea factory, can be achieved through additional separation or better separation concepts. Accessibility dictates robust subsea separation solutions capable of handling increasing water production over the field's life time. Resins dissolved in the water phase affect the stability of both dispersed water droplets in the oil phase and dispersed oil droplets in the water phase, which in turn affects the separation. This research is focused on predicting the content and characteristics of those crude oil resins, namely naphthenic acids and bases, as they distribute themselves between the oil and water phases in the separator based on inlet conditions, like pressure, temperature and water cut. Knowledge of the content of dissolved naphthenic acids in produced injection water is also of interest as it has been shown that these acids lower the interfacial tension of oil drops in the water and cause pore blockage in the reservoir through precipitation. Experimental setups involve oil-water systems with representable resin concentrations and variation of parameters like pH and the presence of asphaltenes or calcium salts. To get an overview of how acids and bases of different molecular size would distribute themselves, we started studying the behavior of single acids and bases. Then a method to analyze the content and characteristics of complex crude oil acid mixtures, which contains thousands of unique molecules, was developed. The aim was to measure and model the phase distribution of the whole acid mixture, and molecular mass ranges within the acid mixture.

Results show that crude oil acids are far more water soluble than crude oil bases. Acid molecular mass ranges in different crude oil acid mixtures produce similar results, which means that the obtained results can be applied to other crude oils. In collaboration with the project "Produced water quality and injectivity" it has been shown that dissolved resins in water affects crude oil droplets, by either increasing or decreasing the droplet stability drastically for different crude oils, affecting the separation efficiency. We have also pushed new boundaries in dissipative particle dynamics (DPD) simulation in a collaboration with IFE, where results from laboratory experiments can now be reproduced with computer simulations.

The project results could be applied to anticipate water separation efficiency, evaluate the compatibility of injection water with the reservoir and predict compatibility with stricter regulations for water discharge to the sea. The results could be especially relevant for aging fields with reduced pressure and consequently higher pH, where subsea water separation would give high rewards.



Schematic of the transfer of acids and bases between the oil phase and the water phase.

- The pressure drop in the well stream from the reservoir through the well and subsea process equipment releases dissolved acidic gas from the water phase. The consequent rise in water phase pH induces a transfer of acids from the oil phase to the water phase.
- Asphaltenes are solubilized by acids and bases in the oil phase.
- Dissolved salt in the water phase reacts with crude oil acids to form metal naphthenates or soaps at the oil-water interface, which may impair the separation of the two phases.

Modelling of coalescence

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

POSTDOCTORAL FELLOW:
ALEKSANDAR YORDANOV

PROJECT MANAGER AND MAIN SUPERVISOR:
ASSOCIATE PROFESSOR BRIAN A. GRIMES

In order to best utilize the capacity of the subsea equipment such as pumps and compressors, subsea separation of well fluids will become necessary. The challenges involved in subsea fluid separation will require the development of new models for design, monitoring, and control of subsea separators. Although, liquid-liquid separation is driven by droplet buoyancy, this process can be sped up with coalescence (merging of smaller droplets forming larger droplets). However, coalescence can be difficult for hydrocarbon fluids depending on the composition of the crude oil (e.g., high asphaltene content). Thus, a model for coalescence times of liquid drops specifically tailored to petroemulsions and the crude oil composition will be critical to provide accurate calculations in subsea separation engineering such as model based control and monitoring of produced water quality.

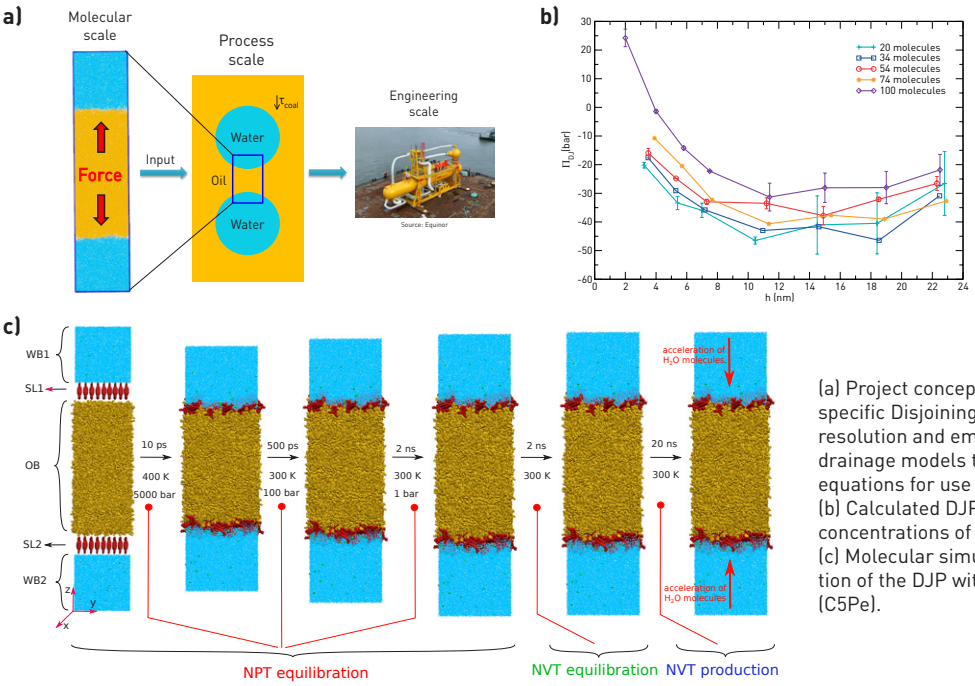
The main objective of the project is to obtain a new expression for the coalescence time (time for two droplets to merge) that includes a basic link to crude oil chemistry. Coalescence time in general is an important equation in both simple and complex separation and transport models. Therefore, there is a need to search for an improved approximation of the coalescence time tailored to crude oil emulsions. The exact chemical composition of crude oil is not known, but it can be represented by different crude oil fractions – Saturates, Aromatics, Resins and Asphaltenes (SARA). In our model, we are taking into account this SARA composition of real crude oils in order to obtain a new expression of the coalescence time.

DEVELOPMENTS DONE IN THE PROJECT

- Molecular dynamics formulation of a crude oil based on SARA composition
- A novel non-equilibrium molecular dynamics methodology for the calculation of disjoining pressure in liquid-liquid systems
- Calculation of the disjoining pressure from Molecular Dynamics simulations as a function of an asphaltene model compound and film thickness for water-in-oil systems
- Fitting of the disjoining pressure isotherms to an analytical function

POTENTIAL APPLICATION OF THE RESULTS

- Application of the disjoining pressure into a film drainage model for the calculation of the coalescence time in water-in-oil emulsions. Using the disjoining pressure from the Modular Dynamics simulations into the film drainage model is an improved way to account for the chemical composition and the asphaltene concentration at the interface. Therefore, a more accurate approximation of the coalescence time should be expected.



(a) Project concept to calculate surfactant specific Disjoining Pressure (DJP) at molecular resolution and employ the DJP curves in film drainage models to generate coalescence time equations for use in engineering models.
(b) Calculated DJP curves for different interfacial concentrations of asphaltene molecules.
(c) Molecular simulation protocol for the calculation of the DJP with model asphaltene molecules (C5Pe).

A logical choice

When Jost Ruwoldt is down by the harbour in Trondheim, hearing the seagulls cry, smelling the salty sea air and seeing boat sails waving in the wind, he is reminded of the harbour in his home town of Hamburg. He's not home sick, though!

'If you think it rains a lot in Trondheim, you haven't been to Hamburg. Every time I've been away for a while and get off the plane, it's raining. From that perspective, Trondheim is a dry city,' he says and chuckles.

His father loves sailing, which is why Jost is so fond of the sea. 'I've been sailing with him many times. The nice thing about Trondheim is its proximity to the sea. I can walk from work at university through the city centre, and I'm practically stumbling in to the water. I like the fact that the city is so small with short distances. It's very different from Hamburg.'

Hamburg is the second biggest city in Germany and it is a port like Trondheim. It is quite a prosperous city compared to other cities in Germany, and is situated in the heart of the EU. He grew up in the city, and after upper secondary school, he started technical college.

ALWAYS KNEW

As a child, Jost found out at an early age that he was good with numbers and could build things. 'I remember building little wooden boats when I visited my grandparents as a child.' So it comes as no surprise that he has helped to build the lab rig that he uses for his experiments.

He decided early on that he wanted to go to university. 'It was logical. I was good at maths and wanted to pursue that interest.' The combination of his mother being a teacher and his father an electrician meant that he brought with him a good dose of both academia and craftsmanship. He started studying General Engineering Science at the University of Hamburg in 2009. In 2013, he started his master's degree and graduated in 2015.

And then, you thought: What now?

'No, not really. I'd known I wanted to take a PhD ever since I took my bachelor's degree, so the question was rather, where? As a young man without any obligations, I sent applications to institutions across the whole of Europe and the people in Trondheim seemed to like me. I applied for a position at SUBPRO and got it.'

'They said: come and do something about wax in crude oil. And I did!'

WHY DOES IT WORK?

Crude oil contains wax crystals. The wax crystals form when the crude oil is cooled during transport. It is the same way as a candle forms when the liquid candle wax has cooled enough. With crude oil, however, the wax may plug the pipes that transport the oil to the platform.

'There are already many solutions to this problem. The industry has been using this for more than 20 years. What I'm trying to understand even better is how chemical additives work. Because many of them work well, but we don't know enough yet about just why they work and whether it matters what kind we use, for example. I'm trying to study the mechanics in methods intended to prevent wax formation.'

And how many eureka moments have you had in this project?

Jost laughs. 'Research can be very up and down. Sometimes, you have an eureka moment, while other times, you don't get any results whatsoever. How many I've had it's hard to count, but I guess I've had a few. I normally shout down the corridor when I've discovered something new.'

He also likes to be a part of a larger project.

'Being part of SUBPRO is awesome and I'm really happy to be here. It's well organised and you are in contact with other people and learn a lot about other subjects. Knowledge sharing is a key aspect here. And the fact that the industry is in on it makes it even more inspiring and motivating.'

JUMPED INTO IT

What did you know about Norway when you first came?

'Well, what did I know about Norway?' Jost stops and thinks. 'In Germany, Scandinavia is quite hot at the moment. Many people come here to see the landscape, the winter, the northern lights and the midnight sun. I didn't really know anything. It was a bit like jumping into the cold water, as we say in Germany when we don't really know what we're getting into.'

He knows now, however, and likes what he sees and does.

LANGUAGE TRAINING

He'll probably be in Norway a while, though. It is hard to move when he lives with his Norwegian girlfriend. 'She probably wants to stay here. We feel that Norwegian and German cultures are not that different, and that probably helped me feel at home here quite quickly.'

In his spare time, he likes to go to concerts and is a great fan of Norwegian black metal music. He thanks metal music for the fact that he speaks Norwegian so well and has many Norwegian friends.

'English is the main language at the university since there are so many different nationalities in one place, and I don't meet that many locals here. But when you go to a concert, it's a different matter. I've also made it a rule that I always speak Norwegian when I meet my Norwegian friends at gigs or out in the town. Always. Otherwise I would never have managed to learn Norwegian. And, I've been warmly welcomed, which I really appreciate'.

SOON FINISHED – AND THEN WHAT?

Now, it's nearly all about getting his PhD finished. 'I did some research before I started about how to do a PhD. The advice I found was try not to reinvent the wheel, but to make things better than they are now. I suppose I've discovered some new things that I'm going to publish. But what I'm basically doing is improving solutions that are already in operation.'

And since Jost has had clear plans so far, he probably has a plan for what comes next?

'Well,' he hesitates. 'This is actually the first time I haven't. I don't know whether I want to continue with research or work in the industry. That feels a bit strange.'

Jost Ruwoldt

AGE 28
FROM HAMBURG, GERMANY

TAKING A PHD IN SEPARATION
– FLUID CHARACTERISATION

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.

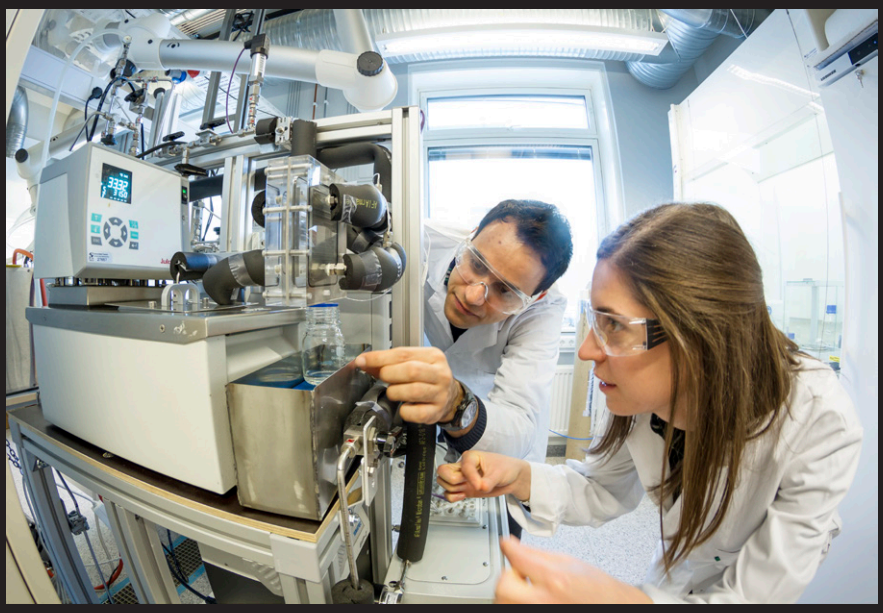
The second case could be a completely subsea based field where the hydrocarbons are exported directly into a seabed pipeline or subsea storage facility. This is an alternative for extremely deep waters or harsh conditions (for instance in the Barents sea).

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. In the first four years of SFI SUBPRO, the focus is on following concepts:

- Membrane gas dehydration process
- Combined H_2S and hydrate control for gas transportation and export
- Compact subsea separation concepts (liquid-liquid separation)

Fluid particle breakage, which is a factor influencing phase separation process efficiency, is being studied through fundamental modelling and experimental investigations.

Prof. Hugo Atle Jakobsen
Research area manager



PhD students Mahdi Ahmadi and Eirini Skylogianni working with the membrane thermopervaporation setup for gas dehydration testing.

Membranes for gas dehydration

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

PHD STUDENT: KRISTIN DALANE

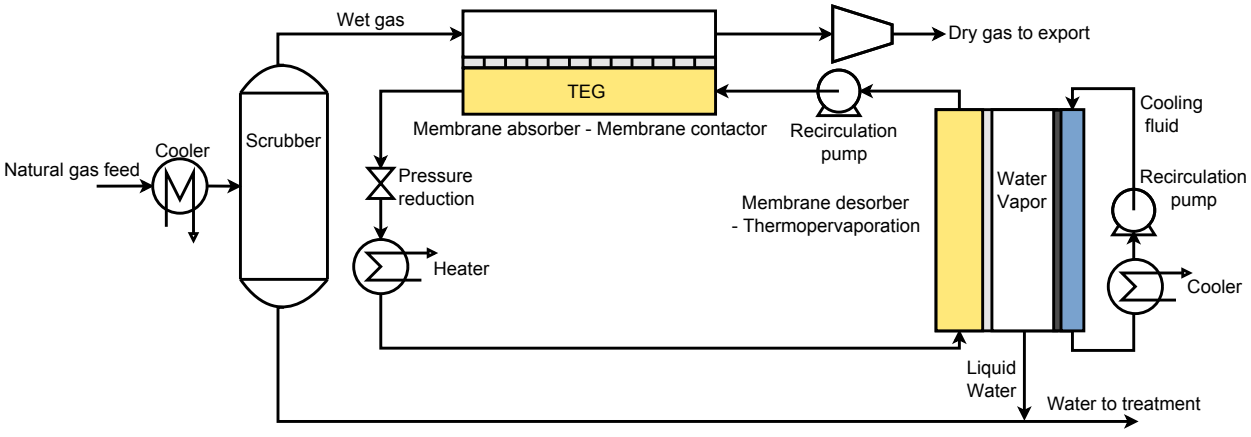
PROJECT MANAGER AND MAIN SUPERVISOR: ASSOCIATED PROFESSOR LIYUAN DENG

CO-SUPERVISOR: PROFESSOR MAGNE HILLESTAD

The main objective for this project is to evaluate the feasibility of a new membrane process design for subsea natural gas dehydration (see the illustration) through modelling and simulation. The goal for the dehydration process is to provide dry natural gas which meets the pipeline specifications for water content (-18°C at 70 bara), and simultaneously prevent transport challenges caused by water (e.g. hydrate formation, corrosion and erosion). Conventional dehydration technologies are considered unfeasible for application subsea due to the process equipment complexity. Membrane processes meet the subsea requirements with high modularity, flexible operation and compact design, which make them interesting for subsea operation. Subsea dehydration with direct export of the gas in export pipelines will enable tie-in of new fields to existing platforms with limited gas processing capacity, as no further topside treatment is needed. With acceptable water levels in downstream pipelines, there is no need for other mitigation techniques such as continuously injection of prevention chemicals like mono-ethylene glycol (MEG) or methanol. In addition, dehydration in an earlier processing stage will reduce the cost and complexity of the downstream equipment.

In order to predict the performance of membrane separator solutions, mathematical models of the absorber (membrane contactor) and desorber (thermopervaporation) membrane modules have been developed and validated against experimental results. The membrane contactor model predicts the amount of water removed from the natural gas within a mean absolute error of 3-7% compared to high-pressure experimental data. The developed models are implemented into the simulation software Aspen HYSYS for an overall process design evaluation and optimization of the dehydration process. The effect of the membrane parameters and operation conditions will be evaluated to find the optimum operation conditions for the system and evaluate the feasibility.

The first simulation results shows that the membrane contactor, under given operation and module parameters, is able to dehydrate 25 MSm^3/d of natural gas to the required specifications, with approximately 164 membrane units of 1 m length and 30 cm diameter. The first results from the thermopervaporation model indicates that several stages of the regeneration with inter-heating will probably be required to achieve the high purity of the TEG feed to the membrane contactor. Further experimental work will be required to better validate the model, improvements of process design and optimization.



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

Membrane testing for gas dehydration

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

PHD STUDENT: MAHDI AHMADI

PROJECT MANAGER AND MAIN SUPERVISOR:
ASSOCIATED PROFESSOR LIYUAN DENG

CO-SUPERVISOR:
POSTDOCTORAL FELLOW LUCA ANSALONI

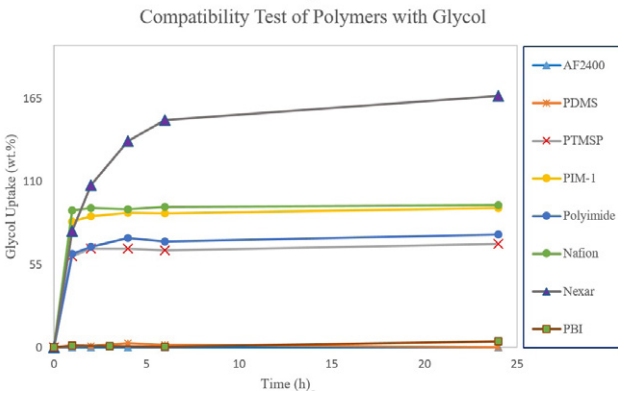
The goal of this project is to test membranes for natural gas dehydration. The project is an experimental follow up of the modeling work in the project "Membranes for gas dehydration". A closed loop process was designed to dehydrate natural gas using glycols as solvent, including a membrane absorption unit to absorb water from natural gas and a thermopervaporation unit for the glycol regeneration. A liquid mixture of glycol and water at a higher temperature (ranging from 30 to 90°C) flows through the upstream side of the membrane, where the water evaporates and passes through the membrane. The water vapor is then condensed in the air gap by contact with a cooling plate at a lower temperature similar to that of the subsea sea water (down to 4°C).

Assessment of different membrane materials with respect to the compatibility with the solvent and natural gas as well as the membrane separation performance is the primary stage in the evaluation. Most instruments and facilities are available for the tasks, while as thermopervaporation for glycol dehydration is a novel method, a new setup and a thermopervaporation module for glycol regeneration has been designed and built in house (see figure).

Compatibility of the membrane materials with glycol together with their long-term chemical and mechanical stability are of critical importance for subsea application. Membrane material should also be stable and compatible with all components available in natural gas at high pressure and operating temperature. In addition to compatibility and stability, a highly selective and permeable membrane is required in order to reduce the capital and operating costs. The diagram below shows some preliminary results of the compatibility between different membrane polymers with glycol. The tests on membrane performances are on-going.

The performance of the thermopervaporation process depends on operating parameters, including temperature and composition of the feed, temperature of the cooling water, thermal resistance of the condensation plate and membrane, air gap thickness, flow rates of the feed and cooling water, and the geometry of the membrane module. In order to optimize the aforementioned parameters for a specific membrane material and improve the performance, more experiments will be performed in the next stage.

Thermopervaporation test rig for glycol regeneration.



Compatibility test of different membrane polymers with glycol.

H_2S and hydrate control

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

PHD STUDENT: EIRINI SKYLOGIANNI

PROJECT MANAGER AND MAIN SUPERVISOR:
ASSOCIATE PROFESSOR HANNA K. KNUUTILA

CO-SUPERVISOR:
PROFESSOR EMERITUS HALLVARD SVENDSEN

Produced gas delivered to export pipelines must comply with quality requirements related to content of water, carbon dioxide (CO_2), hydrogen sulfide (H_2S) and heavy hydrocarbons. Today on a typical top side platform, water is removed by triethylene glycol, while acid gases are removed by amine processes. In addition to these, monoethylene glycol is used for hydrate control in the well flowlines, giving in total three different chemical systems. Simplifying the chemical systems and moving processing equipment to subsea could ensure higher energy efficiency and better utilization of resources.

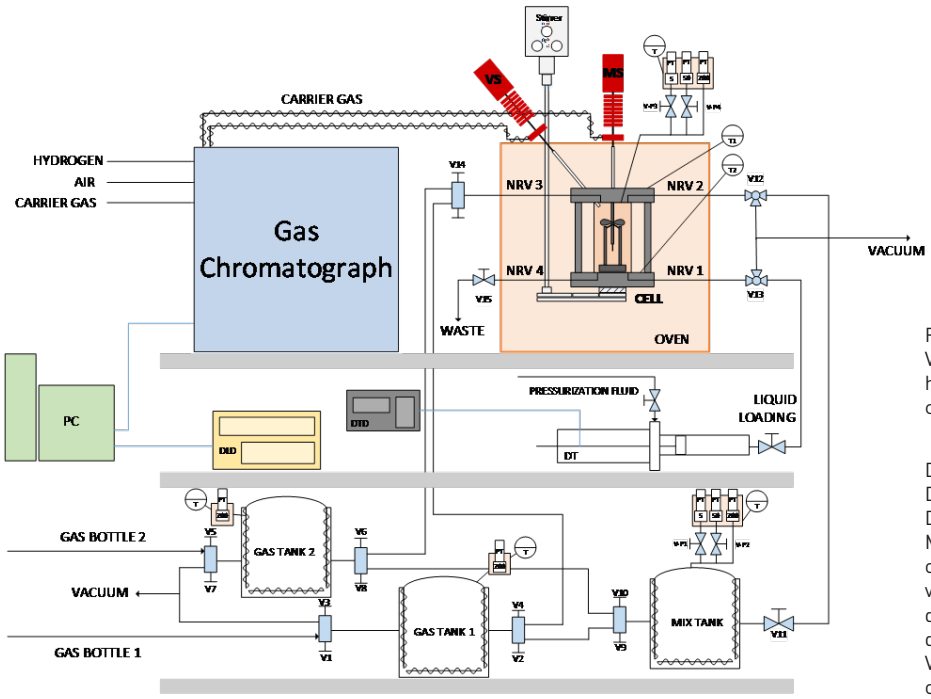
The objective of this project is to develop a regenerative process whereby both hydrate formation is controlled and H_2S is removed subsea. A combination of a glycol and an amine seems a promising chemical for this process. Since it would be a regenerative process, significantly higher concentrations of H_2S could be treated than what is normally the case today.

In order to design, develop and optimize a gas treatment process, knowledge of the thermodynamic behavior of the system is necessary. Models for the prediction of the system behavior are commonly used by the industry for design and simulation of a process plant, however the available models today cannot predict accurately the behavior of the combined system we propose, due to lack of experimental data.

In this direction, research collaboration with the School of Mines ParisTech in France, and its specialized Centre of Thermodynamics of Processes (CTP), has resulted in new experimental data for the proposed glycol-amine system. The measurements have been conducted by the PhD student in the High-Safety Laboratories of CTP and will continue in the NTNU laboratory premises. The experimental results will be employed to develop or extend a thermodynamic model for the accurate prediction of the combined H_2S removal and hydrate control process. In addition, supplementary studies on the physical properties of this system will be performed, providing further knowledge on the feasibility of this process for subsea application.

FACTS

- Hydrogen sulfide (H_2S) can, in the presence of water, cause severe corrosion problems leading to premature failure of pipelines and other equipment
- Natural gas production from fields with high H_2S concentration is challenging, due to stringent pipeline specifications, i.e. 4 ppm
- A possible subsea gas processing solution is depending on reduced weight, size and energy consumption



Flow diagram of the High-Pressure Vapor-Liquid Equilibrium setup. The heart of the setup is the equilibrium cell.

DDT: Displacement Transducer Display, DLD: Data Logging Device, DT: Displacement Transducer, MS: Mobile Sampler for the analysis of liquid phase, NRV: Non-Rotating valve, PC: Personal Computer for data acquisition, PT: Pressure Transducer, T: Thermocouple, V: Valve, VS: Vapor Sampler for the analysis of gas.

Experimental investigation of particle breakup in turbulent flow conditions

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

PHD STUDENT:
EIRIK HELNO HERØ

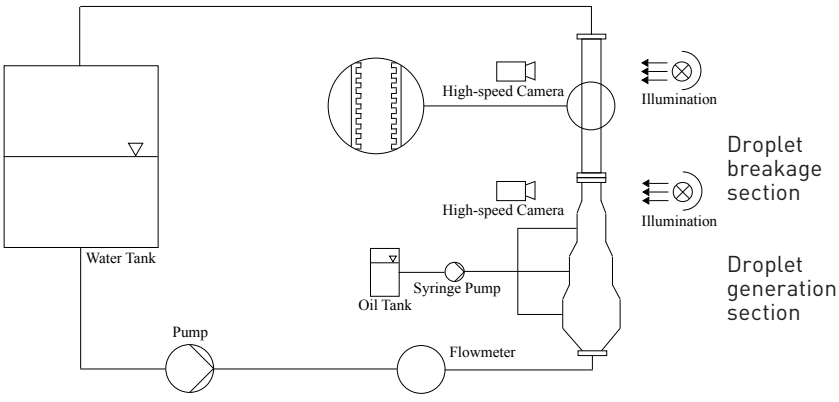
PROJECT MANAGER AND MAIN SUPERVISOR:
PROFESSOR HUGO A. JAKOBSEN

RESEARCHER: NICOLAS LA FORGIA

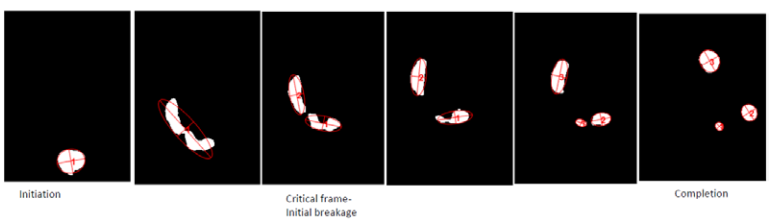
SUPERVISOR:
PROFESSOR HUGO ATLE JAKOBSEN

Understanding of phase separation processes is key to many industrial processes, especially for subsea processing. In particular, the separation of oil and water plays a major role in subsea processing, yet the design of oil-water separators is not simple. It requires the use of accurate models to predict droplet size distribution in oil-water mixture, where the size distribution is affected by droplet coalescence (merging) and droplet breakage processes. These processes are in turn dependent on the flow conditions, which in most cases are turbulent. The results of the project could be used for designing internal geometry of separators and other processing equipment, for improving flow conditions and to avoid turbulence and shear forces, in order to reduce droplet particle breakage, and thereby contribute to more efficient separation.

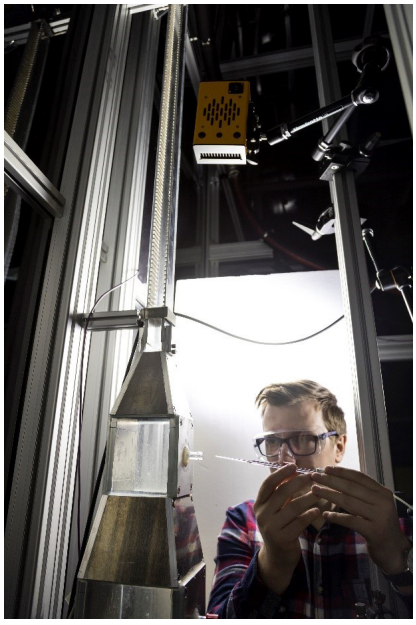
The project has developed an advanced test rig for studying breakage of single oil droplets immersed in a continuous water phase and exposed to turbulent flow under controlled conditions. The turbulence was measured by Laser Doppler velocimetry (LDV). The particle breakage is analyzed by high speed photographing and image processing algorithms. The measurements include breakage probability, mother and daughter size distribution, breakage time, deformation prior to breakage, and flow condition, among other significant statistical quantities. The test rig contains an injection region (see schematic figure) in which the oil droplets are injected through a glass needle into the flow stream by means of a syringe pump. Once the oil droplet is detached it is transported with the flow until it reaches the particle breakage section. Once in the breakage section, turbulence is induced by a roughness profile on the wall, which causes the breakage of the droplet. The breakage is recorded by high speed imaging, which is used to extract the relevant breakage information. These measurements can be used to understand breakage mechanisms and to improve predictive models for turbulent flows.



Schematic of experimental facility



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



Test rig for study of particle breakup with droplet generation section (lower chamber) and droplet breakage section (upper column).

Compact separation concepts

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

PHD STUDENT: HÅVARD S. SKJEFSTAD

PROJECT MANAGER AND MAIN SUPERVISOR:
ASSOCIATE PROFESSOR MILAN STANKO

CO-SUPERVISORS:
PROFESSOR SIGBJØRN SANGESLAND
PROFESSOR GISLE ØYE

The main objective of this project is to design, develop and test innovative solutions for separating produced water at the seabed, and perform experimental and numerical investigations of separator-concept performance. Development focus is on robust, effective and compact solutions.

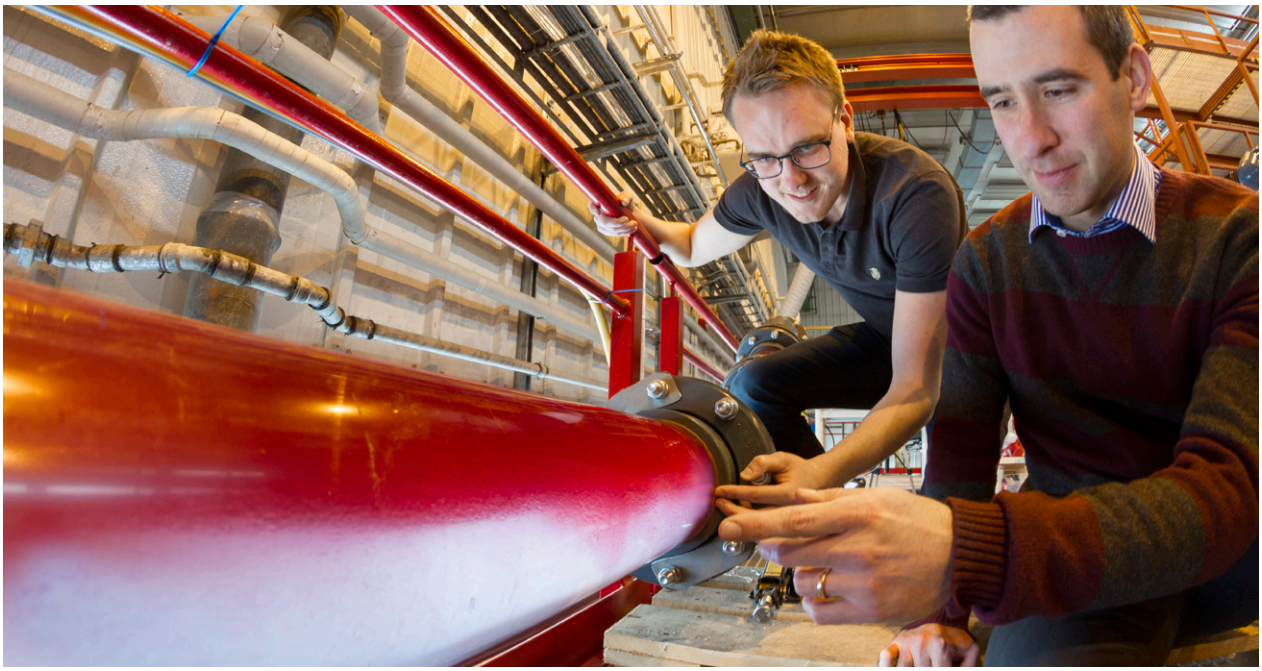
For mature oil fields, produced water is gradually taking over as the main extracted reservoir fluid, causing challenges in production. On the Norwegian Continental Shelf, 181 million standard cubic meters of produced water was reported for 2016. This accounts for more than twice the amount of produced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

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

At an early stage of this project a systematic evaluation of existing technologies was performed, identifying shortcomings in current subsea separator solutions. Size-, weight- and footprint-reduction were identified as future focus points for deep-water installations. Based on the performed evaluation and feedback from key industrial partners a concept was chosen for further development. The design is pipe based, taking advantage of the reduced settling distance offered by a decreased separator diameter, and is currently subject to experimental performance evaluation. The focus has been on developing compact separator solutions, allowing easy installation and retrieval at deep waters as well as reduced transportation cost.

Project deliverables will be an experimentally and numerically evaluated separation concept, which will be available to partners for further development and future subsea application.

As of date, the laboratory test rig for experimental validation of compact separator concepts has been constructed. In addition, the designed concept has been built and installed in the test rig, and performance evaluation is currently taking place.



PhD Candidate Håvard S. Skjefstad (left) and main supervisor Associate Professor Milan Stanko (right) investigating oil (red) – water (white) separation in the new compact separator test facility.

Kristin Dalane

AGE 27
FROM STAVANGER, NORWAY

TAKING A PHD IN SEPARATION PROCESS CONCEPTS

Having a father and two brothers who have all studied at NTNU, it was fairly certain that Kristin would also end up studying in Trondheim. She was practically raised on stories about student life at NTNU Campus.

Lively and enthusiastic

'There was a lot of technical talk when they were together, I remember that well,' says Kristin and laughs. 'And I remember thinking that I was definitely not going to study the same thing as them! Their subject was marine technology, but there are so many other interesting subjects.'

'The fact that I ended up with chemistry was a bit of a coincidence, and that I ended up at NTNU too.' She considered medicine, biotechnology and a career in research, but after having consulted NTNU's student advisers, she decided to apply to an engineering study at the university. 'I concluded that a master's degree in engineering would hopefully make it easier to get a job, and that it would give me a broader academic basis. Today I'm very pleased with my choice.'

SCIENCE ENTHUSIAST

'I've always liked science, but chemistry was not my favourite subject. And I was a little surprised when I came here and they said: So, you're taking five years of chemistry. What – I am?' She laughs again. But a good student? She hesitates. 'OK, I guess I've always been good at school, but it is a result of hard work.'

Then Kristin started the chemistry study. In the third year of studies, she had an aha moment when they were working with process simulations. She found it interesting and continued with a master's degree on the same topic. But a PhD was not on her list of things to do before she turned 30. However, the timing turned out to be perfect. And the fact that there were already two PhDs in the family was also encouraging.

NEW POSSIBILITIES

'When I finished my master's degree in chemical engineering, the job market wasn't exactly brimming with opportunity, to put it that way. But then SUBPRO came along. The position seemed both exciting and interesting and some of it was in a field I was already familiar with. Among other things, I had some experience in simulation and modelling. I applied for the position and got it. I remember thinking: Wow, I'm really going to do this.'

Kristin works on membranes and natural gas dehydration. She studies new technologies used for natural gas dehydration. 'It's fairly specific, and I can clearly see what the goal of it is. It's the first step to find out if it's possible to use this technique in a subsea environment. The cool thing about it is that it's a new concept. We see that the industry is interested in what we do and sees the benefit of me testing this. That's an additional motivation.' She laughs again.

CHEERFUL

In fact, Kristin laughs quite a lot. And it's words like lively, positive and cheerful that come to mind when describing her.

'I'm quite a sociable person. I like spending time with people and being active. In the work context, I'm both efficient and determined and want to get to the point and solve the problem. I also really enjoy knitting. I learned knitting and needlework from my grandmother and my mother. Along with outdoor activities, it is definitely one of my favourite hobbies. If I've got nothing else on after work, I often turn to knitting.'

Kristin also prioritises walks in the nature. She has solved many problems on a forest footpath. 'It gives me peace and calmness to think about both good things and to solve problems relating to what I'm doing at the time.'

GREW UP AROUND OIL

Kristin grew up around oil. Stavanger is the hub of Norwegian oil production, and both her father and her brothers work in the oil and gas industry.

'It wasn't really my plan to work in the sector, but since I work on natural gas, I guess I'm doing it anyway. I think that oil and gas will be around for a long time still. The shift will come eventually, however. Until then, we must make the production and use of natural gas, for example, as environmentally friendly as possible. I've had some thoughts on the matter, though,' she says, suddenly serious.

'We took an ethics course the first year where I really had to reflect on what I'm doing and whether it's the right thing do to. Yes, I guess I've made a conscious choice.'

PRAISING SUBPRO

Kristin Dalane is very pleased to be part of SUBPRO. It gives her an environment to work in.

'Unlike many of the others here, I'm affiliated to a group and meet other people who work on completely different things. Questions are asked here that I've never thought of. You learn a lot from that. And the threshold for contacting both lecturers and professors is incredibly low. So being part of SUBPRO is simply fantastic.'

RESEARCH AREA

System control

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

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

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

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

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

Sub-projects of the System Control Research Area:

- Dynamic simulation model library
- Modelling and multivariable control of subsea systems
- Process control algorithms for subsea separation
- Adaptive control of subsea processes
- Estimation of un-measured variables
- Virtual multiphase flow metering
- Control for extending component life
- Production optimization under uncertainty

Professor Sigurd Skogestad
Research area manager

System control team, work session

Dynamic simulation model library

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

POSTDOCTORAL FELLOW:
CHRISTOPH J. BACKI

PROJECT MANAGER:
PROFESSOR SIGURD SKOGESTAD

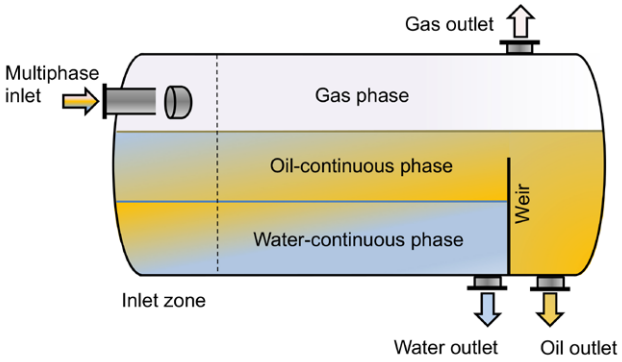
CO-SUPERVISOR:
ASSOCIATE PROFESSOR JOHANNES JÄSCHKE

With the developed models, controllers and observers, production and processing can be optimized with respect to efficiency and investment costs. This includes enhanced prediction of separation efficiency, slug handling with small volumes using predictive control techniques, substitution of physical measurements by virtual metering, and more accurate models by improved parameter identification.

The goal of the project is to start a model library for the use in the oil and gas industry. This model library will not only include the mathematical descriptions of technical systems, but also the respective concepts for controller- and observer-design based upon these models.

New developments in the project include
- A simple model for separation efficiency calculation in gravity separation devices
- Virtual metering approaches for the above gravity separator model to determine inflows to the separator
- A predictive controller for the above gravity separator model that can protect downstream equipment (e.g. hydrocyclones) from severe slugging events ("Virtual harp")
- A novel method for parameter identification in systems without full observability
- An extension to a Greitzer surge model for compression systems based on actuation by a close-coupled valve (CCV) as well as the drive torque
- Control- and estimation-structures for the above (extended) compressor model

Potential use and fields of application of the above developments:
- The gravity separator model in combination with the virtual metering and the predictive control for slug avoidance ("Virtual harp") potentially have a direct use in the oil and gas industry since these software solutions can replace hardware. They can be implemented in brown as well as in green fields, where they can help reduce CAPEX investments.
- The novel parameter estimation method is a broad methodology and can be used in many fields of application. It is best suited for off-line identification of parameters, but can potentially be used on-line as well.
- The compressor surge model together with its control and estimation algorithms have a use for distribution of gas in pipeline networks.



Schematic of a gravity separator with different zones and phases.

Modelling and multivariable control of subsea systems

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

PHD STUDENT:
TORSTEIN THODE KRISTOFFERSEN

PROJECT MANAGER AND MAIN SUPERVISOR:
ASSOCIATE PROFESSOR CHRISTIAN HOLDEN

CO-SUPERVISOR:
PROFESSOR SIGURD SKOGESTAD

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

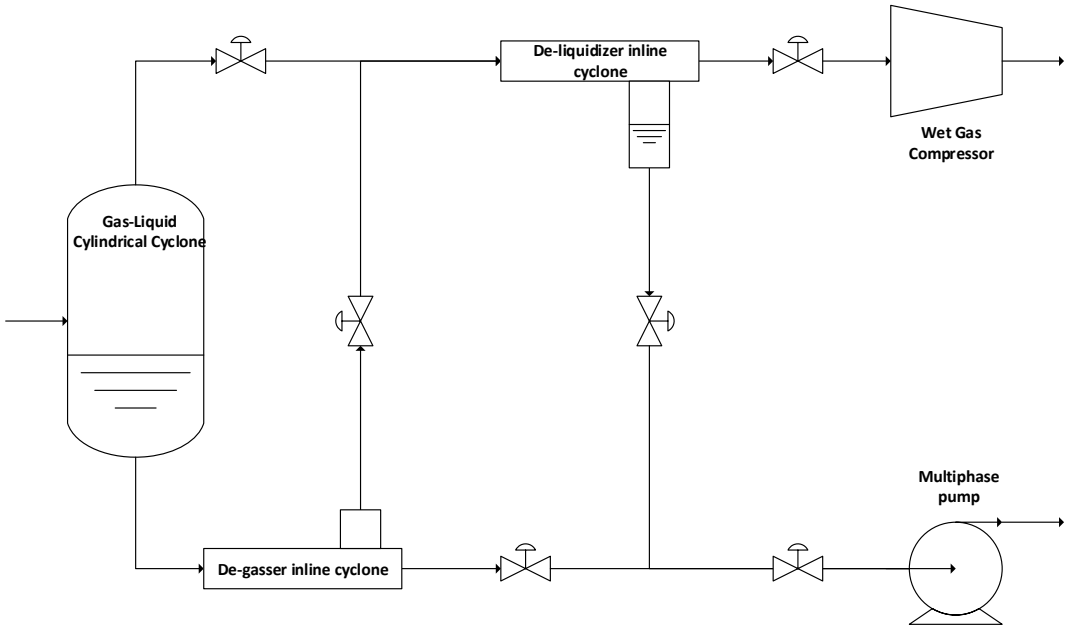
- safe and optimal operation, enabling reduced downtime and increased product quality and throughput
- estimation of unmeasured variables, enabling reduced need for instrumentation and additional insight
- simulation of various scenarios enabling testing of process changes and operator training.

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

So far, we have developed a mathematical model of a Gas-Liquid Cylindrical Cyclone (GLCC) separator and, based on this, demonstrated a potential of software for safe, efficient and optimal process control as well as estimation of unmeasured variables.

Further work on this model will include implementation of a more complex droplet distribution model for increased accuracy and validation against experimental data.

At the moment, we are developing a mathematical model of a Wet Gas Compression (WGC) system and development of a safe and efficient control software. Planned future work includes modification of the model for development of a mathematical model of a Multiphase Pump (MP) system.



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

Automatic control of subsea separation

Digital solution to reduce environmental foot print

PHD STUDENT: MISHIGA VALLABHAN

PROJECT MANAGER AND
MAIN SUPERVISOR:
ASSOCIATE PROFESSOR CHRISTIAN HOLDEN

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

THE GOAL FOR THIS PROJECT IS TO:

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

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

The efficiency of the water treatment process can be improved by designing model-based controllers. In this project, we are deriving mathematical models for hydro cyclones. Later, this model will be used to develop advanced control algorithms which can handle the unforeseen process disturbances in the field and automatically stabilize the system with minimal human intervention. The efficiency of hydro cyclones is normally measured by means of the concentration of oil in the water outlet (underflow). However, Oil-in-Water sensors are expensive and the sampling rate is low. Most of the current control strategy is based on an indirect method, where pressure drop ratio (PDR) is maintained to control the flow split ratio and thus indirectly the purity of the produced water. A dynamic physics-based mathematical model of hydro cyclones could enable the design of estimators for Oil-in-Water, and thus provide a more efficient measurement method.

We are building a compact separator laboratory consisting of hydro cyclones, gas liquid cylindrical cyclones, compact flotation units and an associated pump system. We will be able to validate the mathematical models, estimators and control algorithms developed by this and other projects in SUBPRO, by doing laboratory experiments using real and model oils.

Subsea control system test rig with Gas liquid cylindrical cyclones, Compact flotation separator and associated pump system.

Adaptive control of subsea processes

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

PHD STUDENT: SVEINUNG OHREM

PROJECT MANAGER AND MAIN SUPERVISOR:
ASSOCIATE PROFESSOR CHRISTIAN HOLDEN

CO-SUPERVISOR:
PROFESSOR SIGURD SKOGESTAD

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

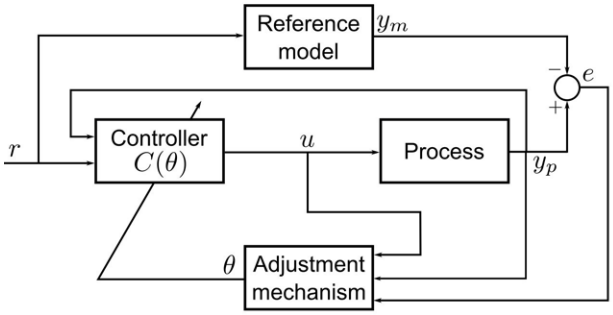
In the production and processing of oil and gas, operational conditions are often changing. The pressure in the wells decreases, the temperatures fluctuate, unforeseen situations occur, and equipment degrades and fails. All of this affects the quality and quantity of the products and the environmental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

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

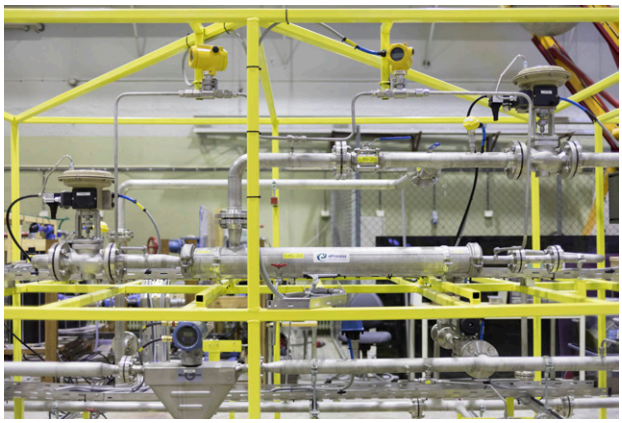
So far, we have developed an adaptive control algorithm for a gas liquid cylindrical cyclone and we have implemented an adaptive control solution for anti-slug control of a pipeline-riser system. We have also developed a simple model for a subsea pump station, but unlike the project "Modelling and multivariable control of subsea systems", the focus of this project is on developing controllers. We are also collaborating with other sub-projects within reliability to investigate if adaptive control can decrease the amounts of hazards in a subsea process.

At the moment we are researching if it is possible to use an adaptive controller to enforce a certain dynamic response on a system and use these known dynamics in an observer, in a Kalman filter or in a model predictive controller. If this proves to be possible, it would greatly simplify the design of observers and model predictive controllers as the real model of the system, which could be difficult to obtain, is no longer necessary.

Adaptive controllers can replace or cooperate with controllers currently implemented in a process/production facility and help increase the level of autonomy and improve the overall stability and performance of a process.



The basic structure of an adaptive control system.



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

Estimation of un-measured variables

Model based process monitoring/process control solutions for separation systems

PHD STUDENT: TAMAL DAS

PROJECT MANAGER AND MAIN SUPERVISOR:
ASSOCIATE PROFESSOR JOHANNES JÄSCHKE

CO-SUPERVISOR:
PROFESSOR SIGURD SKOGESTAD

Subsea processes rely on functioning process control and reliable process monitoring solutions. However, it is often difficult or even impossible to obtain accurate measurements of important process variables. One approach to address this situation is to combine the available data and models, in order to estimate variables that are not measured directly. These estimates can then be used to monitor or control processes.

In order to obtain estimates that can be used in real-time decision making, the models and the estimation algorithms must give results with minimal computational delay.

This is addressed in two ways in this project. 1. Development of fast Moving Horizon Estimation algorithm, and 2. Development of models which are running fast enough to be used in online applications, while still representing the relevant properties of the system accurately.

The first part of this project has developed a fast sensitivity based Moving Horizon Estimation (MHE) algorithm that can be used to obtain estimates of relevant process variables in very short time. MHE is an optimization-based approach that is especially suitable when the estimated variables have to honor bounds, such as e.g. in the estimation of compositions in high-purity separators. Here the concentrations can be ensured to have nonnegative values.

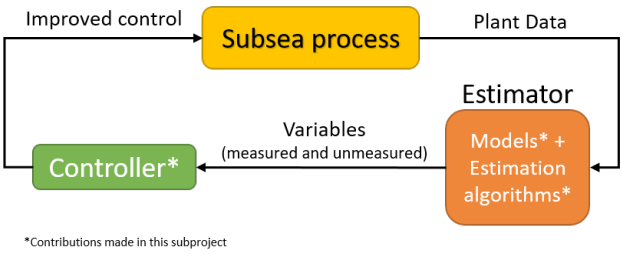
The second part of this project is dedicated to developing representative models and use estimation methods in conjunction with operational data to extract the values of relevant variables. These estimates then form the basis for either stabilizing control or optimizing control. These models are also suitable for analyzing the process, and developing a robust control structure.

The modelling efforts in this project have focused on developing simplified control- and estimation-oriented first principles models for commonly used separators, such as a three-phase gravity separator, an inline de-oiling hydrocyclone and a compact flotation separator. These models can form the support system for state and parameter estimation algorithms, and also for the design of reliable control systems.

RESULTS SO FAR

- Development of a new and efficient sensitivity-based moving horizon estimation
- Modeling results
  - Simplified gravity separator with coalescence
  - Inline Hydrocyclone
  - Compact flotation separator
- Simplified model of a well-riser system for testing of estimation algorithms

The results from this project can be used for automated process control/monitoring tools to improve the operation of separation systems. The models can also function standalone as digital twins to the real process.



A structure for subsea operation with estimator and controller in the loop.

Enhanced virtual flow metering

A new method for cheap and accurate multiphase flowrate estimations in subsea production.

PHD STUDENT: TIMUR BIKMUKHAMETOV

PROJECT MANAGER AND MAIN SUPERVISOR:
ASSOCIATE PROFESSOR JOHANNES JÄSCHKE

CO-SUPERVISOR:
PROFESSOR SIGURD SKOGESTAD

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

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

This project is dedicated to improving the understanding of this technology including identification of critical parameters, applicability of the concept and developing an optimal strategy for flow metering in terms of cost and accuracy. This may include a combination of hardware sensors and suitable modelling techniques.

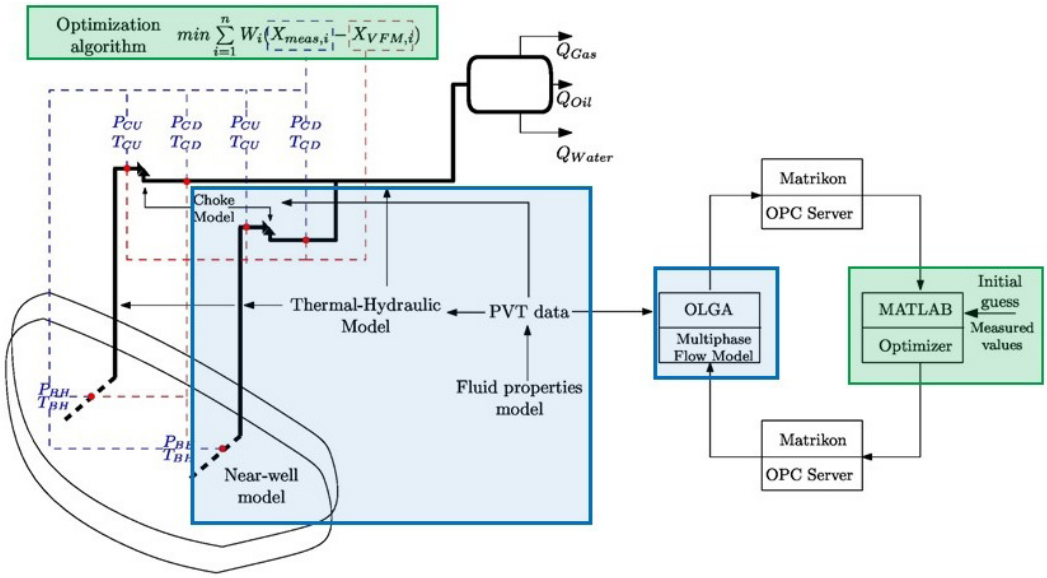
So far, the following has been done:

- A VFM software based on OLGA and MATLAB has been developed
- Analysis of the influence of sensor degradation on flowrate estimates based on Monte Carlo simulations and the constructed VFM software

The future plans include:

- Perform a sensitivity study to identify the most critical measurements which influence the accuracy of VFM
- Identify the dependence of errors caused by sensor degradation on different conditions (e.g. different Gas Oil Ratio values)
- Identify an optimal strategy for flow metering in terms of cost and accuracy by implementing VFM technology
- Evaluate the possibility of improving the flowrate predictions by using additional measurements
- Evaluate the possibility and conditions of applying data-driven methods for VFM.

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



Virtual Flow Metering concept implemented using MATLAB-OLGA interaction. The optimizer minimizes the difference between measurements and OLGA predictions.

Control for extending component life

A new method for safe and economical operation.

PHD STUDENT: ADRIAEN VERHEYLEWEGHEN

PROJECT MANAGER AND MAIN SUPERVISOR:
ASSOCIATE PROFESSOR JOHANNES JÄSCHKE

CO-SUPERVISOR:
PROFESSOR SIGURD SKOGESTAD

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

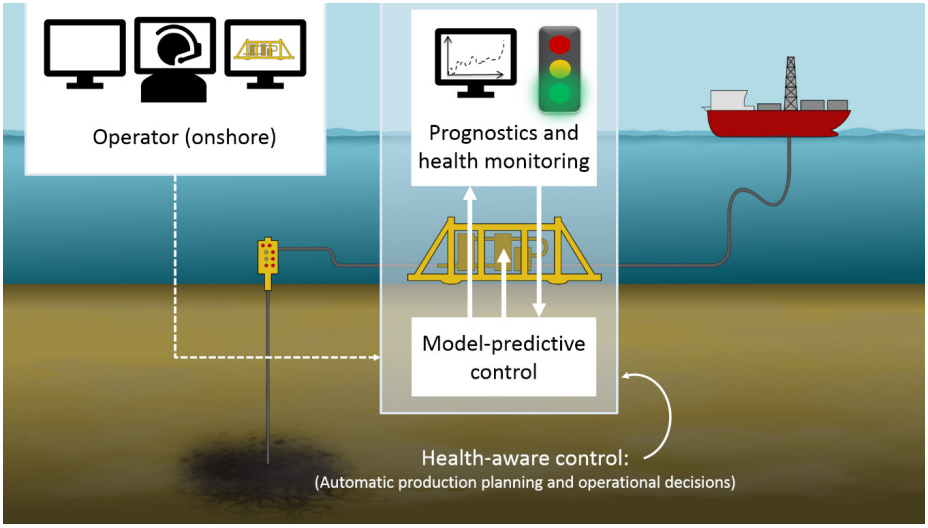
Our idea is to combine health monitoring and control of available degrees of freedom to find the optimal operation strategy. The goal is to ensure that the remaining useful life of the equipment is longer than the time to the next planned maintenance stop, while maximizing production. In other words,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

So far, the following has been developed:

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

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

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



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

Production optimization under uncertainty

Digital solutions to assist daily production optimization under uncertain conditions.

PHD STUDENT: DINESH KRISHNAMOORTHY

PROJECT MANAGER AND MAIN SUPERVISOR:
PROFESSOR SIGURD SKOGESTAD

CO-SUPERVISOR:
ASSOCIATE PROFESSOR JOHANNES JÄSCHKE

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

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

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

Results so far

- An optimization workflow that uses transient measurements to incorporate real-time data into real-time decision making.
- A feedback-based real time optimization algorithm where optimal operation can be achieved by feedback control.
- A scenario optimization tool to optimize production over several scenarios to account for the uncertainty.

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

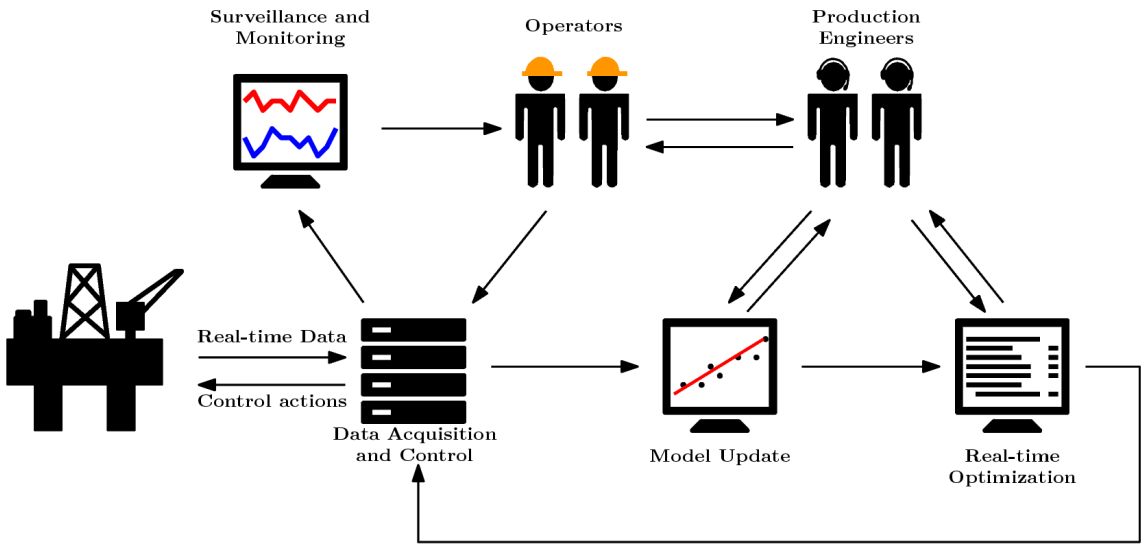
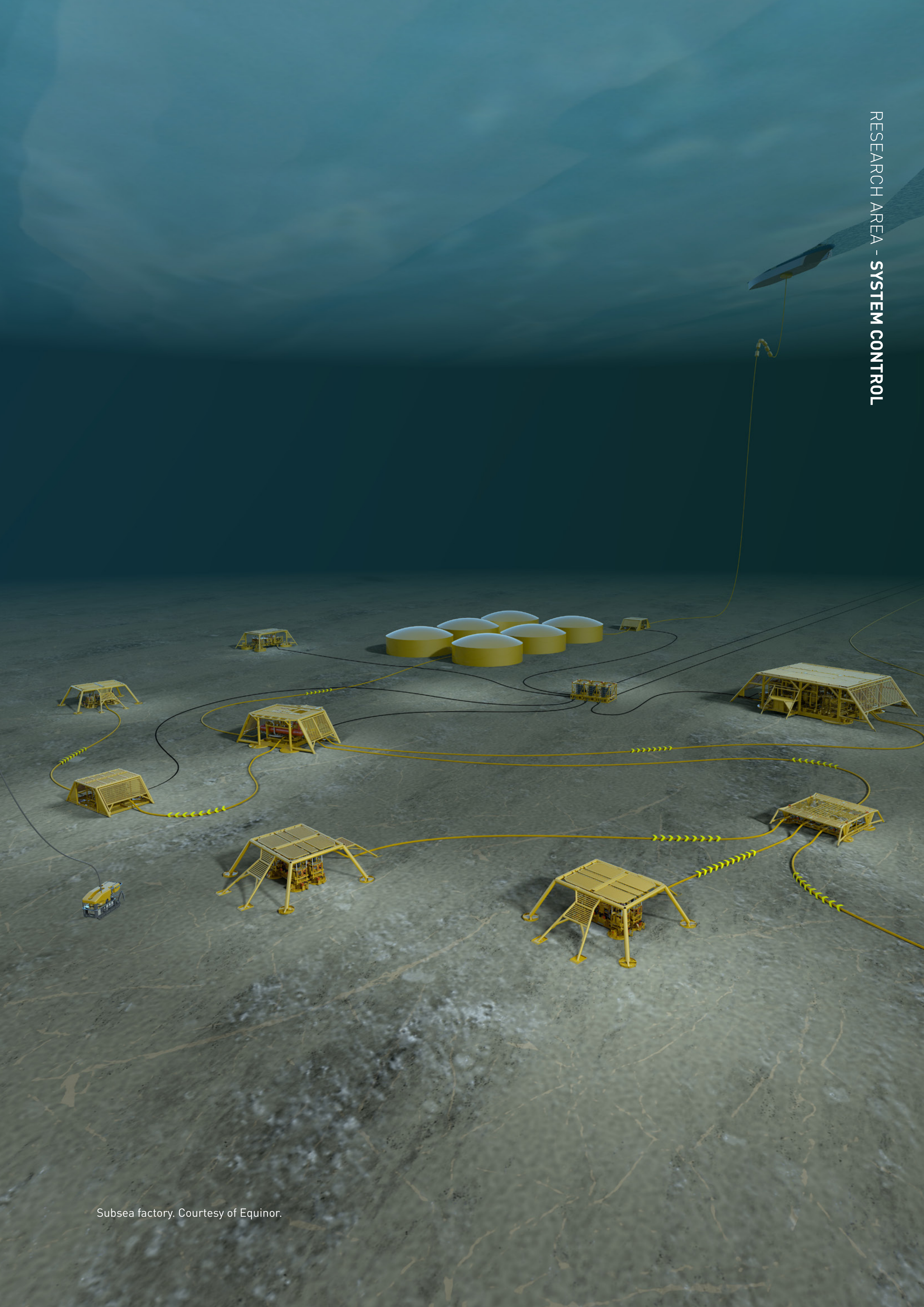


Illustration of the automated production optimization workflow for an oil and gas production network.



Subsea factory. Courtesy of Equinor.

Sveinung Ohrem

AGE 30
FROM SANDEFJORD, NORWAY

TAKING A PHD IN SYSTEM CONTROL

Metal and maths

A year at folk college, civilian national service at a library and working at a café are valuable experiences to bring into the world of cybernetics. A dose of black metal is not a bad idea either.

Sveinung Ohrem first came to Trøndelag to attend a folk college. Guitar was his main instrument and metal his favourite genre. And when Sveinung Ohrem said farewell to Skogn Folk college in 2008, he wanted to make a living as a guitarist. 'But I didn't have enough will to practise. Succeeding as a musician requires an enormous amount of practice. I couldn't find the motivation for it.'

Sveinung works in a building that NTNU and SINTEF share at Valgrinda, close to the NTNU campus. Surrounded by researchers, professors and students, this is his world now. He is well under way on completing his PhD in system control under the SUBPRO project. He still has a year and a half to go, but time flies. A PhD was not really on the cards for him, but while taking his master's degree in cybernetics, he received an email from his supervisor Christian Holden about SUBPRO and 25 vacancies. 'I read through it and saw that the system control position seemed really interesting. It corresponded with issues I was dealing with in my master's thesis.'

Sveinung asked for more information and was invited for a meeting. His grades and CV meant that he got an appointment right away. 'And I was offered the job there and then,' he says with a grin. It was completely unexpected and came out of the blue.

CONFIDENCE BOOST

'The idea that I wasn't good enough for a PhD had crossed my mind. The people I knew who were taking a PhD were so clever, but me? But when I was offered the opportunity, I couldn't say no!'

It was a massive confidence boost, but that feeling gradually dissipated. 'When you're admitted to a PhD programme, you feel clever and smart. But after a while, you realise: Oh god, I don't understand any of this! That's when you realise what you know and what you don't know. And that's a lot! But it's mainly enjoyable work. Of course, it's stressful and difficult at times, but on average, the positive aspects outweigh the negative.'

NEW METHODS

The field Sveinung Ohrem is taking his PhD in is System control. The title of his thesis is 'Improved control of demanding subsea processes'.

'What I do is to test new methods. It's not that the ones we have now don't work, but new methods have come along, and a lot can be done about the old ones to make them more functional. So, I'm looking at the different dynamic processes involved in a subsea process plant. In other words, things that change and that must be controlled in one way or the other. My job is to find control algorithms that work better than the ones we have today. We then want to prove mathematically that the equation I've found will work in simulations and, eventually, at a test lab facility, for example.'

FROM TREASURE HUNTS TO CYBERNETICS

As a child, he wanted to be a treasure hunter. 'I asked my mother what I had to study to become a treasure hunter, and we concluded that archaeology was the closest thing. With time, however, I found out that it maybe wasn't as exciting as I had thought. And I think my parents felt that I should choose a different path.' He loved mathematics in primary school, but struggled more in lower secondary. 'And in upper secondary school, I thought: "What is maths really good for anyway?" I didn't choose mathematics and chemistry as specialisation subjects, so it wasn't really obvious then that I would end up at NTNU.'

THINGS CHANGE

But once he had completed a year at folk high school and his civilian national service – a great year at Trondheim public library – as well as a trip around the world, he regained his interest in numbers. He worked at one of the most popular cafés in Trondheim, retook subjects to improve his grades and started on a bachelor's degree in automation at Sør-Trøndelag University College. 'It was then I realised the wealth of things you can use maths for. I found electronics and control theory, and how to calculate the controller, incredibly interesting. This experience determined my road ahead. I knew I wanted to learn more about this, and the next natural step to take was a two-year master's degree in cybernetics at NTNU.' Which then ended up in a PhD.

'Taking a PhD at SUBPRO feels great. I had no special expectations what it would entail, but I've been pleasantly surprised. There's a lot of focus on the social aspects, and that's a good idea, I think. I like spending time with people. Here, it's not like they put you in an office and then you're stuck there for three years.' Sveinung likes the interdisciplinary and international nature of the environment. 'The fact that we come from different backgrounds makes for interesting conversations.'

COOKING ENTHUSIAST

He describes himself as very sociable person, and one of the things he likes to do is cook for his friends. 'It's something I learnt from my father, who's an enthusiastic amateur cook. When I was young, I helped him out in the kitchen, so that's probably where I got it from.' Another good childhood memory is long dinner parties with family and friends. 'It's a habit I've taken with me to Trondheim.' And his lucky guests are often served Indian or Asian food. But he keeps his guitar playing to himself. For the time being, he only practises at home. It's hard-hitting stuff. His fascination for Finnish and Norwegian metal goes way back. They're extremely skilled musicians.

After 10 years in Trondheim, Sveinung is practically a native trønder. 'I don't make an effort to become one, but I don't feel like a native of Sandefjord either. After all, Trondheim is where I've spent my entire adult life, so it's where I call home. But I've kept the dialect, even if a few local dialect words sometimes pop up without warning.'

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, practical project planning, working in teams, sharing of knowledge across disciplines and building an international network. 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 three departments and two faculties at NTNU. The industry urges the researchers to stick their heads together and create synergies between the projects. Gradually, this has become the working culture of SUBPRO. The PhD students arrange colloquia at regular intervals, and many of the projects collaborate on common development tasks.

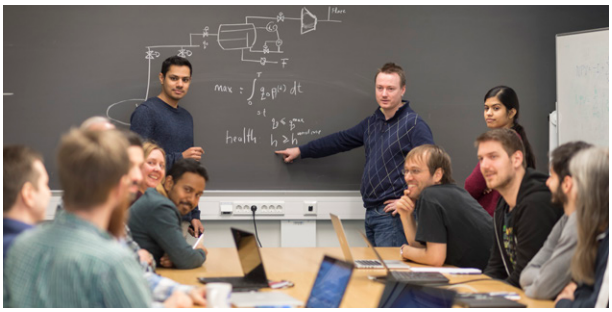
INTERNATIONAL COLLABORATION
The PhD students have the opportunity to visit or work for periods at other universities and research institutions around the world.

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

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

Carefully listening; Industry partners participating in a reference group meeting.

A team of researchers from SUBPRO presented highlights from the Centre at the Subsea Valley Conference in 2017.
From the left: HyungJu Kim, Adriaen Verheyleweghen, Kristin Dalane, Are Berheussen, Mary Ann Lundteigen and Mariana Diaz.



Team session in the System control group.

Master students at SUBPRO

Every year approximately 25 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, SUBPRO has motivated the master students to keep on studying petroleum related subjects and invited to master theses in the field of subsea technology.

SUBPRO has also hired students for summer internships.

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

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

Experts in Teamwork

Training for work in multidisciplinary teams

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

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

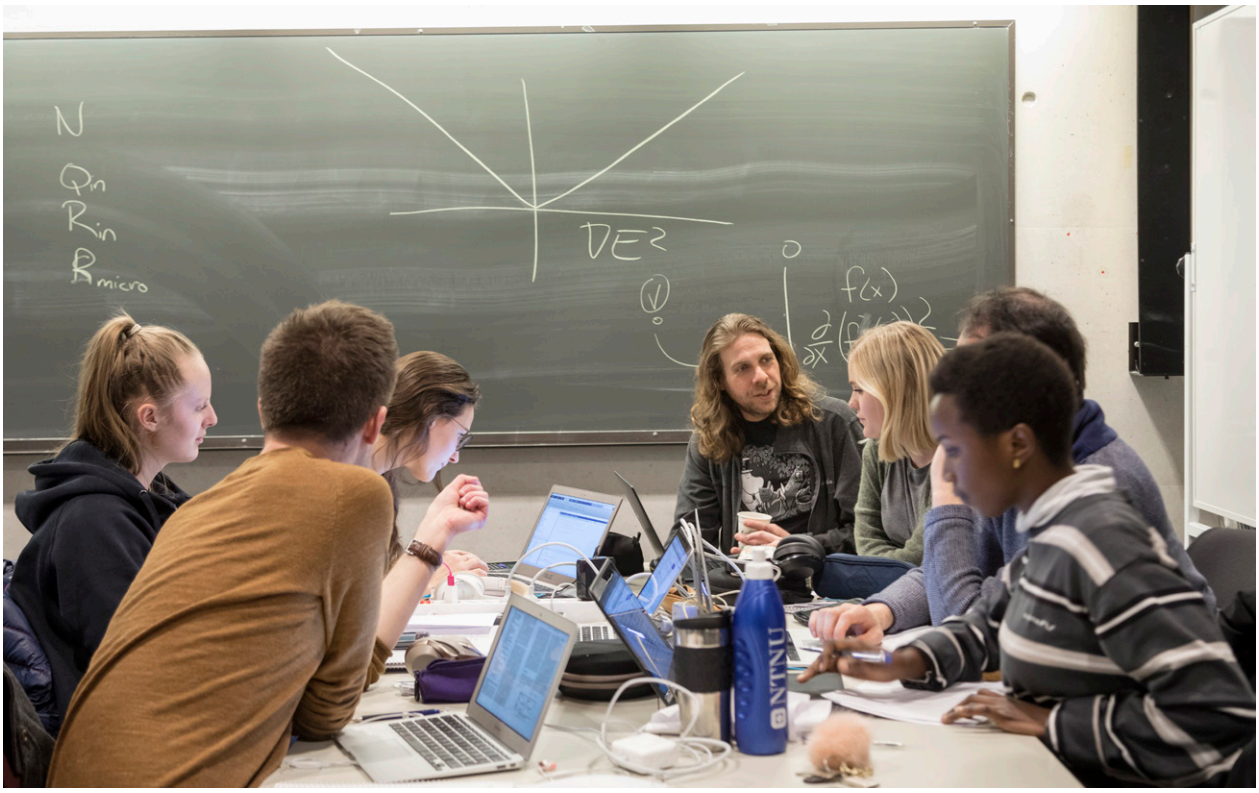
SUBPRO is providing industry relevant topics and involvement from industry partners and faculty at NTNU to one of the EiT Villages every year.

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

- Digitalization in the petroleum industry
- Green RAMS (Reliability, Availability, Maintenance and Safety)
- Technical, economic, and CO2 emission aspects of produced water treatment
- New concepts in liquid-liquid separation

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

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



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.

student from the Department of Industrial Economics and Technology Management.

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

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

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

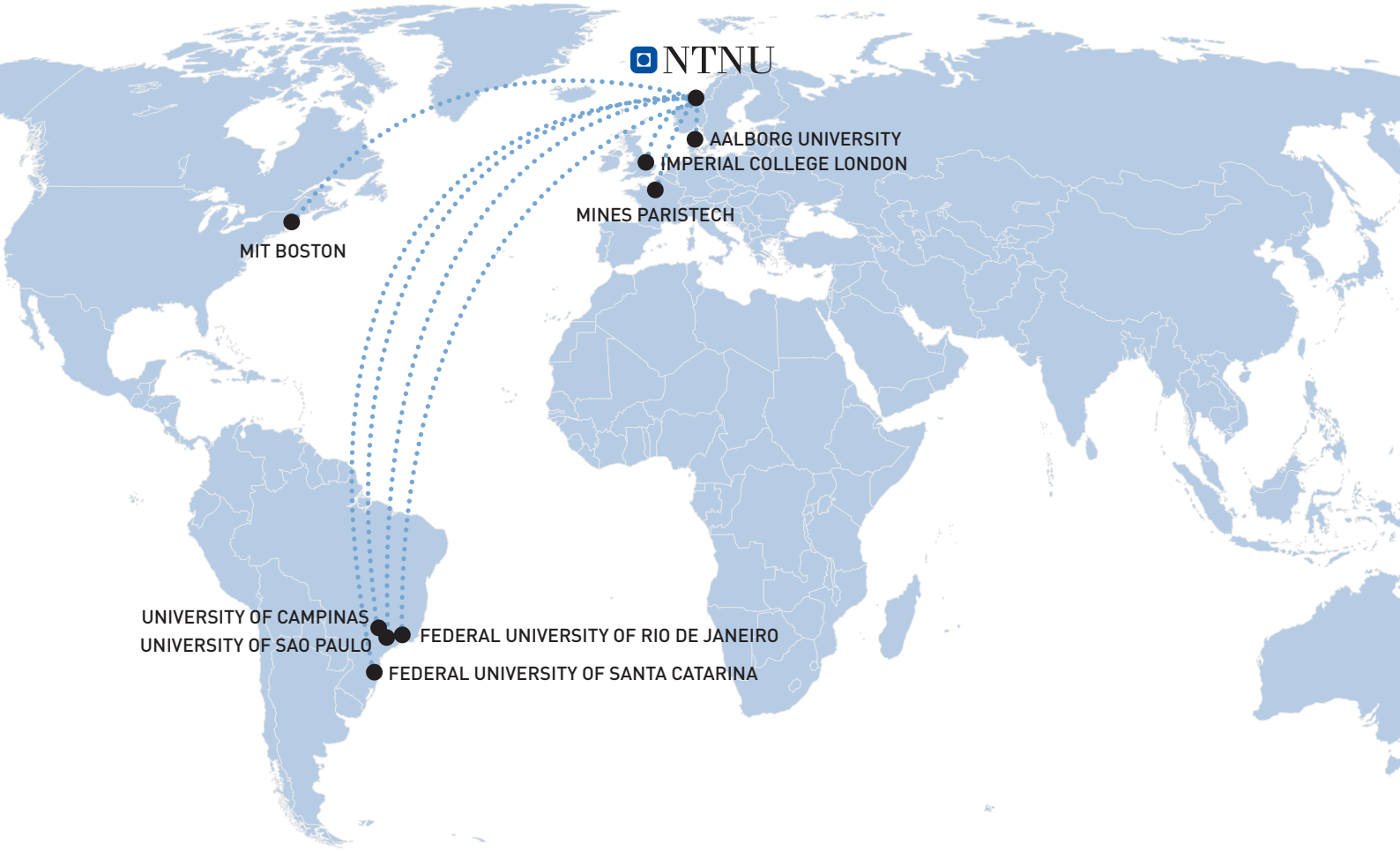
What will they deliver?
- The students will deliver a project report of about 25-50 pages.

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

International Collaboration

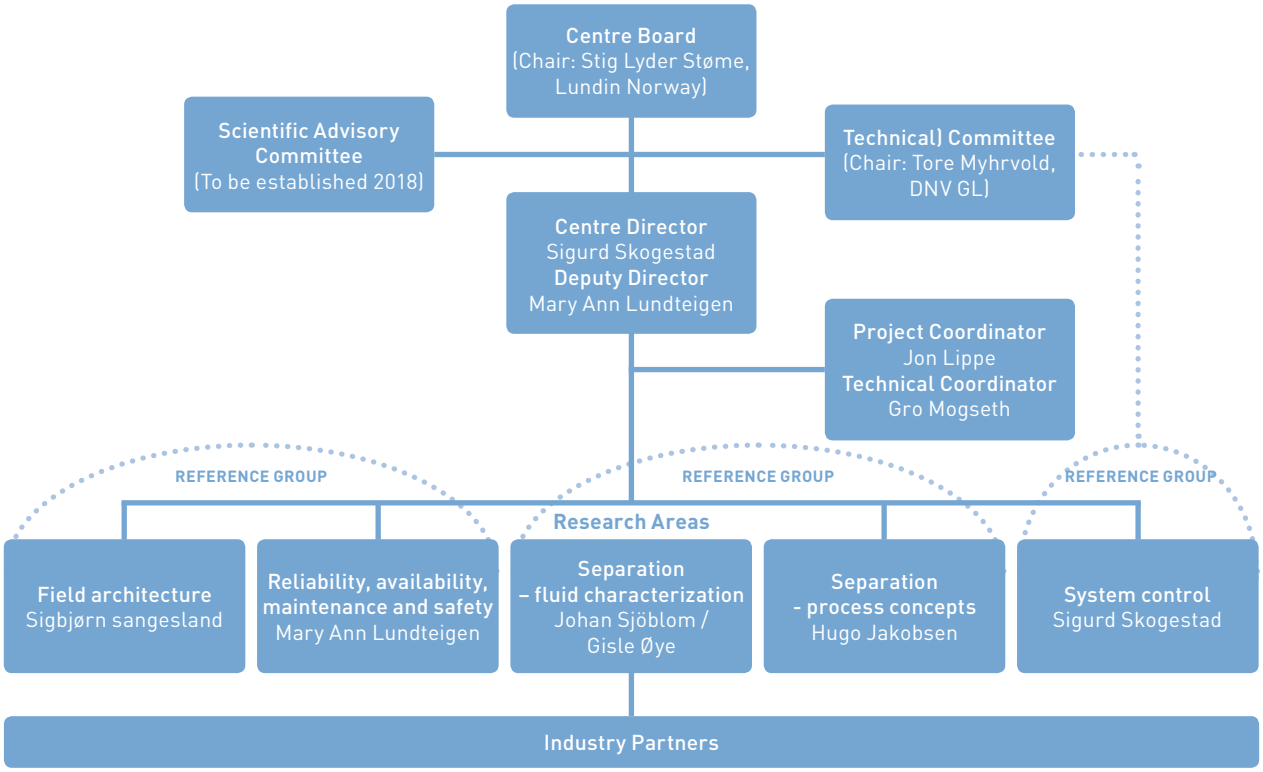
SUBPRO has organized collaborative research activities with 8 renowned international universities. The collaboration involves research collaboration and exchange programs for professors, PhD students and Master students.

- MIT Boston, Professor Paul Barton – Collaborative research on production optimization
- Federal univeristy of Rio de Janeiro, University of Sao Paulo, Federal university of Santa Catarina, University of Campinas – INTPART project on Subsea technology, exchange of PhD and Master students between Brazilian universities and NTNU, annual workshops in Brazil and Norway
- Mines ParisTech, Professor Christophe Coquelet – Collaboration on experiments with H_2S extraction from natural gas
- Imperial College London, Professor Kang Li - Collaboration on gas dehydration
- University of Aalborg - collaboration on rig design and process control methods



Organization of the Centre

GOVERNANCE STRUCTURE



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Collaboration between NTNU and the industry partners

CENTRE BOARD
The Centre board has one representative from each partner. The board adopts goals and strategies for the Centre and decides 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 and results and giving feedback to further research and innovation activities.

SCIENTIFIC ADVISORY COMMITTEE
The Scientific Advisory Committee which will be established in 2018 will consist of one academic expert for each of the research area. The committee shall assess the quality of the ongoing research activities and give advice for further planning of research projects.

TECHNICAL CONTRIBUTIONS TO THE RESEARCH ACTIVITIES
The industry partners also contribute directly to the research projects through industrial cases, field data, oil samples, knowledge and advice.

HSE

SUBPRO follows NTNU's HSE system, and reports events and mitigations to the SUBPRO Centre board twice a year.

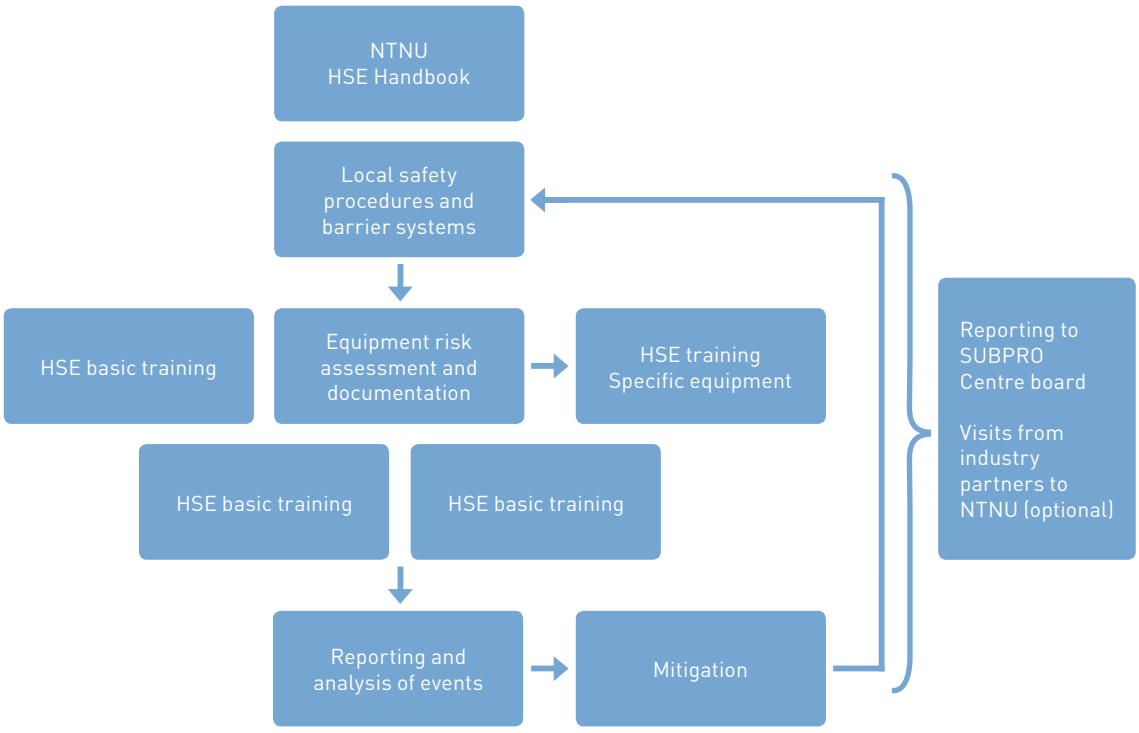
The industry partners have the right to visit the work sites of NTNU whenever desired.

During 2017 no events have been reported from SUBPRO activities.

The core of the HSE system is risk analyses, which are carried out for all laboratory activities as well as external activities like exchange visits and excursions. Based on the risk analysis, necessary precautions are organised and individual training is given. This is particularly important for new PhD and Master students doing experimental work.

SUBPRO/NTNU has also learned from the experience of the industry partners regarding HSE. When a new H_2S laboratory was built for a SUBPRO project at NTNU, the project team visited Equinor RDI Centre and received knowledge about regulations, practical laboratory work procedures and risk assessments, which was then transferred to NTNU.

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

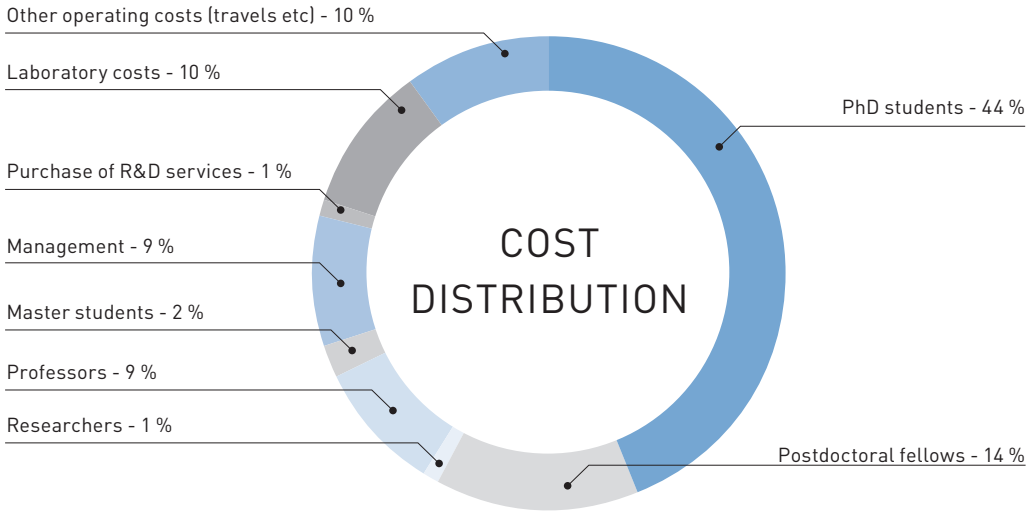


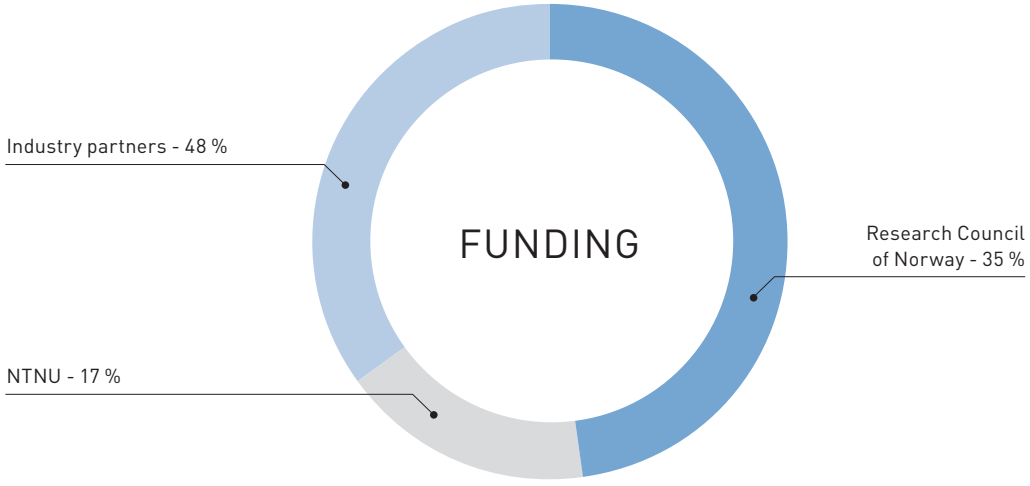
NTNU/SUBPRO HSE system

Key figures

PROJECT DURATION	AUGUST 2015 – AUGUST 2023*		
Total annual budget	32 mill. NOK		
Personnel	Total period 2015-2023	2015-2018	Female percentage
PhD students	34	20	25 %
Postdoctoral scholars	9	6	33 %
Researchers	7	7	15 %
Professors	22	22	20 %
MSc students (per year)	25	22	22 %

*Provided funding from RCN granted for the last 3 years of operation





Publications

Journal papers, conference papers and presentations published in 2017

FIELD ARCHITECTURE

Diaz Arias, Mariana JC; Sangesland, Sigbjørn; Stanko, Milan. **"Field Architecture within SUBPRO".** 1st Workshop in BN Subsea Operations Consortium (24-25 April 2017).

Diaz Arias, Mariana JC; Stanko, Milan; Sangesland, Sigbjørn. **"Exploring an Alternative Approach in Subsea Field Architecture".** The Subsea Gate Box. SSV conference (4-6 April 2017).

Nunez, Gilberto; De Andrade, Jesus; Golan, Michael; Sangesland, Sigbjørn. **"Modelling the Performance of Subsea Multiphase Boosting".** MPUR Europe 2017" (21 September 2017).

RELIABILITY, AVAILABILITY, MAINTENANCE AND SAFETY

Kim, HyungJu; Lundteigen, Mary Ann; Holden, Christian. **"Managing Hazards and Risks in Subsea Facilities - Current Practices"**. SSV Conference 2017 (6-4 April 2017).

Zhang, Juntao; Liu, Yiliu; Lundteigen, Mary Ann. **"Framing Reliability Specification in Early Design Phase Of Subsea Systems"**. Proceedings of the 23rd ISSAT International Conference on Reliability and Quality in Design 2017.

SEPARATION – FLUID CHARACTERIZATION

Bertheussen, Are; Simon, Sebastien Charles; Sjøblom, Johan. **"Equilibrium Partitioning of Naphthenic Acids and Bases and their Consequences on Interfacial Properties".** Colloids and Surfaces A: Physicochemical and Engineering Aspects 2017.

Bertheussen, Are; Simon, Sebastien Charles; Sjøblom, Johan. **"Equilibrium Partitioning of Naphthenic Acids and Bases and their Interactions"**. PETROPHASE 2017 (11-15 June 2017).

Bertheussen, Are; Simon, Sebastien Charles; Sjøblom, Johan. **"How Crude Oil Acids Partition Between Oil and Water Phases"**. Advanced Hybrid Separation Techniques in Industrial Wastewater Management (8-9 December 2017).

Dudek, Marcin; Dumaire, Thomas; Øye, Gisle. **"Microfluidic Method to Study Coalescence of Crude Oil Drops in Water - The Effect of Crude Oil and Water Composition".** The 21st International Conference on Miniaturized Systems for Chemistry and Life Sciences (MicroTAS 2017) (22-26 October 2017).

Dudek, Marcin; Kancir, Eugènie; Øye, Gisle. **"Influence of the Crude Oil and Water Compositions on the Quality of Synthetic Produced Water".** Energy & Fuels 2017.

Dudek, Marcin; Øye, Gisle. **"Microfluidics within Produced Water Research"**. Advanced Hybrid Separation Techniques in Industrial Waste Water management. (8-9 December 2017).

Ruwoldt, Jost; Simon, Sebastien Charles; Norrman, Jens; Oschmann, Hans-Jörg; Sjøblom, Johan. **"Wax-Inhibitor Interactions Studied by Isothermal Titration Calorimetry and Effect of Wax Inhibitor on Wax Crystallization"**. Energy & Fuels 2017.

Ruwoldt, Jost; Simon, Sebastien Charles; Oschmann, Hans-Jörg; Sjøblom, Johan. **"Isothermal Titration Calorimetry for Assessing Wax-Inhibitors"**. Chemistry in the Oil Industry XV: Enabling Efficient Technologies Programme (6-8 November 2017).

SEPARATION – PROCESS CONCEPTS

Ansaloni, Luca; Josefsen, Natalie T.; Dalane, Kristin; Deng, Liyuan. **"Subsea Regeneration of Triethylene Glycol for Natural Gas Dehydration using Pervaporation Technology".** International Conference on Membranes and Membrane Processes 2017 (29 June-4 August 2017).

Dalane, Kristin; Dai, Zhongde; Mogseth, Gro; Hillestad, Magne; Deng, Liyuan. **"Potential applications of Membrane Separation for Subsea Natural Gas Processing: A Review"**. Journal of Natural Gas Science and Engineering 2017.

Dalane, Kristin; Hillestad, Magne; Deng, Liyuan. **"Membrane Contactor Modelling for Subsea Natural Gas Dehydration"**. 11th International Congress on Membranes and Membrane Processes 2017 (29 June-4 August 2017).

Dalane, Kristin; Hillestad, Magne; Deng, Liyuan. **"Membrane Processes for Subsea Natural Gas Dehydration"**. Subsea Valley Conference 2017 (4-6 April 2017).

Herø, Eirik Helno; Shi, Jing; Solsvik, Jannike; Jakobsen, Hugo Atle. **"Experimental and Numerical Study on Single Droplet Breakage in Turbulent Flow"**. 12th International Conference on Computational Fluid Dynamics in the Oil & Gas, Metallurgical and Process Industries (30 May-1 June 2017).

Skartlien, Roar; Bertheussen, Are; Simon, Sebastien Charles; Sjøblom, Johan. **"Development of Electrochemical DPD Molecular Simulations for Oil/Water Partitioning of Organic Acids at Varying pH".** Journal of Dispersion Science and Technology 2018.

Skjefstad, Håvard Slettahjell; Stanko, Milan. **"Subsea Water Separation: A State of the Art Review, Future Technologies and the Development of a Compact Separator Test Facility".** 18th International Conference on Multiphase Technology (7-9 June 2017).

Skylogianni, Eirini; Mundal, Ingvild; Pinto, Diego Di Domenico; Knuutila, Hanna K; Coqueiet, Christophe. **"Vapor-Liquid Equilibrium Data for the Systems H_2S-MDEA-H_2O and CH_4-H_2S-MDEA-H_2O at High Solvent Concentrations and High Pressures"**. AIChE Annual Meeting (29 October-3 November 2017).

SYSTEM CONTROL

Backi, Christoph Josef. **"A Control- and Estimation-Oriented Gravity Separator Model".** VI Oil and Gas Production Optimization Workshop (26 April 2017).

Backi, Christoph Josef. **"Modeling and Control in Subsea Engineering"**. Colloquium Series at Aalborg University (9 May 2017).

Backi, Christoph Josef. **"Modeling of Subsea Processes"**. 1st Workshop of the Brazilian-Norwegian Subsea Operations Consortium (24 April 2017).

Backi, Christoph Josef; Grimes, Brian Arthur; Skogestad, Sigurd. **"Population Balance Equation for Calculation of the Inlet Distribution for Oil and Water Droplets in Continuous Gravity Separators"**. 2017 AIChE Annual Meeting (29 October-3 November 2017).

Backi, Christoph Josef; Skogestad, Sigurd. **"A Simple Dynamic Gravity Separator Model for Separation Efficiency Evaluation Incorporating Level and Pressure Control"**. 2017 American Control Conference (24-26 May 2017).

Backi, Christoph Josef; Skogestad, Sigurd. **"A Simple Dynamic Gravity Separator Model for Separation Efficiency Evaluation Incorporating Level and Pressure Control"**. American Control Conference (ACC) 2017.

Backi, Christoph Josef; Skogestad, Sigurd. **"Virtual Inflow Monitoring for a Three-Phase Gravity Separator"**. 2017 IEEE Conference on Control Technology and Applications (CCTA). IEEE conference proceedings 2017 (27-30 August 2017).

Das, Tamal; Backi, Christoph Josef; Jäschke, Johannes. **"A Model for Subsea Oil-Water Gravity Separator to Estimate Unmeasured Disturbances"**. Computer-aided chemical engineering 2017.

Jahanshahi, Esmaeil; Backi, Christoph Josef; Skogestad, Sigurd. **"Anti-Slug Control based on a Virtual Flow Measurement"**. Flow Measurement and Instrumentation 2017.

Krishnamoorthy, Dinesh; Skogestad, Sigurd. **"Novel Approach to Steady-State Gradient Control using Transient Measurements"**. 21st Nordic process control workshop (18-19 January 2018).

Krishnamoorthy, Dinesh. **"Production Optimization under Uncertainty"**. 6th Brazil-Norway production optimization workshop (27-28 April 2017).

Krishnamoorthy, Dinesh. **"Undervanns Produksjons Optimalisering under Usikkerhet"**. NFA Subsea conference (12-13 September 2017).

Krishnamoorthy, Dinesh; Foss, Bjarne Anton; Skogestad, Sigurd. **"Gas Lift Optimization under Uncertainty".** Computer-aided chemical engineering 2017.

Krishnamoorthy, Dinesh; Foss, Bjarne Anton; Skogestad, Sigurd. **"Model Predictive Control under Structural Uncertainty"**. AIChE Annual meeting (29 October-3 November 2017).

Krishnamoorthy, Dinesh; Straus, Julian; Skogestad, Sigurd. **"On Combining Self-Optimizing Control and Extremum Seeking Control - applied to Ammonia Reactor Case Study"**. AIChE Annual meeting 2017 (29 October-3 November 2017).

Kristoffersen, Torstein Thode; Holden, Christian. **"State and Parameter Estimation of a Gas-Liquid Cylindrical Cyclone"**. 21st Nordic Process Control Workshop (18-19 January 2018).

Kristoffersen, Torstein Thode; Holden, Christian. **"Model Predictive Control and Extended Kalman Filter for a Gas-Liquid Cylindrical Cyclone".** 2017 IEEE Conference on Control Technology and Applications (CCTA). IEEE conference proceedings 2017 (28-30 August 2017).

Kristoffersen, Torstein Thode; Holden, Christian. **"Nonlinear Model Predictive Control of a Gas-Liquid Cylindrical Cyclone"**. 25th Mediterranean Conference on Control and Automation. IEEE conference proceedings 2017 (3-6 June 2017).

Kristoffersen, Torstein Thode; Holden, Christian; Egeland, Olav. **"Feedback Linearizing Control of a Gas-Liquid Cylindrical Cyclone".** 2017 IFAC World Congress (9-14 July 2017).

Kristoffersen, Torstein Thode; Holden, Christian; Egeland, Olav. **"Feedback Linearizing Control of a Gas-Liquid Cylindrical Cyclone"**. IFAC-PapersOnLine 2017.

Kristoffersen, Torstein Thode; Holden, Christian; Skogestad, Sigurd; Egeland, Olav. **"Control-Oriented Modelling of Gas-Liquid Cylindrical Cyclones"**. American Control Conference (ACC) 2017 (24-26 May 2017).

Ohrem, Sveinung Johan. **"Control of Separators"**. BN Subsea Consortium Workshop (24-25 April 2017).

Ohrem, Sveinung Johan; Holden, Christian. **"Modeling and Nonlinear Model Predictive Control of a Subsea Pump Station"**. Control Conference Africa (7-8 December 2017).

Ohrem, Sveinung Johan; Holden, Christian; Jahanshahi, Esmaeil; Skogestad, Sigurd. **"L1 Adaptive Anti-Slug Control"**. American Control Conference (ACC) 2017 (24-25 April 2017).

Ohrem, Sveinung Johan; Kristoffersen, Torstein Thode; Holden, Christian. **"Adaptive Feedback Linearizing Control of a Gas Liquid Cylindrical Cyclone"**. 2017 IEEE Conference on Control Technology and Applications (CCTA). IEEE conference proceedings 2017 (28-30 August 2017).

Verheyleweghen, Adriaen. **"Risk-Based Health-Aware Control of Subsea Systems"**. Nordic Process Control Workshop (18-19 January 2018).

Verheyleweghen, Adriaen. **"Process Control for Extending Component Life"**. Subsea Valley (SSV) Conference (5 April 2017).

Verheyleweghen, Adriaen. **"Smart Production Optimization: How to Maximize Production without Risking Equipment Health?"**. OG21 (8 November 2017).

Verheyleweghen, Adriaen; Jäschke, Johannes. **"Framework for Combined Diagnostics, Prognostics and Optimal Operation of a Subsea Gas Compression System"**. IFAC-PapersOnLine.

Verheyleweghen, Adriaen; Jäschke, Johannes. **"Health-Aware Operation of a Subsea Gas Compression System Under Uncertainty".** Foundations of Computer Aided Process Operations/ Chemical Process Control 2017 (8-12 January 2017).

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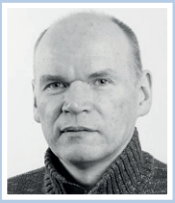

Prof. Hugo Atle Jakobsen, Separation – Process concepts

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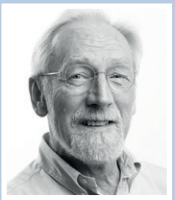
Postdoctoral fellow Jesus De Andrade, Multiphase booster models



Prof. Tor Berge Gjersvik, Optimizing subsea production facilities layout

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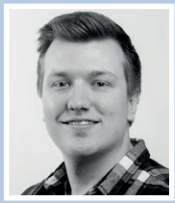
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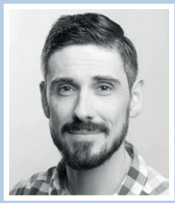
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SUBPRO

SUBSEA PRODUCTION AND PROCESSING

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

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