sfi Centre for Research-based Innovation
The Research Council of Norway

SUBPRO

SUBSEA PRODUCTION AND PROCESSING

REPORT 2017

including Annual Report 2016

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 – basis for industrial innovation
- Internationally high level of graduated master and PhD students

WHY SUBPRO?

- There are still gaps in knowledge and technology for subsea systems that need to be covered, to:
  - increase the recovery from existing fields
  - enable development of new and more demanding oil and gas fields
  - reduce cost and complexity of subsea field developments
- Many future challenges require multi-disciplinary collaboration
- Help industry to accelerate the level of innovation within selected areas of oil and gas field development and operation

CONTENT

Front page: Environmental Engineering and Reactor Technology Lab at NTNU, Department of Chemical Engineering. Photo: Thor Nielsen.

Centre director

We are very satisfied with year two of SUBPRO. 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 even got a new partner and welcome VNG Norge as an industrial partner of the SFI SUBPRO from 2017.

We work in an area where Norway has a strong position and a world leading industry. It is therefore important for us to have a good collaboration with active industry partners.

Most of the research work is done at NTNU, where we at any given time have about 20 PhD students and postdocs, in addition to supervisors and support personnel.

During 2016 the first batch of PhD students and postdocs has been focusing on their research activities and lots of new results are being generated. The idea is that this fundamental research work will form the basis for innovations among the industrial partners. Better knowledge is the basis for "digitalization", which is buzzword in the subsea industry at the moment.

So, it's a large activity and it makes it the largest academic subsea activity in the world! We have large ambitions and we think we will fulfill them.

We have managed to develop a centre model with strong structures and mechanisms for collaboration both between industry partners and the academia and within the industry.

Among all the tasks that have been fulfilled in 2016 I am happy to see that we have succeeded in making very good working conditions for the PhD students and postdoctoral fellows. That is through study groups, excursions and courses. One of our PhD students Eirini Skylogianni won a prize for her poster presentation at Student Poster Competition in Techno-Ocean Conference 2016. We also have a focus on social activities, and we hosted the reference group meetings and technical committee meetings during the year.

Prof. Sigurd Skogestad
Centre Director

NTNU as the host for the SUBPRO Centre

What is the role of SUBPRO in achieving NTNU goals and strategy?

NTNU has a national role in research and education within technology. As the largest university in Norway, NTNU has strong research ambitions in this and other fields, and SFI SUBPRO is one important measure to fulfill these ambitions. Topically, SFI SUBPRO also supports the strategic area NTNU Energy. We expect SFI SUBPRO to develop basic scientific knowledge at the highest international level on novel methodology to be applied in subsea production and processing infrastructure for the oil and gas industry. The scientific issues addressed should be relevant for the industry and paving the ground for innovations in the field. Education of highly qualified master and PhD candidates is an integral part of these objectives. 21 PhD students and postdoctoral fellows are currently well into their studies in the centre, producing valuable results by experimental and modelling studies. Another 5 PhD students and postdoctoral fellows will start new projects in 2017. An asset of these activities is the development of the research topics in close collaboration with our industrial partners. The success of SFI SUBPRO to develop new insight and foster innovative solutions and improvements to the benefit of the industrial partners will contribute to NTNU realizing its charter on research and innovation.

Anne Borg
Dean
Faculty of Natural Sciences

Ingvald Strømmen
Dean
Faculty of Engineering

Chairman of the Board

Our goal is to be the best in the world, i.e. to be a world-leading research centre for subsea production and processing. We see considerable potential in bringing the industry and the best researchers in their respective fields together, and this is an area where Norway is already well ahead of the pack. This is perhaps SUBPRO's greatest advantage. We have been able to pick from the top shelf in numerous disciplines and combine these resources in a joint project: SUBPRO, a centre for research-based innovation (SFI). Together we can achieve great results for the future of subsea technology.

As chairman I have a good overview of SUBPRO's activities, and I believe we have been able to establish a well-managed and professional organization in this short time-span. It is very important to bring in more industry partners in the years to come. We lost Aker Solutions as a partner in 2016, and that was tough for us. Going forward, it is important that we highlight how participation in SFI SUBPRO can benefit the industry.

It is crucial that we get the supplier industry on board. They can take the research one step further and help realize products from results. The suppliers have the expertise on how solutions are made and tested. This is essential, both in the short and long term. We are therefore trying to bring more suppliers on board. We were pleased when VNG Norge contacted us in late 2016, and they have agreed to become partners. SUBPRO has proven itself as a key meeting ground, and participants are now much more willing to share than they were before. I see a trend toward more openness between oil and gas companies and the possibility of joint projects, even in collaboration with academia. We do not do research for our benefit alone, and we recognize that joint technological developments benefit all parties involved, and improve the likelihood that the new technology will be implemented. Research results may also be immediately relevant for internal application by the oil companies.

Experience has shown that the more the industry puts into the projects in terms of specific challenges, data and calculations, the more it gets back in terms of useful results. One of the project's strengths is its many excellent PhD students. Our candidates are researching relevant problems that will result in better subsea solutions in the long term. In the future, we have to convince candidates to focus on problems the industry finds relevant in their PhD research, as we are facing a slew of short- and long-term challenges, and SUBPRO intends to face these head on to develop new and better solutions.

CO_2 footprints are a central concern, even in the type of projects SUBPRO is working on. Through research, we can contribute to the development of more energy-efficient extraction solutions, reducing emissions per produced unit in new fields.

Our research could potentially also have applications beyond the petroleum industry. It may also be relevant for systems technology, process, control engineering and reliability solutions. These technologies play a major role in renewable energy.

What can be achieved in eight years?

SUBPRO is still in the start-up phase. Two years have passed, and we have already seen some results. A collaboration with Brazil is underway; we are hoping to establish an exchange programme for students, similar to the one we have with the French university Mines ParisTech. We will be educating almost three generations of PhD students during the project period, and I want our PhD students and postdoctoral fellows to feel that they have contributed to changing how we approach subsea work in the future!

Our goal must also be to make some progress on the challenges we can see coming, and to get the industry to implement some of our solutions, either directly through the oil companies or through new products offered by suppliers.

Audun Faanes, Statoil
Chairman of SFI SUBPRO

PARTNERS

Statoil
Shell
VNG Norge
DNV·GL
The Research Council of Norway
ABB
Lundin Norway
ENGIE
NTNU
Norwegian University of Science and Technology

AS NORSKE SHELL

How do you regard the potential value for Shell of participating in the SUBPRO project?
SUBPRO has the potential, through collaborative innovation, to provide insight in and solutions to current and future subsea challenges. For Shell, the main potential is both in contributing to and harvesting from the knowledge that is generated between the partners.

How does the realization of the Centre so far meet your expectations?
The realisation of the Centre is on plan, and follows our anticipation and is to our satisfaction. The students and post docs at the Centre are working on highly relevant topics important for the future of the subsea industry.

Richard Arntzen
Senior Engineer AS Norske Shell

VNG NORGE

What are VNG Norge's expectations to SUBPRO, as a new industry partner?
Subsea technology, innovation and knowledge is an enabler for future subsea field development successes, and SUBPRO may become an important contributor to these successes with the established research centre. We are excited about becoming a SUBPRO member.

Jørgen Berntsen,
Field Development Engineer,
VNG Norge AS

THE RESEARCH COUNCIL OF NORWAY

What are the expectations to SUBPRO from the Reseach Council of Norway, and how do you consider the organization of SUBPRO with respect to meeting these expectations?
The SFI scheme is the Research Council's flagship for long-term industrial research with internationally recognized quality. The Research Council has high expectations to the centres. The centres will strengthen innovation and doctoral education areas that are important for development of a competitive business environment.
They will provide important stimulation for cooperation between research and businesses, and also between universities and research institutes and between businesses. The centres will contribute to making Norway more visible on the international arena. SFI SUBPRO has good possibilities for meeting these expectations. The centre works in an area where Norway has a strong position and has the world's leading industry. The centre is firmly rooted in the host institution NTNU and has industry partners which are committed and actively participating. The collaboration with the industry is characterized by transparency and trust. The Research Council is looking forward to follow SUBPRO in the years to come.

Kai Mjøsund
Department Director,
Department for Research Based Innovation, The Research Council of Norway

Industry meets research – Research meets industry

Opportunities and challenges for innovation in the interface between research and industry.

We invited Tone Schanke-Jørgensen, Chief Engineer Subsea Systems at Lundin Norway, and Mary Ann Lundteigen, Professor at NTNU and Co-Director in SUBPRO, to a meeting in Oslo. The idea was to initiate a discussion on the opportunities and challenges of collaboration between industry and research. It didn't take long for them to get warmed up.

We'll begin with the importance of the kind of long-term perspective SUBPRO requires.

TONE: When the question of participation in SUBPRO first came up, I remember thinking that starting this kind of centre now, focusing on subsea research, was extremely poor timing. The industry is in decline. But then again, this is exactly what we need now. From our perspective, participating in SUBPRO gives us an opportunity to gather our thoughts and look forward with a long-term perspective; we don't often have time to do that in good times.

TONE SCHANKE-JØRGENSEN is Chief Engineer Subsea Systems at Lundin Norway.

MARY ANN: It's good to hear your take on the benefits of the centre. In any innovation project like ours, industry partners are essential in terms of providing purpose and direction for the research activities. We are excited about a new partner at the centre, VNG Norge, and we hope they will experience just what you're describing now, Tone. A centre for research-based innovation, or SFI, also serves as a network that ensures that we don't lose sight of the long-term perspectives and all they entail, which is easy when we are so focused on short-term, current problems.

TONE: Yeah, I often think that we are dedicating so much focus to things that must be solved today, that we don't have time to focus on the things coming up down the line. Without a dedicated research department of our own, the centre is a way for us to get help to develop the solutions we will need in the future – that we don't even know we'll need yet! Our portfolio consists mainly of subsea solutions or projects in the Arctic, which often involve subsea, so SUBPRO is a very good fit for us. This is also an opportunity for us to contribute to pointing academic research in the direction the industry wants and needs.

MARY ANN: Yes, that is a good point, the industry is on the brink of a major transition, particularly in the Arctic region. There is a strong need for new technology, and dimensioning standards will have to be updated. A lot of things have to be identified as new needs, which takes time to develop. I definitely see how SFI SUBPRO gives us the opportunity to keep a finger on the pulse of the industry. That way, we are able to make our courses more relevant, and we can recommend topics for master's theses that, in turn, could contribute to solving future challenges. As a result, we build a comprehensive understanding of the field and the future that can't be achieved in a year. And that's exactly why an SFI with a time frame as long as SUBPRO's is such a good thing.

MARY ANN LUNDTEIGEN is professor at Faculty of Engineering at NTNU and co-director in SUBPRO.

The importance of attracting the best

TONE: That's part of our social contract: safeguarding our organization's expertise, while simultaneously making sure that people with the kind of background we need will be available in the future, too. SUBPRO represents an excellent opportunity to educate PhD and master's degree candidates with relevant competence.

MARY ANN: This is something I'm really passionate about. It's important! I went back and got a PhD after working in the industry for a few years, simply because I wanted to educate myself further. And I have never regretted it. There is great value in getting a PhD as part of a continuing education programme; it may be part of the solution to the transition the industry is facing; we have to acquire new knowledge and new expertise.

TONE: Until now, our graduate students have pretty much had jobs lined up when they finish their master's degrees, which meant that pursuing a doctorate was never even on the table. But we need them in the industry, too! We have to get that message across somehow.

MARY ANN: First we have to recruit them. It has proven quite challenging to get international PhD students to stay in Norway, and we are struggling to get Norwegian graduate students to pursue a PhD.

TONE: We need people who have not been molded by the industry – someone who does not accept the truths we have established as gospel. That's why I feel that one of SUBPRO's strengths is the high number of students. When students start asking questions we haven't asked for 20 years, "because that's just the way it is", things might start to change. And if the goal is to come up with something revolutionary, we need people who think completely outside the box-people who have not been indoctrinated by so-called established truths.

The importance of an interdisciplinary approach, and of thinking outside the box

Another key priority is to establish mechanisms that ensure that new ideas are refined into products with commercial potential. In this regard, SUBPRO is the vessel to get things out. The supplier industry is a critical piece in this puzzle, as they are the link between research and commercialization.

TONE: Our biggest weakness at this point is that we don't have enough partners from the supplier industry. We need them to convert good ideas to good products. The interdisciplinary principle that underpins the centre's entire organization is a great strength in this regard. Participation in working groups with professionals provides a space where ideas can be discussed with others. That's important. The networking opportunities provided by SUBPRO are also rewarding, and sometimes critical, for being able to take something to the next level.

MARY ANN: Bringing in more partners from the supplier industry is definitely a goal for us. We have put a lot of effort into the organizational structure of the centre. We recognize the importance of giving everyone the opportunity to stay informed about new developments and which problems we are currently exploring. This way, we give everyone the opportunity to identify problems they can contribute to solving. We are creating spaces where industry partners and academia come together to discuss. This has the benefit of both improving research and boosting the bottom line. We connect people across faculties; some have worked together before, but some have not. The idea is to be able to see things from a new perspective, approaching a problem from a new angle.

TONE: What we have found, is that the projects where we take part give us an opportunity to think out loudly with someone, and this seems like a productive way to approach any problem. We need the kind of collaboration that allows us to go deep into a specific problem. We also need researchers who go deep. In subsea solutions, sometimes the tiniest of details represent major challenges. Often we do not have the kind of specialized, detailed expertise to resolve these challenges on our own, and we need to collaborate with others. This is especially important for those of us without a dedicated research department.

MARY ANN: Whether we are world-leaders in the field is perhaps a matter of definition, but there is nothing like our combination of academia and industry expertise anywhere else in the world. We have a clear focus, and within the individual disciplines, several of our research communities are among the best in the world. SUBPRO's vision is to further develop the competitive advantage of Norwegian industry in the petroleum sector, and particularly in the field of subsea engineering. At the stage the industry is in now, it is important not to lose sight of this. Knowledge quickly fades if it is not renewed, expanded and further developed.

We need innovation in subsea and SUBPRO is a perfect way of planning the future for subsea operations, says Mary Ann Lundteigen and Tone Schanke Jørgensen.

PROJECT STRUCTURE

Research areas	Field architecture	Reliability, Availability, Maintenance and Safety, (RAMS)	Separation – Fluid characterization	Separation – Process Concepts	System Control
Projects	Subsea gate box	New safety and control philosophy	Produced water quality and injectivity	Membranes for gas dehydration	Dynamic simulation model library
	Field development concepts	RAMS in system design	Modeling of wax deposition	H_2S and hydrate control	Modelling and multi-variable control of subsea system
	Multiphase booster models	Prognostics and condition based maintenance	Sequential separation	Particle breakup and contactor studies	Control of subsea processes
			Modeling of coalescence	Experiments on fluid particle breakage	Estimation of unmeasureable variables
				Compact separation concepts	Process control for extending component life
					Production optimization under uncertainty

In kind contributions from industry partners

FIELD ARCHITECTURE

RELIABILITY, AVAILABILITY, MAINTENANCE AND SAFETY, (RAMS)

SEPARATION FLUID CHARACTERIZATION

SEPARATION PROCESS CONCEPTS

SYSTEM CONTROL

Field Architecture

Prof.
Sigbjørn Sangesland

Research area manager

Improving the technical and economic performance of an integrated subsea production system through simulation of alternative field architectures, distributed well-by-well treatment and boosting and new boosting performance simulation tools.

This research area covers the development of methods, system elements and production process configurations for improving the technical and economic performance of an integrated subsea production system. The subsea system extends from the reservoir, through the wells and the seabed gathering system, the processing and boosting facilities and to the field delivery point, whether it 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 well potentials, 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 developing and operating remote offshore oil and gas reservoirs with low pressure and low temperature in harsh environments. Such strategies include two scenarios; long distance tie-ins and near field receiving facilities.

Three business cases with relevant data and information are formulated to guide and narrow the scope of the R&D work. They represent reference oil and gas fields with current gaps and challenges to subsea production and processing:
Case 1: Gas fieldwith 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

Field Architecture team: From the left: Michael Golan, Sigbjørn Sangesland, Milan Stanko, Mariana Diaz and Diana Gonzalez. (Gilberto Nunez is also a member of the team, not present in the picture.)

Subsea Gate Box

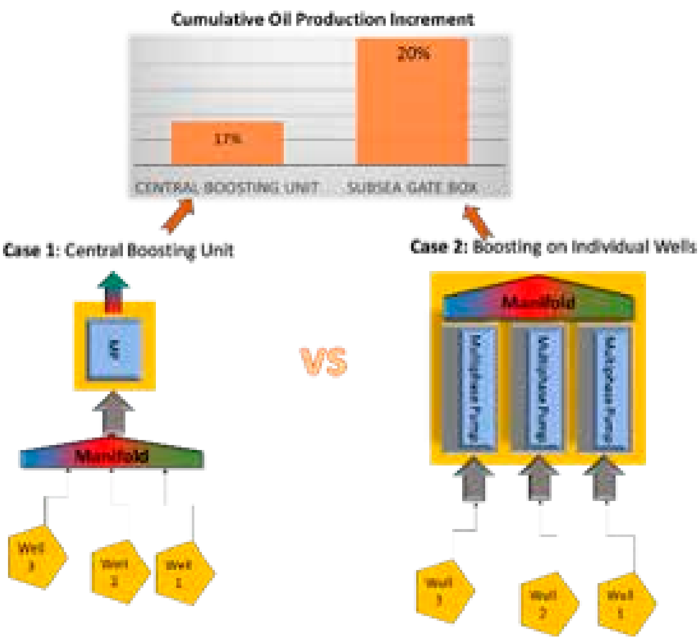
The concept aims to enhance the production management of the individual wells in a field by allowing more operational flexibility and optimizing resource use over the entire life of the field.

Project manager:
Postdoctoral fellow Mariana Diaz
Advisor:
Postdoctoral fellow Jesus De Andrade

The Subsea Gate Box concept is conceived to increase production of the individual wells within the same flow network. In subsea developments the reservoir production relies in fewer wells. The wells should be managed and controlled individually to recover the planned hydrocarbon volumes and reach (or exceed) the expected profitability. However, common subsea field architectures do not consider the individual requirements of the wells, as they are produced towards and commingled into a common subsea manifold regardless of their individual capacity and performance. As a consequence wells with lower productivity determine the system performance while high performing wells are constrained. Hence, the Subsea Gate Box objective is to decouple the production of each individual well from other wells of the same field, and increase system flexibility for the production management. Additionally, it opens for opportunities to optimize the operation of equipment and the utilization of resources over the entire life of the field.

The Gate Box consists of multi-functional modules or distributed structure and accommodates compartments containing appropriate process equipment for individual wells. The functional modules may change according to the wells requirements, and can contain different processing units such as chokes, multiphase flow meters, flow conditioning units, boosters and separators. Each of the process units can be designed to receive production fluids from individual wells or a group of wells, and thus preparing the well stream to be introduced to the production network towards further subsea processing, or towards receiving facilities. The modules assembly could be designed as a single structure in a central location or distributed in individual units adjacent to the well heads.

As a first approach to the concept evaluation, a generic business case based on a standard subsea oil field was defined. Subsequently, simulations using a commercial software allowed computing the production profile of the field considering the interaction among reservoirs, flow in wells and production network. Two alternative cases and the simulated results are shown in the figure below. The results clearly show the potential for significant value creation. Continuing the work, the same approach will be applied using a more realistic case based on information supplied by the partners. Furthermore, some cost analysis could be included to evaluate the concept feasibility. One conference paper is being prepared for presentation in 2017.



Comparing common boosting station after manifold vs subsea gate box concept.

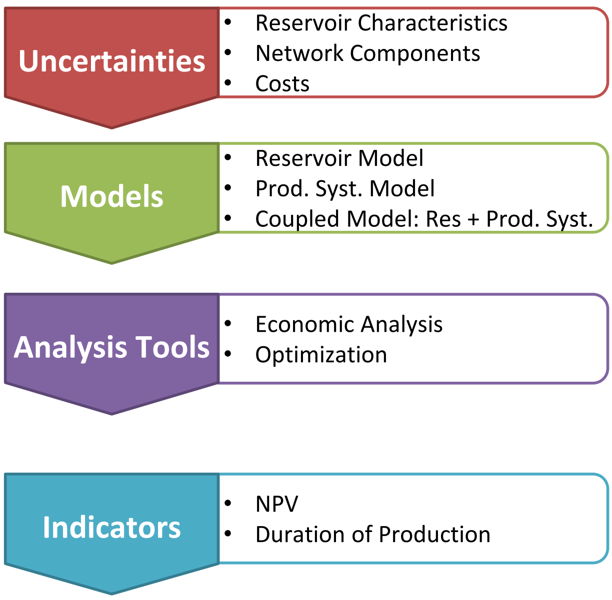
Field development concepts

What is the best methodology to develop a remote offshore oil field with low pressure and temperature?

The main objective of this project is to create tools to determine, analyse and rank cost effective strategies to develop remote offshore oil fields with low energy
- A strategy for the integrated management of uncertainties in the models is under consideration
- A reservoir model based on the characteristics of Wisting field (Barents Sea) was developed

PhD student:
Diana Gonzalez
Project manager and main supervisor:
Associate Prof. Milan Stanko

Over the last years, the world energy demand has increased exponentially, bringing the necessity to develop hydrocarbon resources located in remote areas and with challenging features. However, the development and operation of such type of fields is challenging and, frequently, non-economical. The main objective of this project is to create better methods to determine, analyse and rank cost effective strategies to develop remote offshore oil reservoirs with low energy. A secondary objective is to analyse cost effective solutions for long transportation distances taking into account flow assurance.



Uncertainty Management Tool

To achieve the main objective of this project, tools for evaluation of several field architecture configurations will be developed. For each field architecture, the production profile will be computed by coupling a reservoir model and a model for the production and processing system. Then, a standard economic analysis will be performed where the Net Present Value (NPV) of the system is determined. The "best field architecture" will be one that exhibits the highest profitability and recovery factor. Model-based optimization will be used to determine optimal values of relevant variables such as number of wells, plateau rate, etc.

Additionally, a strategy for the management of uncertainties in models is under consideration. It consists of describing statistically uncertainties in the main parameters of the models and then compute uncertainties in the output values using integrated models. If successful, this approach will be an upgrade to the current development methodology of new fields.

The first steps for the completion of this project were a literature review and a Gap Analysis. After this, a reservoir model based on the characteristics of a low pressure, low temperature and remote oil field in the Barents Sea was developed (Case Wisting). This reservoir model will be coupled with different production system models to compute the production profile of the field architectures to analyse. In parallel, a simplified feasibility study of Cold Flow concepts for wax control in production pipelines was performed. The main principle is to induce the deposition of all wax in a component before the main transportation line. Three types of components where studied: a naked pipe section, a passive cooler and an active cooler, with increasing complexity for wax removal. Results show that the length required for the naked pipe section might be excessive for short tie-backs (<15 km) but promising for longer distances.

Multiphase boosting models

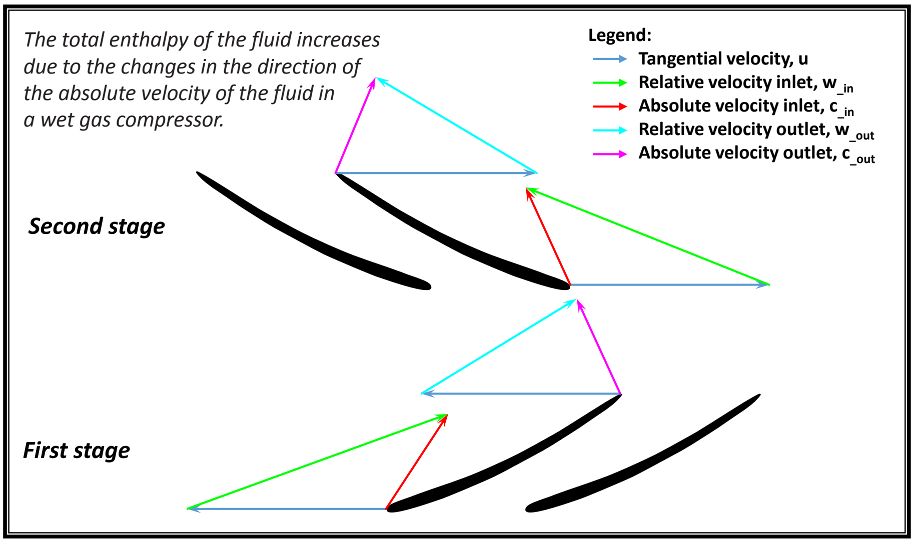
Prediction of boosting performance will contribute to integrated modelling of subsea field solutions and production optimization

PhD student:
Gilberto Nunez
Project manager and main supervisor:
Postdoctoral fellow Jesus De Andrade

Since the late 90s, several subsea boosting technologies have been developed, tested and used commercially in more than 20 fields world-wide. Technologies like multiphase pumping systems have been used for many years over large spans of operating conditions, e.g. differential pressure, temperatures, volumetric flow rates and gas-to-oil ratio. 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. These can now be made available for the partners in SUBPRO, making an integrated modelling of the production system possible in an early design phase of a field development project.

Although simplified performance models do have their limitations, they can be used to increase the understanding of thermodynamic and fluid dynamics phenomena during the boosting process. Implementing such results into a next generation of models for predicting boosting performance is our next goal. It is expected that more comprehensive and accurate modelling tools for the simulation of the complex multiphase boosting phenomena will contribute to better concept selection and model-based decision making during field operations. For example, we have developed a methodology to estimate the pressure increase of an axial counter-rotating wet gas compressor from a thermodynamic and fluid mechanic point of view, applying the fundamental equations of turbomachinery. The energy transferred is quantified based on the flow velocity variations from one row of blades to the next.

Until now, one conference paper has been published and two more publications are planned for 2017. Moreover, there are plans for implementation of the results into other research projects in SUBPRO like the Subsea Gate Box project and Process Control systems projects.



Based on the velocity changes from one row of blades to the next, it is possible to estimate the pressure increase of an axial counter-rotating wet gas compressor

DIANA CAROLINA GONZALEZ RENGIFO

AGE 30 • FROM Caracas, Venezuela • PhD STUDENT AT NTNU Department of Geoscience and Petroleum

Who is Diana?
I am a mechanical engineer, and I came to Norway almost one and a half years ago. I heard about NTNU, because my professor at the university in Venezuela had sent students to Trondheim before. He is very proactive. My supervisor Milan Stanko, for example, was already here, and at field architecture we are now four scientists from Venezuela.

So, it's like having a mini-family here?
Yes, and it is very nice. We are so far away from our families, and therefore it is good to have someone else from my country around.

It helps me understand better when someone is able to answer some of my questions in Spanish, instead of having to go through English or Norwegian. But I do attend Norwegian classes, and I can say "Hei, jeg heter Diana".

In my PhD project, I'm working on evaluating concepts for field development, as well as on finding the best way to develop reservoirs that are remote and make them use low energy.

Did you have any knowledge of this before?
I have studied mechanical flows in connection with simulations for onshore and offshore oil and gas production before, so some of my competence is relevant.

What are you doing right now in your research?
Right now, I am building a reservoir model; we want to work with a specific field in the Barents Sea that hasn't been developed yet. And this is the first bottleneck; we didn't have any information about the reservoir. The biggest challenge is the uncertainty, because we know so little. We have no information, so we are forced to make a lot of assumptions. One thing I am going to do is to compute the production profile and integrate the reservoir model with the production system. This is not the method they use right now in the industry, so this will be a new way of doing it.

Have you always had an interest in solving problems?
When I was a kid, I didn't know what I wanted to do. But as a teenager, I realized that I like to find out how things work, and I wanted to be a mechanical engineer. In my master's thesis, I focused on multiphase flow, and in Venezuela this is important in the petroleum sector. So, that kind of naturally brought me to the oil and gas sector.

Do you think your research could make a difference in the industry?
I don't know. I hope to develop a better methodology for optimizing reservoir development. I would like to simplify the technology and method; it is just one person's work. But I hope that my findings will contribute to a better way of completing the production profile, and I think it could help make oil field development more efficient.

How is it to be a PhD student at NTNU and SUBPRO?
To be a PhD student in SUBPRO is great. I have a network. I have access to knowledge and I learn new methods. We learn from each other, and we regularly share our knowledge with each other. I also feel well cared for. When I need an application for my project I can just ask for it; I have everything I need. And that is very different from Venezuela. I feel very satisfied when I am able to see the connections between the tasks. I feel good when I understand.

Another thing about being in Trondheim is that it is easier to live here in Norway. I do not have to think about going outside and where to go. In Venezuela we have a lot of crime, and you always feel unsafe whenever you go out. At home, I never go outside alone after dark, and I don't take my bike. Here in Norway I can do whatever I want at any time. I love the outdoors, but the winter is horrible.

What about the future? Where do you see yourself in five years?
For me, the thought of going back to Venezuela when I'm finished is hard. I want to go back, but the situation in the country is difficult, so I don't know. The best thing for me would probably be to accept a postdoc fellowship, if possible.

Securing reliable and cost-efficient performance in design and operation

Prof. Mary Ann Lundtegien

Research area manager

Engineers can move mountains! Or almost. Placing a subsea compressor on the seabed, as it was recently done at the Åsgard field at Haltenbanken, is almost like moving a mountain. It was not "just" a compressor, but two compressor trains of the size about half of a football field. Thousands of pieces of equipment, tuned to operate in subsea environment. So, what remains to be resolved after this monumental achievement? There are always opportunities and needs for improvements even for good designs. Different subsea fields will have different constraints, and technology developments like enhanced digitalization may open up for new ways to operate. Finding the most optimal solution with respect to safety, cost and performance and in light of new constraints should always be a target. Determining ways to simplify can be a preferred strategy both from cost and safety perspective. So, how can we help designers and operators in meeting these objectives, without compromising on safety and performance? This is the core question we address in the research area of reliability, availability, maintenance and safety (RAMS). In collaboration with our industry partners, we circled out three main challenges for more specific investigation:

- **How can we reduce complexity, and thereby the size of the installation?** How can we find new ways to simplify the overall design, while ensuring that operation is safe and that equipment is efficiently protected against severe damage.

- **How can we reduce cost of maintenance?** Some equipment is designed with a need for maintanance, while other is expected to require no maintenance during its lifetime. The most driving cost in maintenance, including production losses, is unplanned and non-coordinated maintenance. This happens when we have no control of what is current state and how this affects the future. The main task of our research is to develop models that can utilize monitoring data to predict detoriation processes ahead, and on the basis of this knowledge, produce the best available schedule and coordination of maintenance activities.

- **How can we make right decisions about instrumentation and maintenance strategy already at an early design stage?** It is a paradox that many decisions about design solutions for subsea systems are made in a very early design phase, while most analyses for demonstrating that the decision was good are carried out much later. Poor decisions are costly, and many of them are made because reliability implications in operation are not investigated early enough. The aim of this research is to introduce new models and communication platforms for bridging reliability analysts with system designers as early as possible and when key conceptual decisions are made.

The RAMS group: From left Mary Ann Lundteigen, HyungJu Kim, Anne Barros, Antoine Rauzy, Juntao Zhang, Yiliu Liu and in front Yun Zhang.

New safety and control philosophy for subsea protection systems

The new safety and control philosophies will eliminate overly complex and costly design solutions for subsea processing systems

Postdoc student:
HyungJu Kim
Project manager:
Prof. Mary Ann Lundteigen

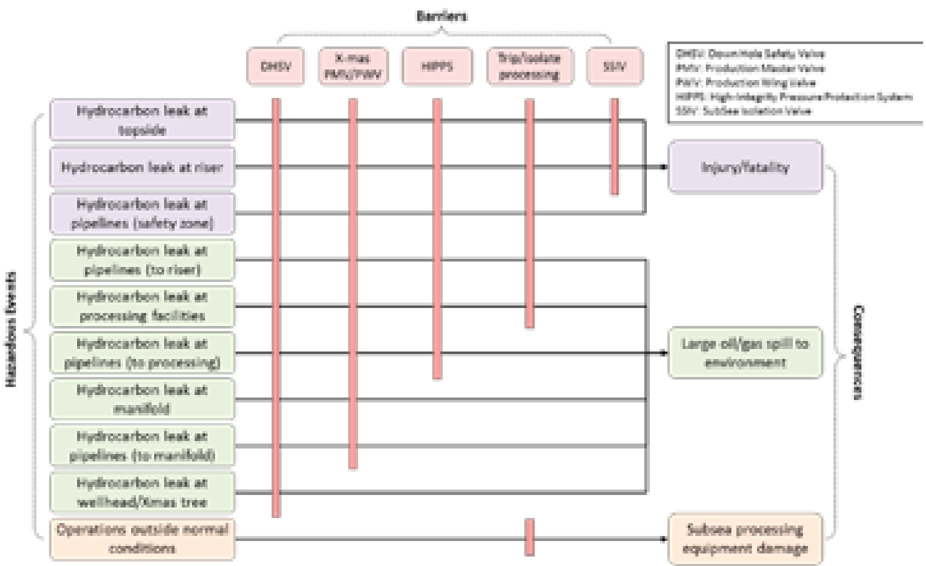
Today, the current philosophies for the design of subsea protection systems build on experience from topside systems. Unfortunately, it is not straightforward to apply the same philosophies for subsea, due to different technical design constraints, different operation conditions, and different associated risks, compared to topside. Applying inadequate philosophies causes overly complex design solutions, which have negatives effect on both safety and cost.

The main objective of this project is to develop and propose new improved philosophies for subsea protection systems. The new philosophies aim to reduce complexity of subsea protection systems and their interactions, while maintaining a high integrity of critical functions.

The first stage of the project has been completed in 2016, and the results are illustrated in the figure. Subsea hazards, associated protection measures, and relevant regulations and standards were identified. It has been found that only a few standards suggest suitable implementations for control and safety of subsea systems. In particular for subsea processing, no standards are available covering subsea-specific control and safety requirements.

In 2017, our goal is to study various philosophies from other industries, as well as new theories, and to develop new philosophies for subsea protection systems. One specific point already identified is the need to distinguish between asset protection functions, preventing damage of subsea equipment (with cost impact only), and safety-critical functions, preventing environmental spills or possible escalation to receiving facilities where also the personnel may be affected. Asset integrity level (AIL) is a measure suggested for the first category, while safety integrity level (SIL) or environmental integrity level (EIL) are used for the latter. SIL and EIL are framed by regulatory requirements and functional safety standards, but it is still needed to investigate how they can best be applied in a subsea context. Using AIL to frame design of equipment protection may call for definition of new requirements and design philosophies, since there is a lack of industry practise and regulations in this area subsea.

The outcome of the project will be tailor-made requirements for subsea protection systems that can eliminate overly complex and costly design solutions, and allow effective protection of humans, environment and asset. It is therefore expected that the outcome will contribute to reduce cost and risks altogether in the future subsea operations.



Subsea risks and associated protection measures

Reliability and availability in subsea design

A tailor-made framework to design the cost-efficient, reliable and safe subsea units

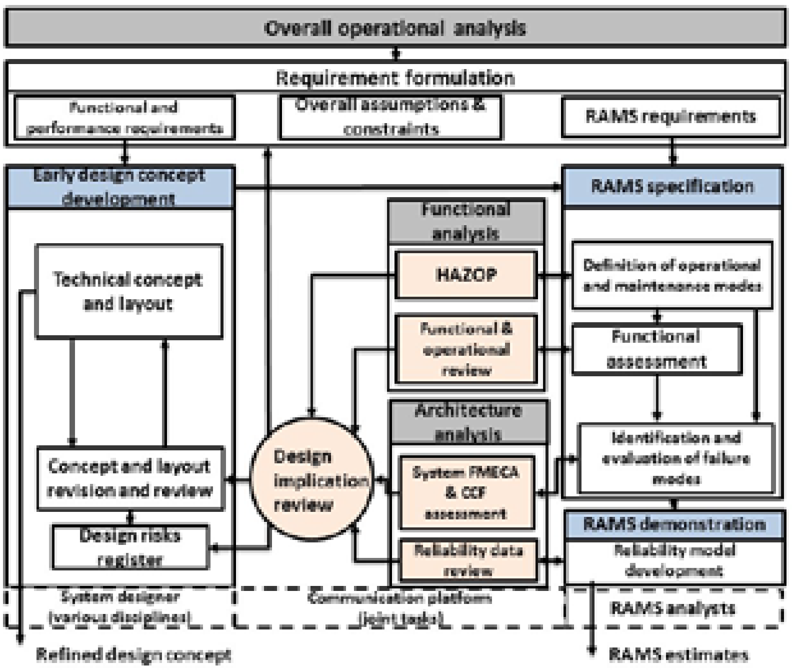
PhD student:
Juntao Zhang
Project manager and main
PhD supervisor: Mary Ann Lundteigen

The main objective of this project is to suggest a new and tailor-made framework for managing reliability and availability in the early design phase of subsea systems.

As of today, most manufacturers and system integrators of subsea facilities have already internal procedures for managing reliability and availability in design. Still, it is often mentioned by several industries that reliability and availability concepts are not well integrated in the earliest design stages. The existing methods and approach in reliability discipline may not be able to give systematic insight of the design concept at early stage. It is of vital importance to integrate the various disciplines involved in design process to give the insight of system (e.g. modularity, demanding operating environment, limited accessibility and the like) and explore the potential of improving existing approaches to be used for early design process.

The first phase of this research, which focused on the investigation on critical steps in early design and corresponding state of art methods, has been completed during the first year. The current stage of this research is to develop the elements of a new framework for managing reliability and availability specification and demonstration, under uncertainty and considering subsea specific issues. The new framework aims to merge the systems engineering discipline with reliability engineering, and suggests also means to structure the communication between system designers, other stakeholders, and the reliability discipline. In collaboration with industry partners and other SUBPROject within SUBPRO, we have identified one case study for to test the framework: the subsea gate box system (described in the research area Field architecture). The intermediate results are presented and discussed in meetings with industry partners, and at relevant conferences and in journals.

The main output of this project is a systematic and holistic framework that is tailor-made for early design of subsea systems. This framework aims to fill in identified gaps in methods and models in the current industry practice. The result of this research can be integrated into technology qualification programs, as amendment to industry standards or internal procedure of oil companies.



Management of reliability and availability in the early design phase

Condition and prognostic based maintenance

PhD student:
Yun Zhang
Project manager and main
PhD supervisor: Prof. Anne Barros

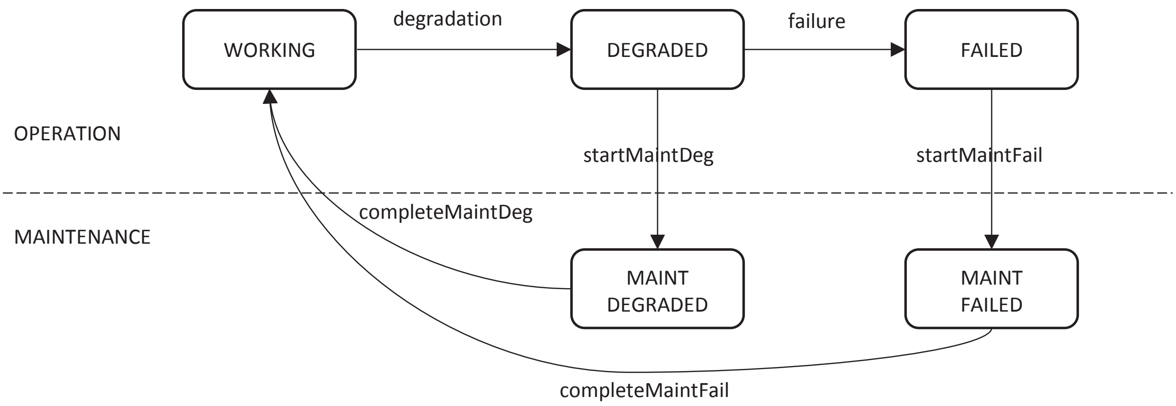
The objective of this project is to optimize the maintenance policies of subsea systems in the arising context of digitalization. Optimization may concern the design phase (e.g. the number and locations of spare units and sensors to monitor degradation processes) and the operation phase (e.g. the number and the frequency of maintenance operations, the maintenance/reconfiguration decisions made during these operations given degradation indicators at hand).

Subsea systems must be highly reliable for both environmental and economic reasons. For topside systems, this high reliability can be obtained by design (by means of redundant equipment) and more importantly by use of continuous monitoring and maintenance in operations. Such an approach is not so simple for subsea systems: planning maintenance actions, reconfigurations, or using monitoring device for the operational phase increases dramatically the complexity of systems. Maintenance operations (including inspections, preventive and corrective actions, reconfigurations) in the harsh subsea environment must be as limited as possible for both technical and economic reasons. It is therefore of primary importance to optimize the design together with the maintenance policy of subsea systems. Ideally, this maintenance policy should also be designed as predictive, i.e. should be able to take into account future data collected by monitoring and future usage in addition to experience feedback.

Developing models to optimize predictive maintenance policies raises however a number of scientific challenges: the definition of accurate degradation models for parts, the characterization of uncertainties in monitoring and inspection data, the integration at the system level of results obtained for parts and the computational complexity of calculation of relevant key process indicators.

The core research activity is based on a joint use of i) stochastic processes as a basis for degradation modeling and prognostics (Remaining Useful Lifetime Prediction) ii) high level language modeling (AltaRica) as a basis for system modeling, calculation of key indicators and decision-making optimization.

At the end, the provided studies, models and tools will allow to simulate and assess the performance of different maintenance strategies for subsea systems (e.g. choke valves, HIPPS, compressor).



Equipment degradation and condition/prognostic based maintenance

JUNTAO ZHANG

AGE 26 • FROM Fuzhou in China

PhD STUDENT AT NTNU Department of Mechanical and Industrial Engineering

Who is Juntao?
I came to Trondheim 3 years ago to complete my master's degree at the RAMS group. And after that, I got the opportunity to take a PhD in the same group, though not on the same subject. In my PhD, I am focusing on subsea facilities.

How did you end up in Trondheim and NTNU after your bachelor's degree?
I completed my bachelor's in Macau in China. If you've been there you know that it is the most crowded city in Asia and similar to Las Vegas, with a lot of casinos. So, after studied there I felt I needed to find a quiet and peaceful city that was suitable for research work. And in Norway, at NTNU, I found both a quiet place and a subject that was compatible with my background.

After 3 years I can say that this really is a quiet city for living and studying. And all my friends who visit from all over the world feel the same way.

What are you doing right now?
In my PhD, I look at reliability in subsea design. Reliability is an important attribute when evaluating the success of system. In many companies, they have internal procedures for managing reliability in subsea designs, but RAMS professionals always come in too late. Therefore, all my work here is focused on integrating RAMS as early as possible in the design phase to prevent unnecessary costs later. That is our main contribution.

So, if we succeed, the results from this research can be integrated into technology qualification programs for new subsea products – an amendment to the existing industry standards or the internal procedures of oil companies.

So basically, your goal is to make designers aware of and introduce RAMS much earlier in the design phase?
Yes. When it's introduced too late, sometimes there is no clear interface between the models that designers use and the ones that RAMS analysts use in current industry practices. RAMS teams and design teams therefore often spend considerable time and money reaching the same design outcomes, and often end up 'agreeing to disagree'. We work on establishing means of exchanging input and output from various disciplines and make designers and RAMS professionals work together from the beginning of field development, to eliminate the risk of having to redesign and implement costly design modifications in later stages.

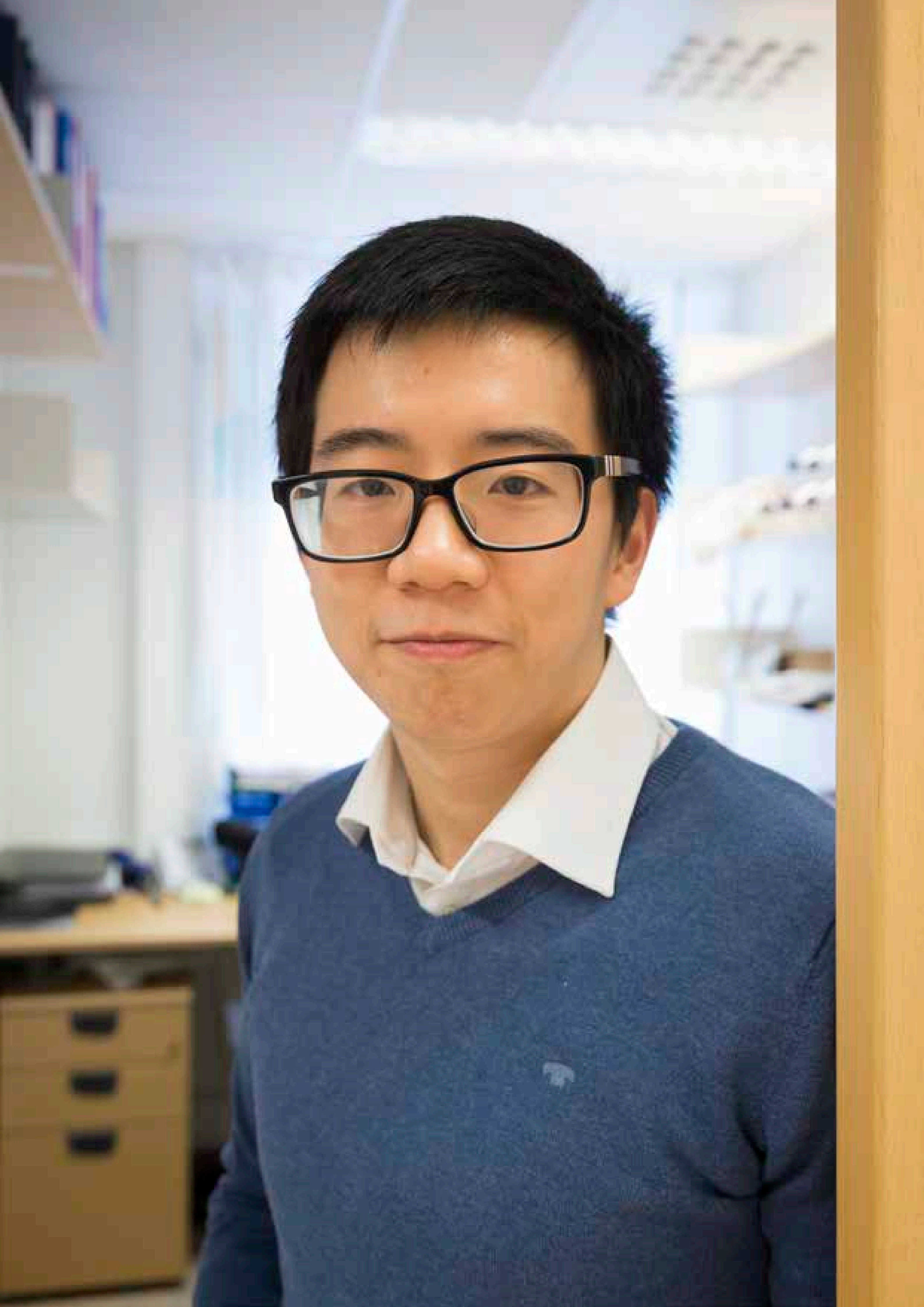
I feel that SUBPRO is a good project for this type of research. Our work is somewhat theoretical, but inside SUBPRO there are other groups working on new subsea design concepts that fit our topic. I'm not only learning how to become a specialist in one topic, but also how to solve difficult problems by getting inspiration from other research areas and input from our industry partners.

Do you think that the work you do can help change the oil and gas industry?
I think that if we succeed, our research results will complement existing procedures for managing RAMS in subsea development. On the other hand, I believe that the aviation and railway industries have the same need of reliability and safety. The study and models from this project will not be limited to any specific industry.

Were you interested in these things as a child as well?
Yes, in high school I was; at university-level I studied mechanical engineering, but I always felt that safety and reliability are important. That was the reason I came to Norway: to work on this in the RAMS group, where I get to experience the strong interface of theoretical and practical areas.

Have you had any "goose bumps moments" in connection with your work?
Yes, I guess so. I remember, for example, when I first learned a new high-level modelling language called AltaRica that was developed by one of our professors and his team. This modelling approach provides a strong mathematical framework for reliability modelling, as well as a new approach to defining the foundation of RAMS analysis. In my research project, I will extract the valuable and interesting part of this modelling language.

So, you feel you are learning something new all the time?
Yes, every time I have a meeting with someone outside or inside our group I learn something new. SUBPRO is a great opportunity for me to learn more about subsea production and processing in addition to being able to specialize in the RAMS field.



Subsea factory. Courtesy of Statoil

Separation – Fluid Characterization

Professor Gisle Øye
Research area co-manager

Professor Johan Sjöblom
Research area manager

Controlled separation of gas, oil and water, efficient treatment and handling of the produced water and reliable transport of the hydrocarbons are central areas in subsea processing. Further, minimal requirements to maintenance of the processing equipment is important. 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 research is currently focusing on the following topics:

- 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.

Fun at the laboratory. From left: Jost Ruwoldt, Marcin Dudek Are Bertheussen and Aleksandar Mehandzhiyski.

Produced water quality and injectivity

PhD student:
Marcin Dudek
Project manager and main supervisor:
Prof. Gisle Øye

The main goal of this project is to study drop and bubble phenomena, occurring during the produced water treatment. Development of the novel microfluidic methodology will enable the study of the phenomena at temperature and pressure conditions similar to subsea processing conditions.

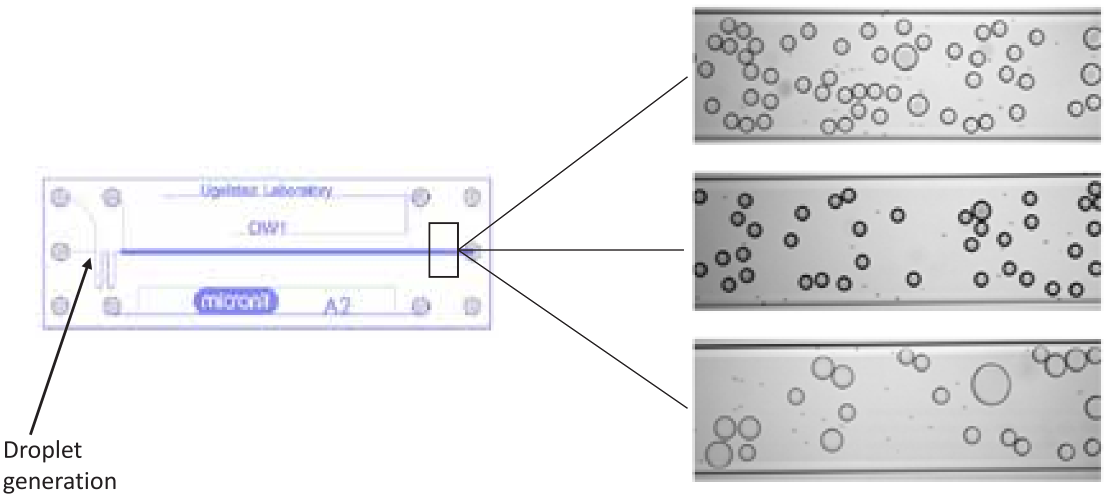
Produced water (PW) is an unavoidable by-product of the crude oil production. Reinjection of the PW is anticipated to be the most beneficial way of handling it during subsea production. For this reason, the produced water must be treated to a certain level of purity to avoid damaging the reservoir. Enhanced gravity separation and gas flotation are methods considered for the subsea removal of dispersed oil from PW. Various interactions between oil drops and gas bubbles will influence the efficiency of the produced water treatments. These processes are usually tested in technical scale facilities, while the interfacial phenomena involved in separation is often overlooked. However, knowledge about the involved fundamental mechanisms can contribute to improved performance of the entire subsea crude oil production system.

A new microfluidic platform has been designed and assembled in the Ugelstad Laboratory to study the drop and bubble phenomena. In this setup, drops and bubbles are generated in a controlled way and their interactions are visualized by microscopy and high-speed imaging. The first part of this research project focuses on how the composition of crude oil and water influences the behaviour of oil droplets under different conditions (see Figure). This is of importance for the gravity or enhanced gravity separation. Interactions between the gas bubbles and crude oil drops will be dealt with in the second part of this project. Both parts are a combination of microfluidic and bench scale experiments.

The project will contribute to a better fundamental understanding of the small-scale phenomena, involved in the produced water treatment processes. Additionally, it will also generate and establish new (microfluidic) methods for studying crude oil systems. The results can be used for improving the design of separators and other adjacent equipment.

FACTS

- Microfluidics is a fairly new branch of science that deals with control and manipulation of fluids on a microscale
- The newly built microfluidic setup is capable of working with temperatures of up to 60°C and pressures of max. 80 bar



Microfluidic chip (left) and frames showing different behaviour of crude oil droplets with the same initial conditions (right). Understanding the influence of different parameters (oil and water composition, pressure, temperature) can lead to increased growth of oil drops, consequently improving the separation process.

Wax deposition

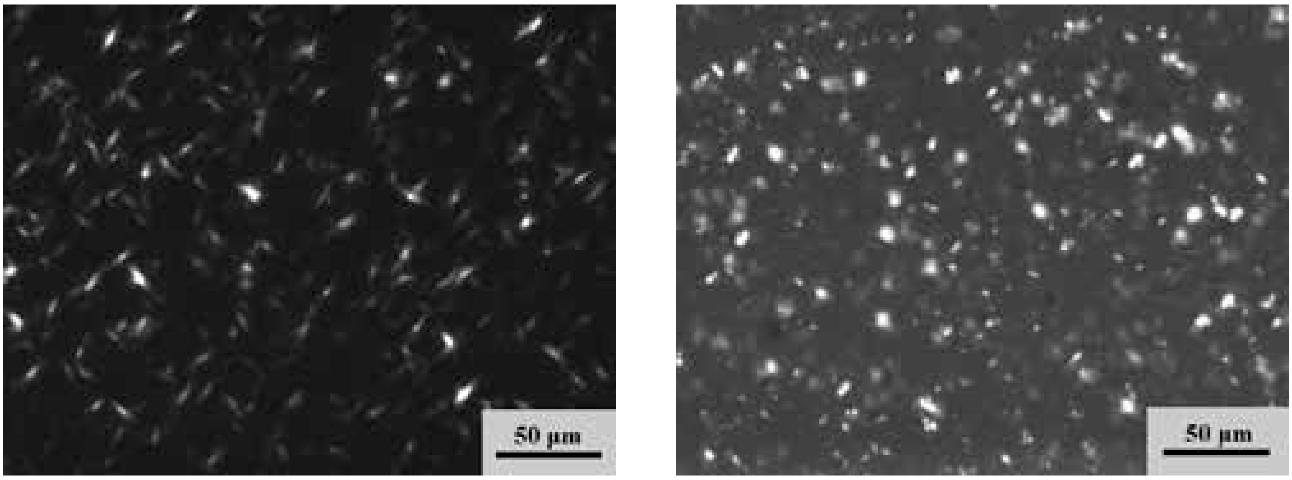
Research on wax inhibitors and pour point depressants helps managing wax related challenges in crude oil production.

PhD student:
Jost Ruwoldt
Project manager and main supervisor:
Johan Sjöblom

Current trends in the oil and gas industry are to explore deeper and harsher environments, but also to increase field complexity and transport distance in subsea production facilities. These trends bring challenges due to paraffin wax contained in the crude oil. When the crude is cooled down below the wax appearance temperature, solid wax precipitates, which can lead to blockage and plugging in the pipeline. One way of managing these challenges is the use of chemical additives. Commonly used are wax inhibitors and pour point depressants, which change shape and size of the formed wax crystals to lower the viscosity of the formed wax oil gel, and ensures proper and unobstructed flow of the crude oil. However, the exact working mechanism of wax inhibitors is still not understood, and inhibitors often have to be adapted to different crude oils or changes in crude oil composition. As a consequence, activities in this sub project are dedicated to:

- Investigate the process of wax crystallization on a fundamental level
- Shed light on the functioning mechanisms of wax inhibitors and pour point depressants
- Help develop crude oil based chemical additives for flow assurance in subsea crude oil production

To fulfil these goals, research is done on the effect of different commercial and non commercial wax inhibitors and pour point depressants on wax crystallization. Established methods are used, such as differential scanning calorimetry, cross polarized microscopy (Figure 1), and rheometry, but also new methods and instruments are applied, such as isothermal titration calorimetry. The gained knowledge contributes to the understanding of what defines a good working inhibitor and how it works. Moreover, the application of asphaltenes as crude oil derived wax inhibitors is investigated. Extracting components from crude oil that can be re injected as wax inhibitors is a technology that has been shown to work, but was never applied on an industrial level. Research in this area could therefore enable the production of a low cost alternative to commercial products that is abundant at the place of use.



Cross polarized microscope images showing the effect of inhibitor: Plate and needle shaped wax crystals (left) are changed to more round and compact structures when crystallizing with a pour point depressant (right). This lowers the degree of three dimensional interlocking, and thereby pour point and viscosity of the formed wax-oil gel.

Sequential separation

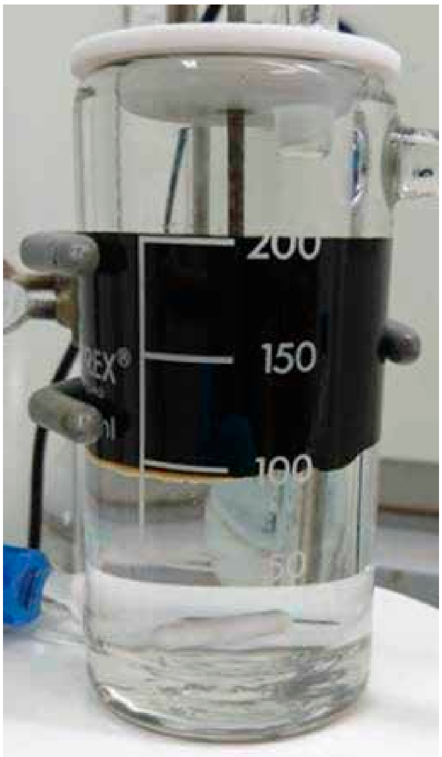
Research on the impact of fluid properties on separation and water quality in subsea processing facilities.

PhD student:
Are Bertheussen
Project manager and main supervisor:
Prof. Johan Sjöblom

Acids and bases in crude oil affect oil-water separation and water quality depending on pH, temperature, molecular weight and pressure.

The partitioning of these polar crude oil components into the water phase is related to the stability of emulsions and precipitate that clog process equipment or cause formation damage.

Part of the complete subsea factory envisioned by industry includes production of export quality crude oil and separation of produced water at the seafloor. Like on topside operations the required oil and water purities are achieved through additional processing. Accessibility dictates subsea processing solutions to be robust and reliable against different production profiles over the field's life time. This sub-project aims to predict how changing inlet conditions to the subsea processing unit will affect the oil and water quality throughout the different stages of the crude oil separation. The research is focusing on the compounds that affect separation and water quality, namely, polar crude oil compounds like naphthenic acids and bases. Central questions are: Which acid and base sizes partition into the water phase at different conditions and at which rate? How does the increasing water cut at the inlet and the decreasing water cut throughout the separators affect the separation and water quality? We started out studying two acid molecules and two basic molecules of different sizes. The equilibrium partitioning of these compounds over a range of pH levels has been successfully modeled. Phase transfers of compounds, depending on pH level, were observed with the large acid and small base. Adding calcium salt to the water phase affected the large acid which precipitated over pH 7. Interfacial tension studies over the pH scale indicate that acid-base mixtures do not interact at the interface. Initial kinetic partitioning studies on the large and small acid, indicate equal partitioning rates and these remain unaffected by presence of another major polar crude oil component; asphaltenes. The next phase of experiments will follow the partitioning of complex naphthenic acid mixtures in model oil and crude oil. This research could give insight into how crude oil acids and bases partition kinetically in the processing system and how this affects the separation and water quality.



FACTS

- Bases adsorb at the water oil interface at low pH while acids adsorb at high pH.
- Crude oil acids and bases can place themselves at the oil water interface or partition into the water phase.
- Bulk phase partitioning of these compounds are related to conditions at the oil-water interface.
- Crude oil acids are both more water soluble and more interfacially active at high pH than crude oil bases are at low pH.

This picture depicts how the partitioning of acids and bases over a flat phase interface is measured. The top part is toluene with asphaltene, acids and bases. The water phase is a buffer with constant pH 8.5 with 3.5 wt % NaCl. The temperature is kept constant at 25 °C. Samples are taken from the oil phase and water phase over time.

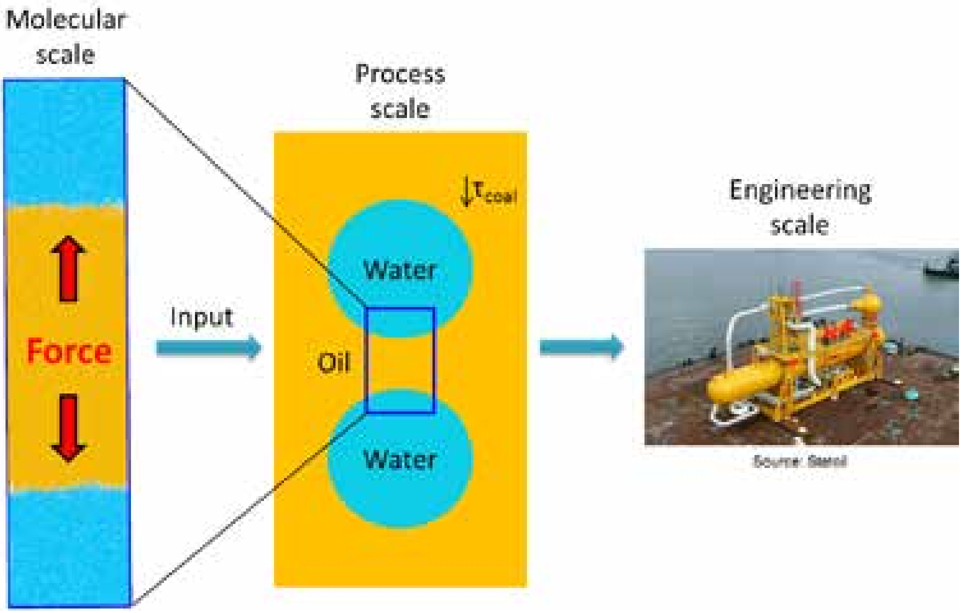
Modeling of coalescence

A multiscale model of coalescence (merging of multiple droplets into one) including the chemical composition of crude oil is being developed. The model will predict the coalescence time based on the chemical composition of crude oil. This knowledge can be applied to model more accurately oil-water separation in order to optimize the performance and design of separators.

Postdoctoral fellow:
Aleksandar Mehandzhiyski
Project manager:
Associate Prof. Brian A. Grimes

In order to best utilize the capacity of the subsea equipment such as pumps and compressors, separation of well fluids will become necessary subsea. 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. However, coalescence can be difficult for petrofluids 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.

Consequently, 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 new expression of the coalescence time. Coalescence is a physical phenomenon which spans from the molecular to the process scale, both on time and dimension scales. With this project we aim to bridge the gap between molecular and process scales using a multiscale modelling approach. Coalescence time based on multiscale modelling which takes into account crude oil chemistry can be employed into separation and transport models to provide more realistic engineering calculations.



Multiscale modelling of coalescence, where τ_{coal} is the coalescence time.

ARE BERTHEUSSEN

AGE 27 • FROM Sandnes, Norway • PhD STUDENT AT NTNU Department of Chemical Engineering

Who is Are?
I grew up in a community where everyone worked in the petroleum industry. In my house, however, things were different; my mother taught German in upper secondary school, and my father worked with electricity at a technical vocational college. So, naturally, I chose to learn French, and I was definitely not going to work with anything related to electricity.

And then, after the military, you went to France for engineering studies in Toulouse. But you came back?
Yeah, I didn't want to do the same thing as everyone else. But my friends told me about the community at NTNU, and I changed my mind. After the first year, I just had to bite the bullet. The environment you study in matters a lot, and I have no regrets. I started studying chemistry, and I was just instantly integrated in the community there. Half and half girls and boys, lots of cool people and courses I excelled at.

What is it about chemistry that made you choose to study it?
Hmm, I don't know, I guess it changes your view of the world in a way; you get insight into how everything is connected.

And I just read some articles from the 1930s about the field. That was awesome. I should have read them sooner. They were so thorough and great at what they did back then, and it's still relevant! And when you think about how they accessed knowledge back then, with no Internet and stuff. That's cool!

What are you working on right now?
I'm in the lab a lot; I plan and execute experiments. And then I find out what happens! What I'm working on right now is subsea oil-water separation. Oil companies dream of setting up subsea factories, where everything happens on the seabed instead of on a platform. To do that they need to separate the oil from the water. Currently, they eliminate 85 % of the water, but if they are going to export (from subsea factories) the water content of the oil can't exceed 0.5 %. And to achieve that, they need additional water separation stages.

How do you achieve that?
What we're looking into is how the acids and bases in the oil sit at the oil-water interface, and perhaps they transfer to the water phase, and then we find out how quickly that happens. When the oil enters the separator, there is a pressure change, and CO_2 is released from the water or the oil, and the pH increases. It's just like when you open a bottle of carbonated beverage; the pH in your beverage increases. And if you can get the pH of the oil to increase, more of the acid will transfer to the water phase. How quickly this process happens, which acids transfer, and at what speeds the larger acids transfer compared to smaller acids are some of the things we are looking into right now.

And this will eventually change how pure it is possible to get the oil?
Yes, both water quality and oil-water separation. This might be a small step on the way to being able to plan how subsea separation will take place across the life span of the entire system. A teeny, tiny step. It's almost like sci-fi; a factory on the seabed producing oil and gas, it's a bit futuristic.

Did SUBPRO live up to your expectations?
I didn't really have any expectations or preconceived notions of how it would be to be part of a research project. But it turned out to be great fun, both academically and socially. We have an active social committee, and all the other students are envious. What's great is that the activities include people of all ages; the professors often participate, too. That's a great way to get to know each other.

Do you believe in this sector, and do you see yourself working in this sector in the future?
I do believe it will be around for many more years to come, especially if subsea becomes the norm.

I want to keep working in this field. But I think I'll either be doing research or work on a project. It will all depend on the jobmarket. In any event, it will be exciting to see if total subsea factories become a reality in my lifetime. After all, we already have so many of the pieces we need to make it happen.

Need for new and innovative solutions

Separation – process concepts

Associated prof. Hanna Knuutila

Research area manager

Prof. Hugo Atle Jakobseb

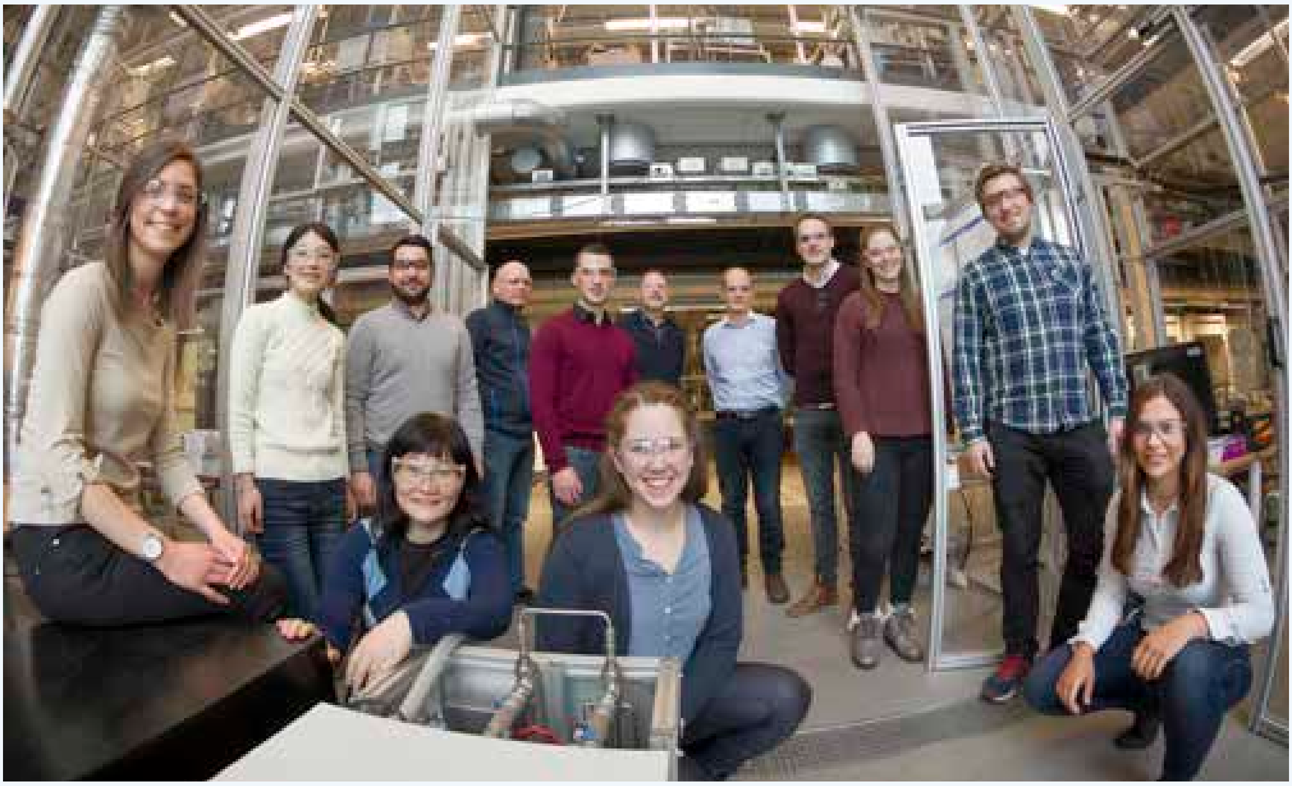
Research area co-manager

The goal of subsea processing is to reduce the need for topside installations and for some fields to move all the needed 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 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 three years of SFI SUBPRO, the focus is on following concepts:

- Membrane dehydration process
- Combined H2S and hydrate control
- Compact subsea separation concepts (liquid-liquid separation)

The process concepts development is supported by fundamental modelling and experimental investigations of fluid particle breakage.



Separation concepts team in the lab. From left: Eirini Skylogianni, Jing Shi, Luca Ansaloni, Hugo Atle Jakobsen, Milan Stanko, Magne Hillestad, Sigbjørn Sangesland, Håvard Slettahjell Skjefstad, Sanna Gangstad, Eirik Helno Herø. In front: Liyuan Deng, Kristin Dalane and Natalie Therese Josefsen.

Membranes for gas dehydration

Subsea dehydration can allow gas processing directly to export pipelines

PhD student:
Kristin Dalane
Project manager and main supervisor:
Associated Prof. Liyuan Deng

The main objective for this project is to evaluate a new membrane process design for subsea natural gas dehydration (see the illustration). The goal is to reach pipeline specifications for water content in the gas (-18°C at 70 bara), and simultaneously prevent transport challenges caused by water (e.g. hydrate formation, corrosion and erosion).

One of the main processing steps in natural gas processing is dehydration, but the conventional dehydration technologies are considered unfeasible for application subsea due to the process equipment complexity. Membrane processes has a potential for subsea operation as it meets the subsea requirements with high modularity, flexible operation and compact design.

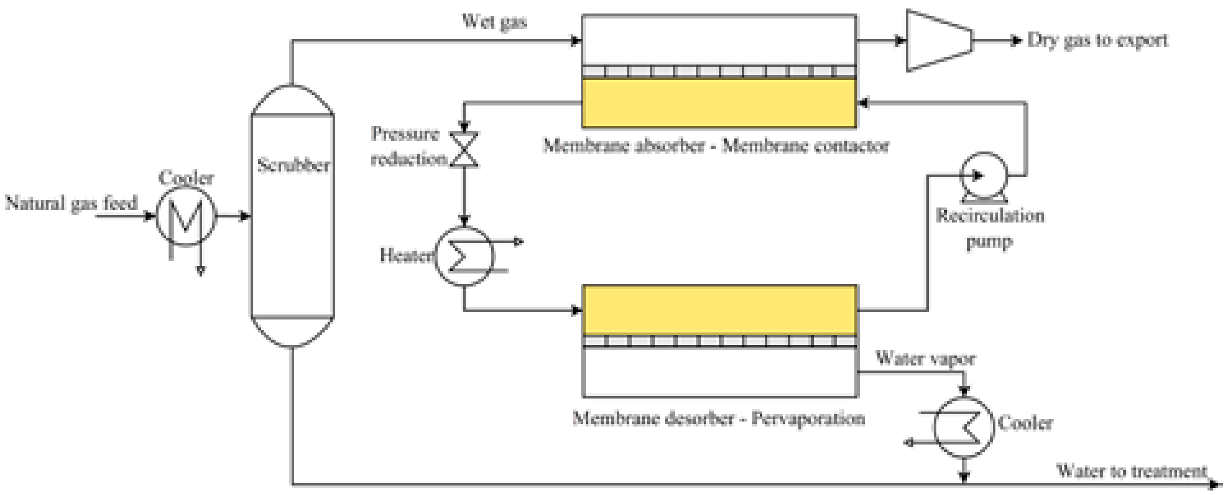
Modelling and process simulation will be conducted to evaluate the membrane dehydration process. Mathematical models of the adsorber and desorber membrane modules will be developed and verified before they are implemented into the simulation tool HYSYS for an overall process design evaluation and optimization. Based on this evaluation a feasibility study of the membrane dehydration process will be conducted.

At the current state, the model for the membrane adsorber (membrane contactor) is developed. The next step is developing a model for the membrane desorber (pervaporation module), before starting on the evaluation of the whole process design. In a later stage, which is outside the scope of the PhD project, there will be a need for verification of models through experimental testing.

With subsea dehydration, water content in downstream pipelines and process equipment will be reduced to acceptable levels, which gives several advantages such as no need for other mitigation techniques such as continuous 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. Moreover, subsea processing of the gas with direct transport in export pipelines, enables tie-in of new fields to existing platforms with limited gas processing capacity.

FACTS

- Membrane contactors can have up to 65-75% reduction in weight and size compared with conventional dehydration towers
- Pervaporation is a more energy-efficient technology compared to distillation.



Preliminary process design for closed loop membrane dehydration with glycol. Water from wet natural gas is absorbed into the glycol in a membrane contactor, and is removed from the rich glycol through pervaporation

Combined H_2S removal and hydrate control

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

PhD student:
Eirini Skylogianni
Project manager and main supervisor:
Associate Prof. Hanna K. Knuutila/
Associate Prof. Diego D. D. Pinto

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. If these requirements cannot be met, oil wells may need to be closed. Today on a typical platform, water is removed by triethylene glycol, while CO_2 and H_2S 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 with separate absorption and regeneration equipment. Simplifying the chemical systems or moving equipment and process elements subsea could ensure higher energy efficiency and utilization of the 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 with e.g. triazine.

In order to design, develop and optimize a treating process, knowledge of the thermodynamic behavior of the system, is necessary. Models for the prediction of the system behavior are available in various simulations tools, which are commonly used by the industry for design and simulation of a process plant. It has been found that the available models today cannot predict accurately the behavior of the combined system we propose due to lack of experimental data availability.

Our research's focus today lies on obtaining new experimental data to satisfy the industrial need for improved simulation tools and models. In this direction, research collaboration with the School of Mines ParisTech in France, and its specialized *Centre of Thermodynamics of Processes*, has been established. Through this collaboration, experimental measurements will be performed, which will later be employed to develop or extend a thermodynamic model for the accurate prediction of the combined H_2S removal and hydrate control process.

Eirini Skylogianni at her laboratory.

FACTS

- Hydrogen sulfide (H_2S) is a highly toxic gas and in the presence of water it can cause severe corrosion problems leading to premature failure of pipelines and other equipment
- Challenging natural gas production from fields with high H_2S concentration due to stringent pipeline specifications, i.e. 4 ppm
- Reduced weight, size and energy requirements are significant factors for subsea application
- A regenerative glycol-amine process could allow for smaller energy-efficient installations and treatment of high H_2S-content fields
- Few available experimental data on this combined system results in modeling limitations

Characterisation of single droplet breakage in turbulent flow

What are the statistical patterns on daughter droplets produced upon a single mother droplet?

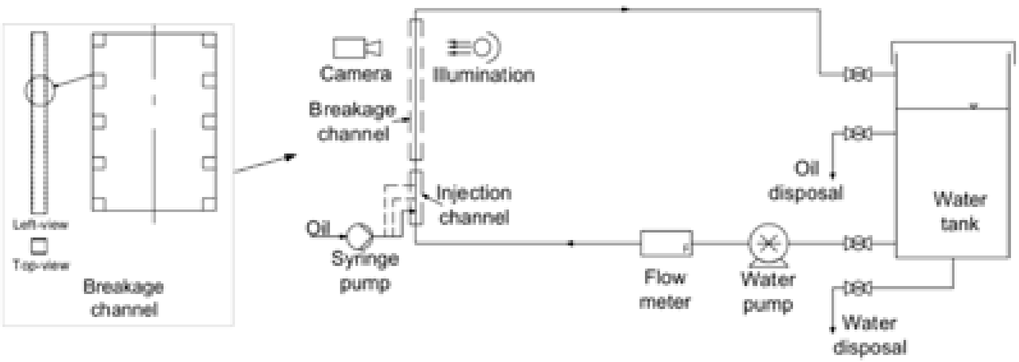
PhD student: Eirik Helno Herø
Postdoctoral fellow: Jing Shi
Project manager and main supervisor:
Prof. Hugo Atle Jakobsen

Phase separation efficiency in separators is severely dependent on the fluid particle size distribution. The fluid particle size is determined by equilibrium between various mechanisms of fluid particle breakage and coalescence. These mechanisms depend on system properties, surface chemistry, operating conditions, and flow phenomena. The current understanding and thus the predictability of these processes are still not sufficient to enable efficient design and reliable operation of the separator units.

In this project, we aim to study the droplet breakage mechanism by experimentation on single droplet breakage in turbulent flow. This project would answer the following questions: Under which conditions does particle breakage occur? What are the statistical patterns for daughters produced from a single mother droplet? What are the physics behind these patterns? The ultimate project result will be improved understanding and model(s) of the breakage process in turbulent flow, which can improve the model prediction accuracy on the droplet size distribution of dispersed liquid-liquid systems with the population balance modelling method. Such models would aid design and operation of separators.

We are carrying out systematical experiments on single droplet breakge in turbulent flow. We use high-speed imaging technique to record the breakage process. For a particular condition (controlled flow rate, i.e., turbulence level, and controlled physical and chemical properties of the continuous and dispersed phase), a sufficient number of breakage events is going to be recorded to obtain statistically meaningful information. With further image processing, we can extract the information of interest, for example, the number of daughter droplets upon a breakage of mother droplet, the size distribution of daughter droplets, and the breakage time. A challenge here is to analyse large amounts of images. It is unpractical to manipulate a commercial software to do the image processing manually. An image-processing programme which is tailored to our specific problem and which enables full automation of image analysis is being developed.

Another challenge is to get information of the underlying turbulent parameters which are related to the breakage process. Computational fluid dynamics (CFD) has been undertaken to provide estimation of the turbulent parameters. Experimental measurement of turbulent parameters is not straightforward. Particle Image Velocimetry (PIV) or Laser Doppler Velocimetry (LDV) would also be used to provide estimation of the turbulent parameters.



Schematic diagram of the experimental setup

Mother drop diameter (mm)	Breakage occur or not	Numbers of daughters upon breakage	Daughter drop 1 diameter (mm)	Daughter drop 2 diameter (mm)	Initial breakage time (s)
5.541	Yes	2	1.407	5.171	0.004

Table 1. Example of information obtained for one sample of breakage event

Compact separation concepts

Novel compact separation concepts for subsea water removal facilitates widespread application of a technology that provides increased returns, increased recovery and more energy-efficient production.

PhD student:
Håvard S. Skjefstad
Project manager and main supervisor:
Associate prof. Milan Stanko

The main objective of this project is to design and develop innovative solutions for separating produced water subsea, and perform experimental and numerical investigations to determine concept performance. Developed concepts should be robust, effective and facilitate easy installation and retrieval.

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, 190 million cubic meters of produced water was reported for 2015. 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 or released. The problem arises when water production increases above designed water treatment capacity, becoming a bottleneck in production. In addition, the high amount of water in the well stream will cause loss of pressure in transportation, lowering production rates and increased energy consumption per barrel produced oil with today's top side separation solutions.

By removing produced water subsea, we can develop more energy-efficient production systems, while at the same time increase production rates and better utilize capacity-constrained infrastructure topside.

At an early stage a systematic evaluation of existing technologies will be performed, identifying shortcomings and future development possibilities. Based on the performed evaluation and feedback from key industrial partners, a concept for further development will be chosen. The focus will be on compact separator solutions, allowing easy installation and retrieval, reduced transportation cost and deep-water installations. By developing a compact and modular design, the cost of installing subsea liquid-liquid separators can be reduced, allowing the business case of subsea water removal to become even more attractive.

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

During 2016, a literature review and Gap-analysis have been completed, preliminary separation concepts have been identified and the laboratory facilities are currently under construction.

Construction of the compact separator test facility is underway, here with master student Espen O. Hestdahl (left) and PhD candidate Håvard S. Skjefstad (right).

EIRIK HELNO HERØ

AGE 26 • FROM Bærum, Norway • PhD STUDENT AT NTNU Department of Chemical Engineering

Who is Eirik?
I always loved math and physics. And since my parents are both graduate engineers, it felt in a way natural for me to come to Trondheim to study mechanical engineering.

What are you working on for your PhD?
I break up oil droplets in a tube of water with turbulence, and I record the process. Then I see how long it takes, and how many daughters my droplet gets. There is a dearth of knowledge about what takes place at the detailed level I'm studying. We need more data. I have two cameras recording the process, and they take 2000 frames a second! These frames are processed by a computer application that converts them to black and white, before it analyzes what happens to the droplets when they are subjected to turbulence.

Did you just come by this project with the droplets by accident?
Yeah, a little, I talked about the project with my professor and it sounded exciting, and it was a chance for me to build on my knowledge. The task itself is a bit more experimental than what I had in mind when I applied for the position. I was and still am very interested in working with turbulence. And in this project we are looking into how turbulence in all phases and forms affects the droplets.

Why is this important?
We want to find out what happens to droplets of oil ascending in a fluid. We want the droplets to be as large as possible, because large droplets have better buoyancy. That's important when it comes to separating the phases; it's easier with large droplets. And to achieve that, we have to know how to avoid small droplets.

So, what you're saying is that finding out what happens at droplet level will decide the future of the petroleum industry?
Yes, at least if we are going to make all installations smaller and go for subsea operation. Having a tool that can help you plan for the future is crucial. The people working with separators always need to know how the droplets are going to behave under different conditions. Everyone who is working with multi-phase technologies will benefit from new and improved models.

What do you expect to learn from these experiments?
Well, I do expect to see a connection between the level of turbulence and droplet size. And that will indicate which theories are the right ones for droplet break-up at that size.

But wouldn't you expect that someone worked this out a long time ago?
Yes, I thought we would have all the simple things figured out by now. But my generation of researchers have access to advanced camera technology and computers that those who came before us didn't, and while others have tried to work this out in the past, it hasn't been possible until now. There are several models for this, but none of them are complete theories yet. There aren't any definitive answers, and it would be awesome if I could be the one to figure it out. My dream would be to develop a data set where I have enough data and experiments to reach a conclusion and say that that's how it is under these conditions. Then everybody else's model would have to be aligned with mine. That is my dream, I would have to say. We already landed on the moon, so that's out, but I can try to land this.

What I'm getting from you here is that research is fun?
Yeah, well, at least I have great respect for research and hold it in high regard. Doing research is among the most important things we do as humans. It is one of the few things we do that we leave behind. It's our legacy.

Nowadays, I find it fascinating to try to understand the "simple" things that often are very complex. At the same time, I also enjoy "nerding out" in the lab by myself sometimes; that's great fun, too!

I really don't see a future without oil in my lifetime – that's why it's so important that we do it right, getting it as pure as possible. The petroleum industry is definitely a potential employment option, as long as the job is exciting. My goal is to work with something where I'm able to apply the knowledge I already have in a new way. And continue to learn new things.

System Control

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

Prof. Sigurd Skogestad

Research area manager

Subsea production and processing requires autonomous operation to a large degree, since these installations are not easily accessible. This means that the systems should to a large extent regulate themselves, hence reducing need for human interaction and monitoring. To reach the goal of autonomous operation, mathematical models are needed

- to design model-based controllers for operation
- to estimate states and parameters to predict unmeasured process conditions
- for production optimization to increase recovery from the reservoir

Modeling is performed by means of first principles based on physical properties as well as empirical observations. Controller, estimator and optimization algorithms will be developed using state-of-the-art methods as well as further enhancements.

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

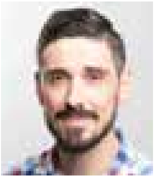
Sub-projects of the System Control Research Area:

- Dynamic simulation model library
- Modelling and multivariable control of subsea systems
- Control of subsea processes
- Estimation of un-measured variables
- Control for extending component life
- Production optimization

System control team in front of a Subsea Distribution Unit from the Njord-field. From left: Sveinung Ohrem, Christoph J. Backi, Sigurd Skogestad, Christian Holden, Tamal Das and Torstein Thode Kristoffersen.

Dynamic simulation model library

A dynamic simulation library for dynamic and steady-state simulation and control of single equipment as well entire processes and systems.



Postdoctoral fellow:
Dr. Christoph J. Backi
Project Manager: Prof. Sigurd Skogestad

The main objective of this project is to develop a library consisting of dynamic and steady-state models for subsea equipment. These models primarily focus on separation technology, such as gravity separators as well as cyclonic devices, e.g. gas-liquid cylindrical cyclones, in-line swirl separators and hydrocyclones. Pumping (single- and multi-phase) as well as compression (dry- and wet-gas) modules are also being developed.

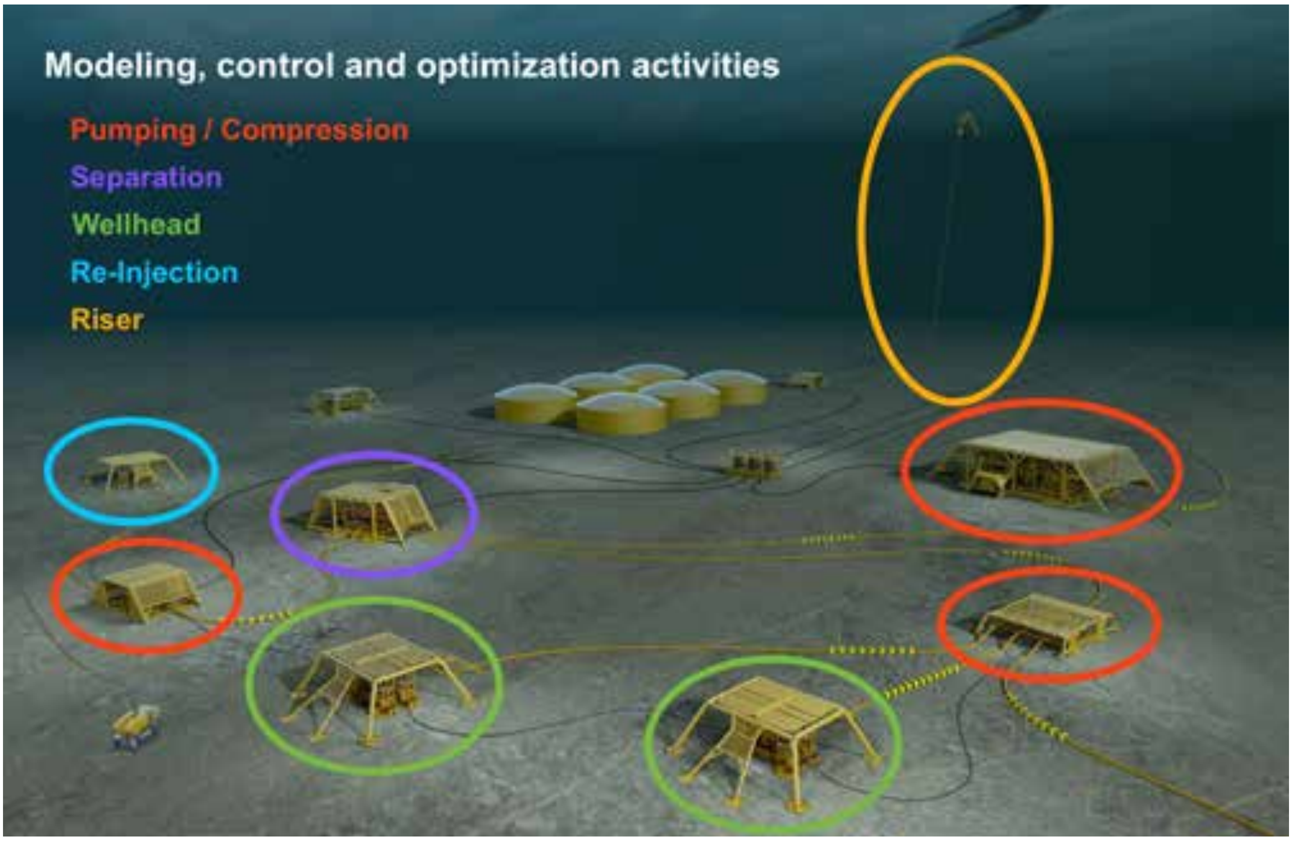
Industry needs simple, yet efficient and accurate models, to describe complex phenomena and behavior of subsea processes. These models are needed for controller design, estimation of un-measurable states/parameters for process condition monitoring as well as for production optimization.

A major part of the project will consist of coordinating the modeling activities in the System Control Research Area. These models will cover the whole chain – from reservoir to product export – and are based on first principles descriptions of the physical phenomena as well as on empirical observations, both accompanied by extensive literature studies. The models should be validated versus real, measured process data as well as laboratory experiments, whenever possible. Furthermore, the choice of simulation environments is crucial to test and verify the models. At first, implementations are tested in MATLAB/Simulink, but later also Modelica as well as other commercial tools, such as OLGA.

Benefits:
With a model library, the industry partners will be able to extend or even replace their already existing models by more sophisticated ones and hence make better predictions.

FACTS

Models in the form of mathematical equations are used to predict the behavior of equipment and processes, develop control and monitoring algorithms for safe operation and for production optimization.



Modeling, control and optimization activities in the research area System control.

Modelling for Control of Subsea Processes

The goal is to develop dynamic models of specific subsea process equipment for the design of advanced control and production optimization systems.

PhD student:
Torstein Thode Kristoffersen
Project manager and main supervisor:
Associate Professor Christian Holden

Traditionally, a large topside processing plant has been the preferred solution for the development and production of offshore oil and gas reservoirs. This technology is expensive but well suited for large fields. However, as smaller fields in deeper waters are considered for production and with the increased focus on cost, the oil and gas industry drives the development towards a complete subsea processing plant.

Digitalization by integrating control and production optimization systems is needed to develop such a plant. Digitalization is a term used to describe the process of achieving optimal remote operation and optimization of process performance and design, based on extended use of instrumentation and dynamic models for utilization in advanced control and production optimization systems. The goal of this project is to contribute to the development of such systems, focusing on the development of dynamic models for:

- cyclonic separators
- wet gas compressors
- multiphase pump
- electrical system

and further combining these models to create a complete subsea separation and boosting plant model (see figure). Additionally, advanced control and optimization systems will be derived to achieve automated and optimal operation and performance resulting in reduced component size, increased capacity and increased product quality.

The dynamic models used to digitalize the operation of different process equipment need to be simple enough to analyze and solve, but complex enough to describe the essential dynamics of the process. By combining the derived models with advanced control algorithms – e.g., Model Predictive Control (MPC) - we can achieve improved control of specific process equipment and thereby reduce buffer volume in separators or reduce capacity of engines driving wet gas compressors.

Moreover, the derived models can be used to predict future behavior, and based on this, the optimal operation (e.g., setpoints normally adjusted by operators) can be calculated automatically and increase capacity, improve performance and reduce the need for human interactions.

So far, we have developed a complete cyclonic separator model and several advanced control algorithms for optimal control, enabling smaller separator size, optimal operation and reducing the need for human interactions. A wet gas compressor model, including the electrical system, is currently under development and the final model will enable further digitalization of a subsea processing plant.

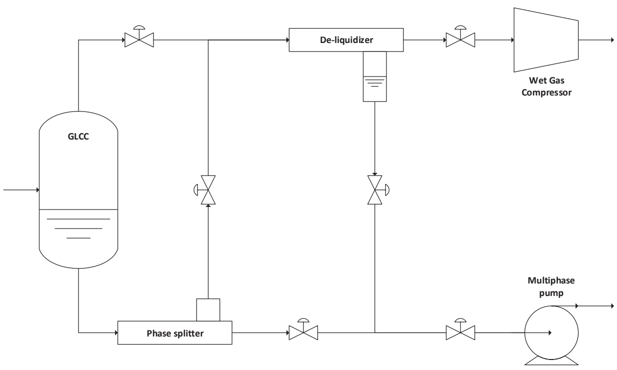


Illustration of the subsea separation and boosting plant to be modeled in this project.

FACTS

- **Dynamic models:** Mathematical models in the form of ordinary differential equations derived from physical laws that quantitatively and qualitatively describe the behavior of the system with respect to equipment design, operation and driving mechanisms.
- **Cyclonic separators:** Thick pipes separators with tangential inlet to create swirl that quickly separates the fluids.
- **Wet gas compressors:** Gas compressor designed to process large quantities of liquid mixed with the gas.
- **Multiphase pump:** Pump designed to process large quantities of gas mixed with the liquid.

Adaptive Control of Subsea Processes

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

PhD student:
Sveinung Ohrem
Project manager and main supervisor:
Associate Prof. Christian Holden

In the production and processing of oil and gas, things are always 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 oil and gas production. In addition, it is not trivial to describe the complex, 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?

Linear controllers, usually designed for a specific operating region, will require re-tuning if the process conditions fall outside the design region. By utilizing new mathematical models of subsea equipment developed by other sub-projects in SUBPRO and field data provided by our industry partners, we will design control algorithms that are robust to the constant changes as well as not being limited to specific operating conditions. In particular, we are designing non-linear and adaptive control algorithms. Adaptive controllers are able to change their parameters based on changes in the process they control and thus re-tune themselves automatically, and non-linear controllers can control systems of high complexity. Changing or updating a control algorithm is economically cheap. By changing a few lines of code, oil and gas companies can increase the quality of the products, decrease the wear and tear of expensive subsea equipment and increase the level of autonomy, which will enable the future of subsea production and processing; the subsea factory.

To validate our controllers and models we are building the Subsea Process Control Laboratory at NTNU (see illustration and fact box). The laboratory includes hydrocyclones, compressors, gas liquid cylindrical cyclones and compact floatation units. The lab can be used with real hydrocarbons at a future date.

Currently, one paper on adaptive anti-slug control has been accepted for publication and one paper on adaptive non-linear control of a gas-liquid cylindrical cyclone has been submitted. We are currently working on several research papers on adaptive, non-linear and model predictive control of gas-liquid cylindrical cyclones and boosting pump stations.

In the Subsea Process Control Laboratory, we will investigate new control algorithms and verify newly developed simulation models. We will also use the lab for education, giving students hands-on experience with subsea related process control.
Photo: Thor Nielsen.

FACTS

Subsea Process Control Laboratory:

Location:	NTNU
Cost:	3.2 MNOK
Physical dimensions (current):	7 x 2 x 2 m
Operational pressure:	25 bar
Max flow:	5000 l/h
Oil type:	Exxol D140
Gas type:	Nitrogen
Operational:	Q3 2017
Completion:	Q4 2018

Estimation of unmeasured variables

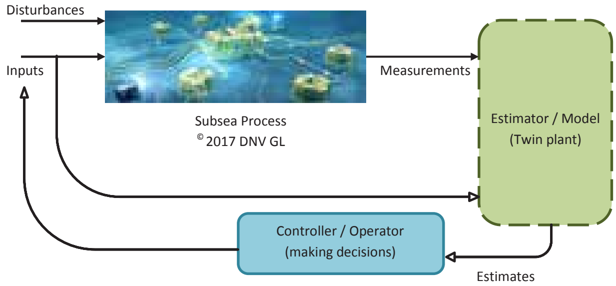
PhD student: Tamal Das
Project Manager and main supervisor: Associate Prof. Johannes Jäschke

In subsea oil and gas production, many important variables are not measured due to lack of reliable or accurate sensors. Some of these variables are essential for process control, monitoring and safety; and useful for planning interventions. State- and parameter estimation is a powerful tool to obtain estimates of unmeasured variables and for improving the accuracy of measurements from inaccurate sensors.

In this project, we want to develop models for subsea processes, such as oil-water-gas separation. These models would form the basis for estimation of variables, such as inflow and oil concentration in water outlet of the separator. We are applying state-of-the-art estimation methods, such as moving horizon estimation, Bayesian estimation, extended Kalman filter etc. Estimation algorithms, if needed, would be tweaked to cater to specific applications, such as online estimation and control.

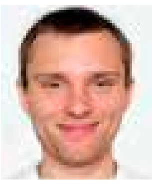
We developed a gravity separator model, which is used for estimation of unmeasured variables, such as inlet flow, inlet water cut and droplet diameter.

Future work shall include estimation of droplet size distribution using a suitable gravity separator model as well as a study of estimation on a separation system.



The measurements and the inputs to the plant are used in the estimation block to estimate unmeasured process variables

Control for extending component life



PhD student:
Adriaen Verheyleweghen
Project manager and main supervisor:
Associate Prof. Johannes Jäschke

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 (large back-off from operational constraints). However, this approach can lead to very conservative operation.

Our idea is to combine health monitoring and optimal 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. We use model predictive control to find the optimal input trajectory, given a mathematical description of the system behavior.

So far we have been looking at the inclusion of first principles degradation models in the decision making process, but we want to include data-driven models as well. If successful, the work could be used to increase profits in a safe manner, by either automating production or in the form of a decision making support system for operators.

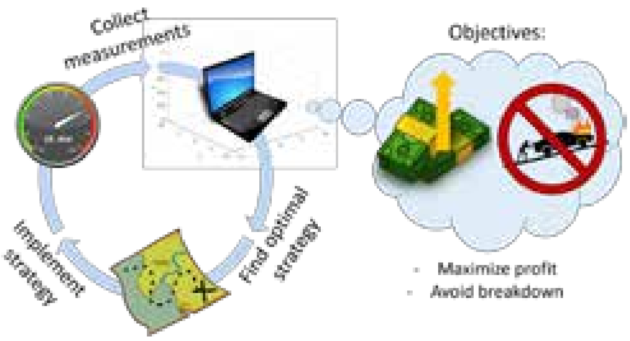


Illustration of the model predictive control principle for extending component life.

Production Optimization under Uncertainty

Efficient optimization strategies for short term production optimization enabling accelerated production

PhD student:
Dinesh Krishnamoorthy
Project manager and main supervisor:
Prof. Sigurd Skogestad

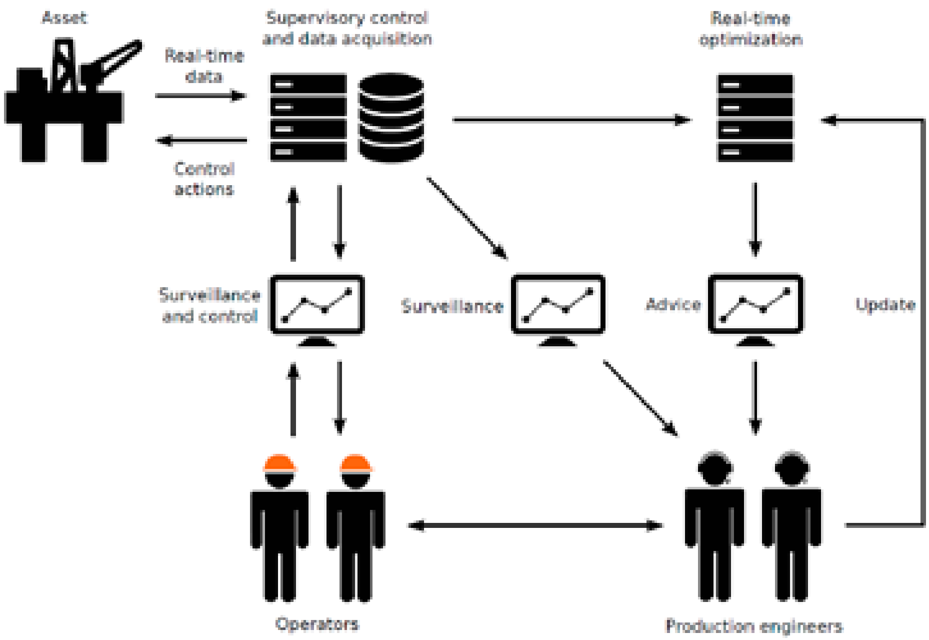
Daily production optimization generally seeks to maximize the oil and gas production and reduce the cost of production. Oil wells producing from challenging reservoirs conditions, wells with advanced completions and complex subsea tie-backs and subsea processing causes decision-making and planning a challenging task due to complex interactions and interconnections between the different wells and subsea processing systems.

Software tools such as PROSPER and GAP are widely used for production optimization by the upstream oil and gas industry. These software tools use steady state models that are updated at irregular intervals. However, due to model simplification, lack of knowledge and sparsity of well test data, the system is subject to wide range of uncertainties. Common sources of uncertainty include Gas-oil ratio, water-cut, productivity index etc. which are crucial for production optimization. This is even more crucial for mature fields where the production is constrained by gas and water processing capacities. The quality of the optimal solution can be enhanced when data and model uncertainty are explicitly taken into account in the production optimization problem.

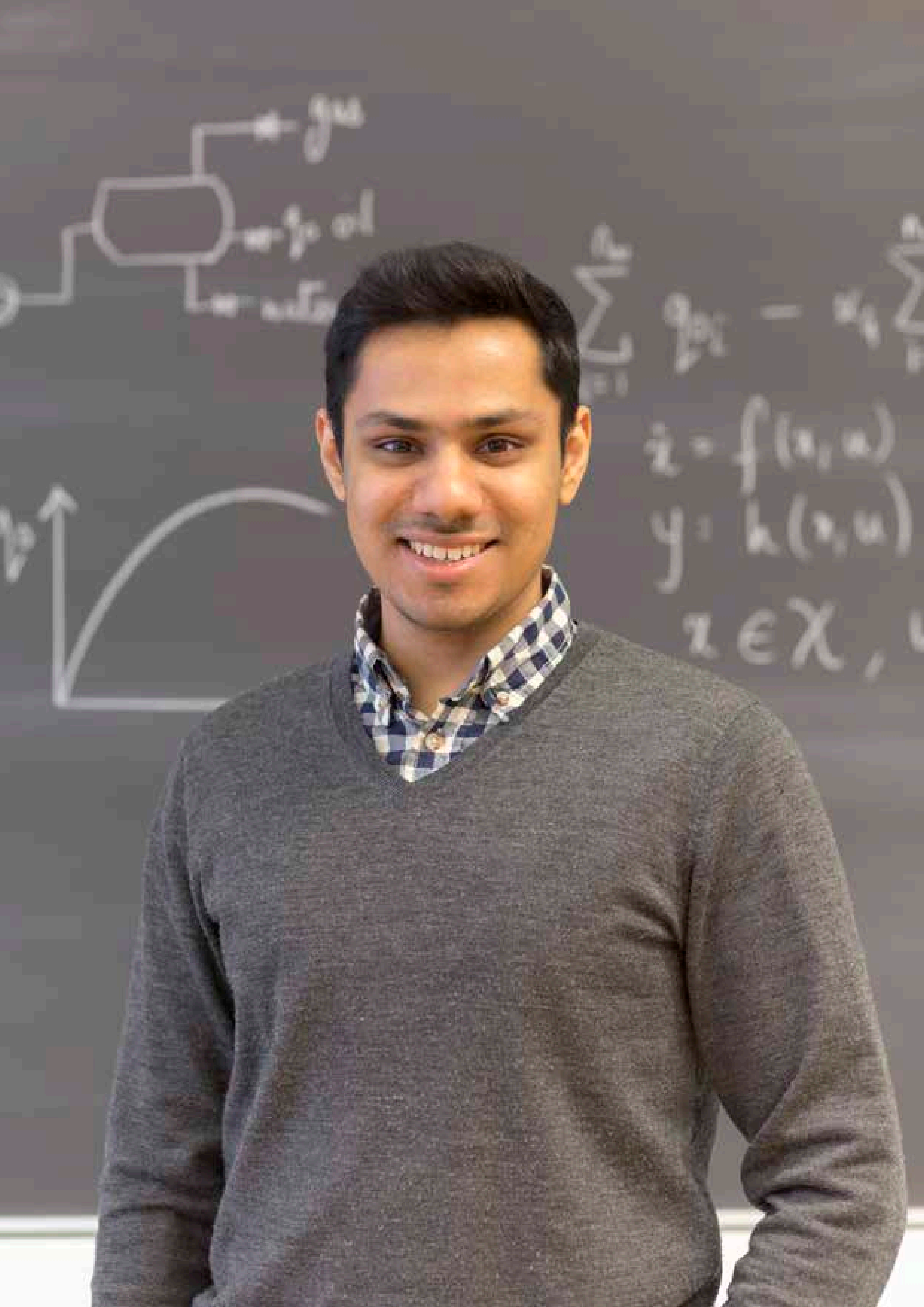
The main focus of this sub-project is to investigate and develop methods for optimal decision making under uncertainty for upstream oil and gas production processes. Special focus will be given to robust and adaptive optimization. In this project, we are mainly concerned with the production network from the near-wellbore reservoir to the inlet separator. The methods will be developed specifically for a cluster of subsea wells producing to a common manifold with a subsea boosting station. Results from this sub-project could be useful for optimizing production from many oil and gas fields by, for instance, exploiting the water and gas handling capabilities efficiently, allocating gas lift optimally among gas lifted wells etc.

FACTS

- Goal: 1-4% increased oil recovery
- Uses existing field infrastructure (no new hardware required)
- Reduced operator workload
- Safe and optimized production



Real time optimization of Subsea production systems (Source: Centre for Integrated Operations in the Petroleum Industry)


gas
$\dot{x} = f(x, u)$
$y = h(x, u)$

DINESH KRISHNAMOORTHY

AGE 26 • FROM India • PhD STUDENT AT NTNU Department of Chemical Engineering

Who is Dinesh?
Ever since I was really young, I have been interested in control systems and robotics. So, that kind of explains my choice of education.

I got my master's degree in control systems at Imperial College in 2012, and soon after that I started working at Statoil's research centre in Porsgrunn. That was four years ago.

What are you doing exactly?
My project is mainly about production optimization in field operations. I am basically developing new methods and software tools to operate fields more efficiently.

The problems that I am working on now are pretty similar to what I was doing in my job at Statoil. Except, now I am looking at them from a more conceptual level, backed by the industrial perspective I gained at Statoil. So, it's a good balance between academic and industrial research. And that is what I find so exciting about SUBPRO. Uncertainty is inherent in any production system. For example, due to the uncertainty in what flows from the reservoir, we may produce more gas or water than we expected. To compensate for this "mismatch", I am developing tools and methods to optimize well operation.

It is very fascinating, because you can think of it as a decision-making process, just like we do every day at home – from choosing what bus to take, to planning a vacation, or what car to buy. We analyze the pros and cons and try to find the best solution. And it is really exciting to be developing decision-making tools that are working with the numbers we have put in.

How difficult is this to do?
It's a challenging problem. You need systems and methods that must be simple enough to implement and easy to understand and operate. Only then can you trust what the computer tells you. So, we have the challenge of human and machine interface.

You were born in India, grew up in Saudi Arabia, went to high school in India, got your bachelor's degree in Malaysia and master's degree in England, and now you are working and studying in Norway – a true globetrotter! Has this background given you any advantages?

It has given me the skills to quickly adapt to new people, places and cultures. And maybe I have a different approach to things with this multicultural background. Both at Statoil and at SUBPRO, we have a lot of different cultures working together, and we represent different technical fields. That is a positive thing about being here, and having my background.

Will your results have any impact on the industry's way of thinking?
One shall at least hope so. And I think that with the strong industry collaboration we have, it is more likely to happen than not. We see that there is a steady increase of interest and focus on digitalization and automation in the oil and gas industry. And the methods we are developing are not just restricted to the oil and gas industry. You know, process control and optimization are at the core of the growing trend of digitalization and automation, and to get to work with that in my PhD is great.

Education and learning

To become an international recognized scientist demands more of you than being one of the best researchers within your academic field of expertise.

«We believe that being a part of the SUBPRO Research Centre, gives PhD students and Postdoctoral fellows a possibility to acquire skills they would not have acquired by following a regular PhD/postdoc program" says Gro Mogseth, Technical Coordinator in SUBPRO.

«During their time in SUBPRO the candidates will for instance get the experience and the ability to increase their competence within planning, status reporting, presentational techniques and multidisciplinary work, something that will be useful for them in their future work as researchers and engineers."

As a part of their projects in SUBPRO the candidates establish detailed research plans, and report regularly the status of their projects to our industry partners. SUBPRO also arranges reference group meetings with the industry partners twice a year, where the candidates present what they are working on and their results. The reference group meetings are also an arena where the partners give input to the ongoing research.

This is from an excursion to Statoil at Rotvoll, to take a closer look at two Subsea Distribution Units from the Njord-field. The SDU's subsea units have been in uninterrupted operation subsea since 1997, in symbiosis with the deep sea corals!

Excursions and workshops

«We have arranged courses, workshops, meetings and excursions, often together with our industry partners. We have for instance arranged subsea introduction courses with Aker Solutions, workshops with ABB and visited Shell's Ormen Lange Pilot project at Nyhavna, Sintef's multiphase flow laboratory at Tiller and Statoil's offices at Rotvoll and Stjørdal", says Mogseth. This enables the SUBPRO team members to gain more knowledge of subsea production and processing in general, and to become more aware of industrial challenges. It also helps the researchers to see their own projects as part of the bigger picture.

Interdisciplinary

Another priority area for SUBPRO has been to encourage interdisciplinary collaboration between the different research areas and projects. One of the most important initiatives has been to arrange monthly PhD colloquiums where the PhD students and postdocs present their research for each other. This allows the candidates to increase their knowledge about each other's research, and hence gives them the opportunity to learn from each other and to explore possibilities for cooperation across different disciplines and projects.

PhD students Are Bertheussen and Jost Ruwoldt are studying sequential separation at the laboratory.

Master students at SUBPRO

Every year approximately 25 students do their masters thesis in association with the SUBPRO research centre.

To recruit students, the Centre invites the 4th grade students to meet the industry partners in SUBPRO and PhD and Postdoc candidates. At this meeting the industry presents themselves and possible problems that the students may dive in to during the master, and the PhD students tell about their work and how it is to be a part of the SUBPRO centre.

Experts in Teamwork (EiT)

The unique feature of EiT is that students not only work on their technical project, but also evaluate the way they work together. Since 2001 EiT is compulsory for all students at second-degree level.

The EiT village "Challenges in Subsea Production and Processing" is coordinated with the SUBPRO centre for research-based innovation. And they are regularly presenting the work they do.

It's been a long day when the membrane group are presenting their preliminary results from the work in the EiT – Subsea village. The room is packed, and there is hardly any air left. They have the ears of the industry with Audun Faanes from Statoil, and a representative from ABB at the first row. The other students and associated professor Brian Grimes, the leader of this EiT village are also listening.

Unique focus on teamwork

– They analyze their teamwork, and based on their understanding they reflect on how they communicate, plan, make decisions, solve tasks, handle disagreements and relate to academic, social and personal differences. In this way, they learn from their own experiences and develop their teamwork skills, says Brian Grimes.

Kasper Kviensland from the membrane group agree. – This is our first teamwork experience, and we are from different disciplines – it has been interesting to work together, but not difficult.

Chairman of the Board, Audun Faanes from Statoil is interested in the work in EiT. Photo: Per Henning.

FACTS

The Experts in Teamwork (EiT) course was created in 2001 in response to demands from business and industry for students to gain experience in working together with people from other disciplines, and for students to be trained in team work, using their academic competence to solve complex tasks.

In kind contribution from industry partners

The supplier companies in SUBPRO have the option to deliver half of the annual membership fee as in kind contribution to the project in the form of work, software, hardware etc. Both ABB and Aker Solutions have done that in 2016.

Aker Solutions arranged a course for PhD's and Postdocs in SUBPRO with focus on system engineering, in addition to updating the technical report they provided in 2015.

The report contains information about

• multiphase pumps
• produced water
• membranes for gas treatment
• subsea reliability
• availability
• maintenance and safety (RAMS)
• input to some of the controls projects

ABB has also arranged two workshops for SUBPRO, where the industry partners were invited in addition to the personnel from NTNU. The first workshop was a 2-day workshop for System Control, with focus on industry practices on estimation of unmeasured variables and online process monitoring. The second workshop was a 1-day workshop within the RAMS area, with the focus on subsea requirements and interpretation of key standards and challenges in applying these subsea.

The feedback on the in kind contribution from ABB and Aker Solutions has been very good, and it has provided valuable industry information to the research projects.

Draugen Subsea Boosting Station – Installation of manifold. Courtesy of AS Norske Shell

Subsea Process Control Laboratory, Separation flow loop

Subsea Process Control Laboratory: Wet Gas Compression

Laboratories and Test Facilities at SUBPRO

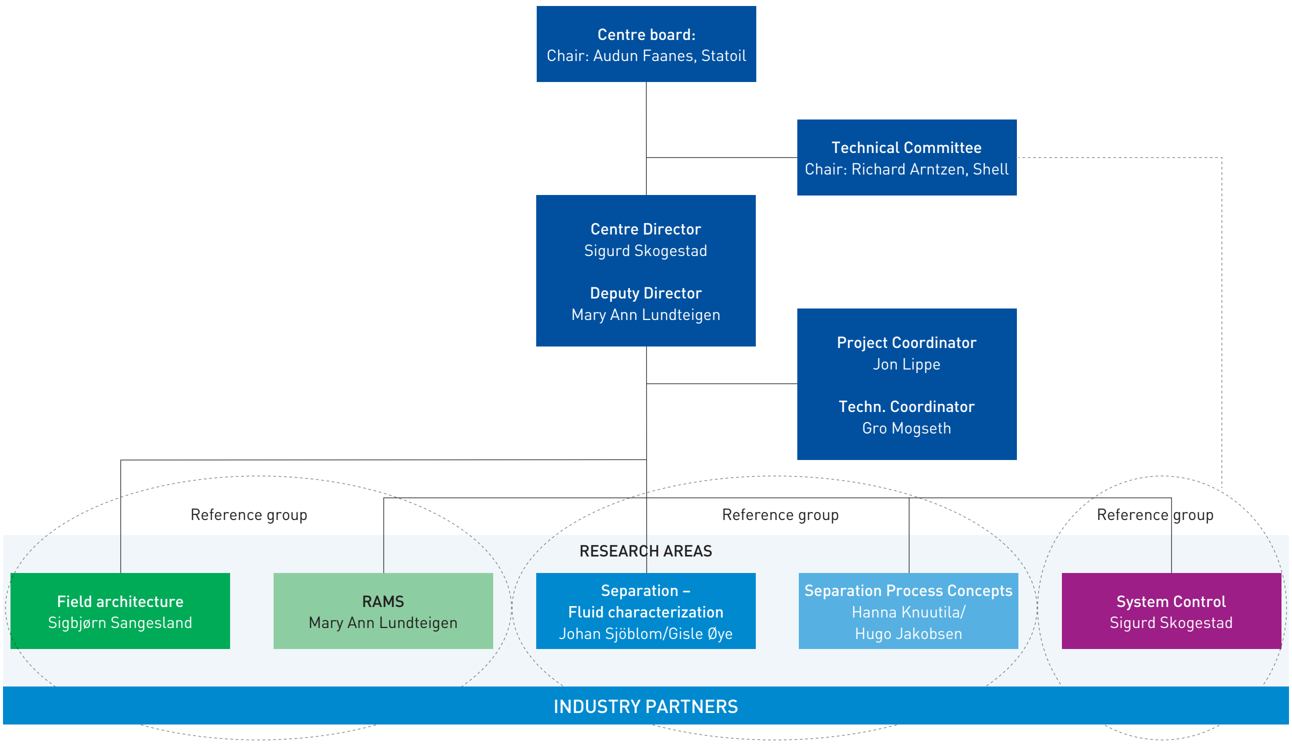
At the Department of Chemical Engineering SUBPRO utilizes testing facilities at the Ugelstad laboratory for testing of surfactant chemistry and flow assurance, in addition to use of other laboratories for solvent characterization, test of membranes and droplet breakage.

SUBPRO is currently also building two new small scale test rigs at the Department of Geoscience and Petroleum and at the Department of Mechanical and Industrial Engineering. One for testing of new concepts for bulk separation and one for testing of operation and control of subsea processing equipment.

In addition, some of the SUBPRO sub-projects will make use of laboratories and test facilities at the premises of our industry partners and at other universities / research institutions.

Organization of the Centre

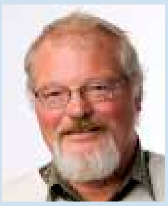
Governance structure



Centre board 2016–2017

Audun Faanes
Statoil
Chair of the board

Tone Schanke-Jørgensen
Lundin Norway



Torolf Hæhre
Shell (up to 2016)

Isabel Waklawek
Shell (from 2017)

Anne Borg
NTNU

Kjartan Pedersen
Aker Solutions
(up to 2016)

Frank Børre Pedersen
DNV GL

Tom Steinskog
ENGIE

Katrine Hilmen
ABB

Jørn Berntsen
VNG Norge AS
(from2017)

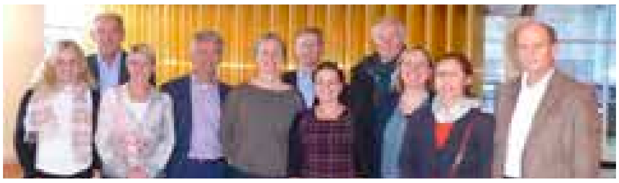
Sigurd Skogestad
NTNU, Centre director
Secretary of the Centre board

Kimberly C. Mayes
Research Council of Norway, Observer

Organization of the Collaboration between NTNU and industry partners

Centre Board

The Centre board has one representative from each partner. The board adopts goals and strategies for the Centre and decides the project portfolio and annual budgets.



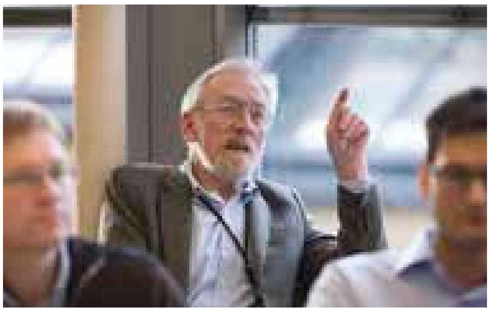
Technical Committee

The Technical Committee has typically 1–2 members from each partner. It monitors the scientific 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 ongoing activities.

Pictures from the last reference group meetings.



HSE – at SUBPRO

The participants at SUBPRO are doing a lot of work in the laboratories. That means that the focus on HSE is very important. Gunn Torill Wikdahl is senior engineer and head of HSE at Department of Chemical Engineering. "Everyone who are to work at one of our laboratories have to take the HSE course. They have to take a written test before they get the license to do work in the lab", Wikdahl says.

After this test they should sign up at a specific laboratory and then talk to the person in charge of this lab about the test they are going to perform. Then there's a personal risk evaluation before they can go on and do the research.

With this system, we have a good overview of whom are using the laboratory facilities, and what they are doing, says Wikdahl. This means that everybody has the same information and understanding of the risks.

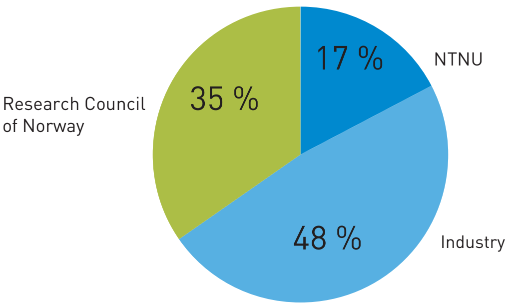
Controlling safety critical equipment is one of the task for head of HSE Gunn Torill Wikdahl. Photo: Anne-Lise Aakervik

Key Figures for SUBPRO

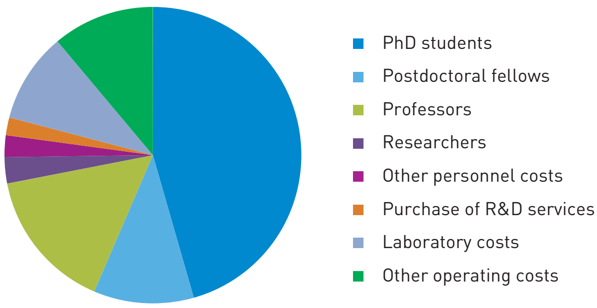
Project duration	August 2015 – August 2023*		
Total annual budget	35 mill. NOK		
Personnel	Planned hired for the total period 2015-2023	Hired up to 2016	Female percentage up to 2016
PhD students	35	16	30 %
Postdoctoral scholars	8	5	40 %
Professors involved at NTNU	20	20	20 %
Other researchers	5	5	40 %
MSc students (per year)	26	26	20 %

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

FUNDING



COST DISTRIBUTION



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4. Adriaen Verheyleweghen, Johannes Ernst Peter Jäschke; «Robust Health Aware Operation of a Subsea Gas Compression System" AIChE Annual Meeting. San Francisco 2016.
5. Adriaen Verheyleweghen, Johannes Ernst Peter Jäschke; «Health-aware operation and control of a subsea gas compression station". Nordic Process Control Workshop 2016. Sigtuna.
6. Christoph Josef Backi, Jan Tommy Gravdahl, Sigurd Skogestad; "Robust control of a two-state Greitzer compressor model by state-feedback linearization". 2016 IEEE Multi-Conference on Systems and Control. Buenos Aires. Pages 1226-1231
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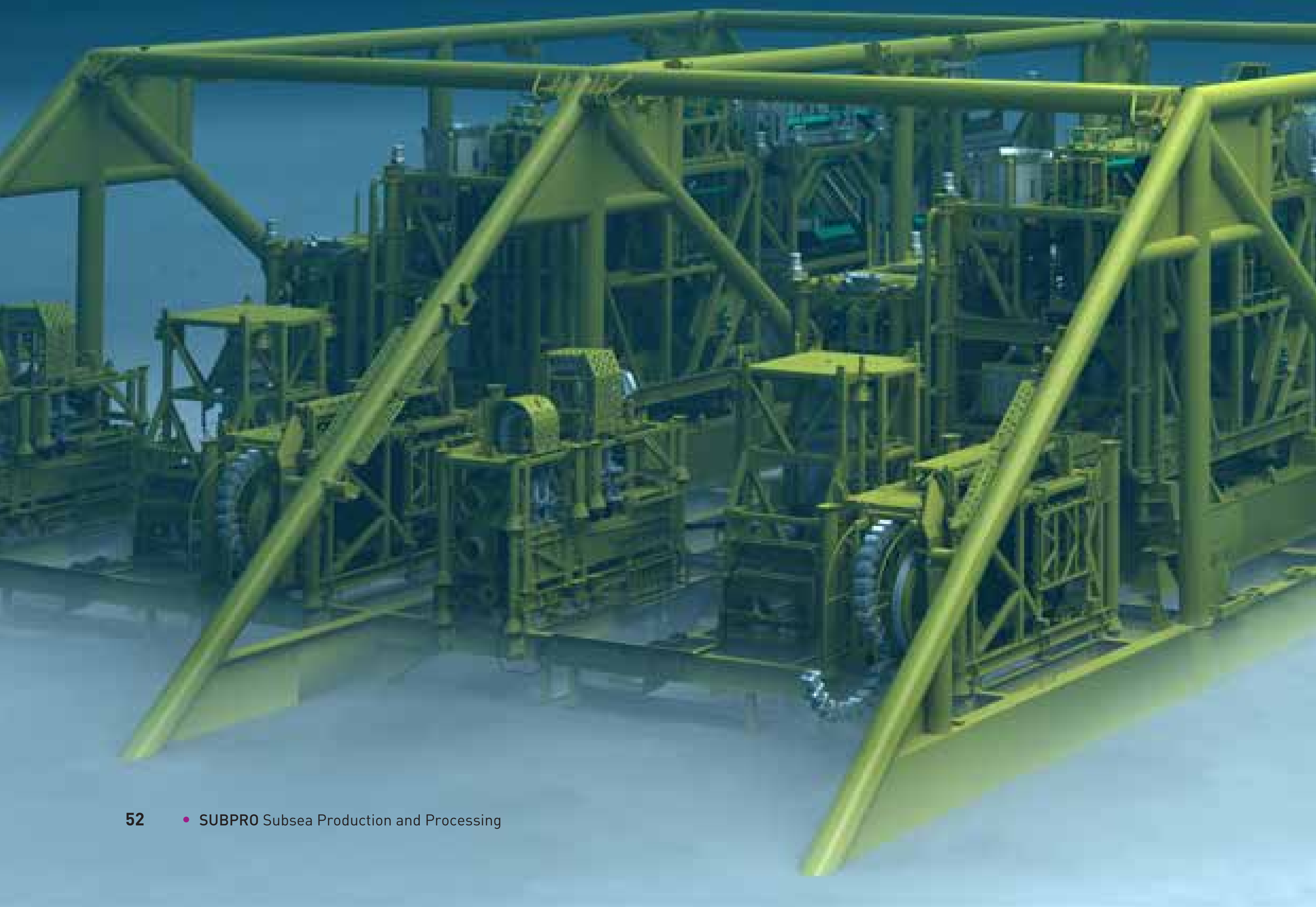

8. Eirini Skylogianni, Mari Iseling Lilleng, Hanna K Knuutila; «Combined Hydrogen Sulfide Removal and hydrate control for Subsea Application Simulation Study”. Techno-Ocean 2016, 6 – 8 October. Kobe.
9. Hyung Ju Kim, Mary Ann Lundteigen, Christian Holden; “A Gap Analysis for Subsea Control and Safety Philosophies on the Norwegian Continental Shelf”. 13th International Conference on Probabilistic Safety Assessment and Management (PSAM13). Seoul.
10. Usman Shoukat, Georgios Fytianos, Hanna K Knuutila; “Thermal Stability and Corrosion Studies of Amines for Combined Acid Gas Removal and Hydrate Control for Subsea Gas Treatment System” Techno-Ocean 2016, 6 – 8 October. Kobe.
10. Christoph Josef Backi, Sigurd Skogestad; “A simple dynamic gravity separator model for separation efficiency evaluation incorporating level and pressure control”. Accepted for presentation at the 2017 American Control Conference, Seattle, USA, 24-26 May 2017.
11. Esmaeil Jahanshahi, Christoph Josef Backi, Sigurd Skogestad; “Anti-slug control based on a virtual flow measurement”. Flow Measurement and Instrumentation, Volume 53, Part B, March 2017, Pages 299-307.
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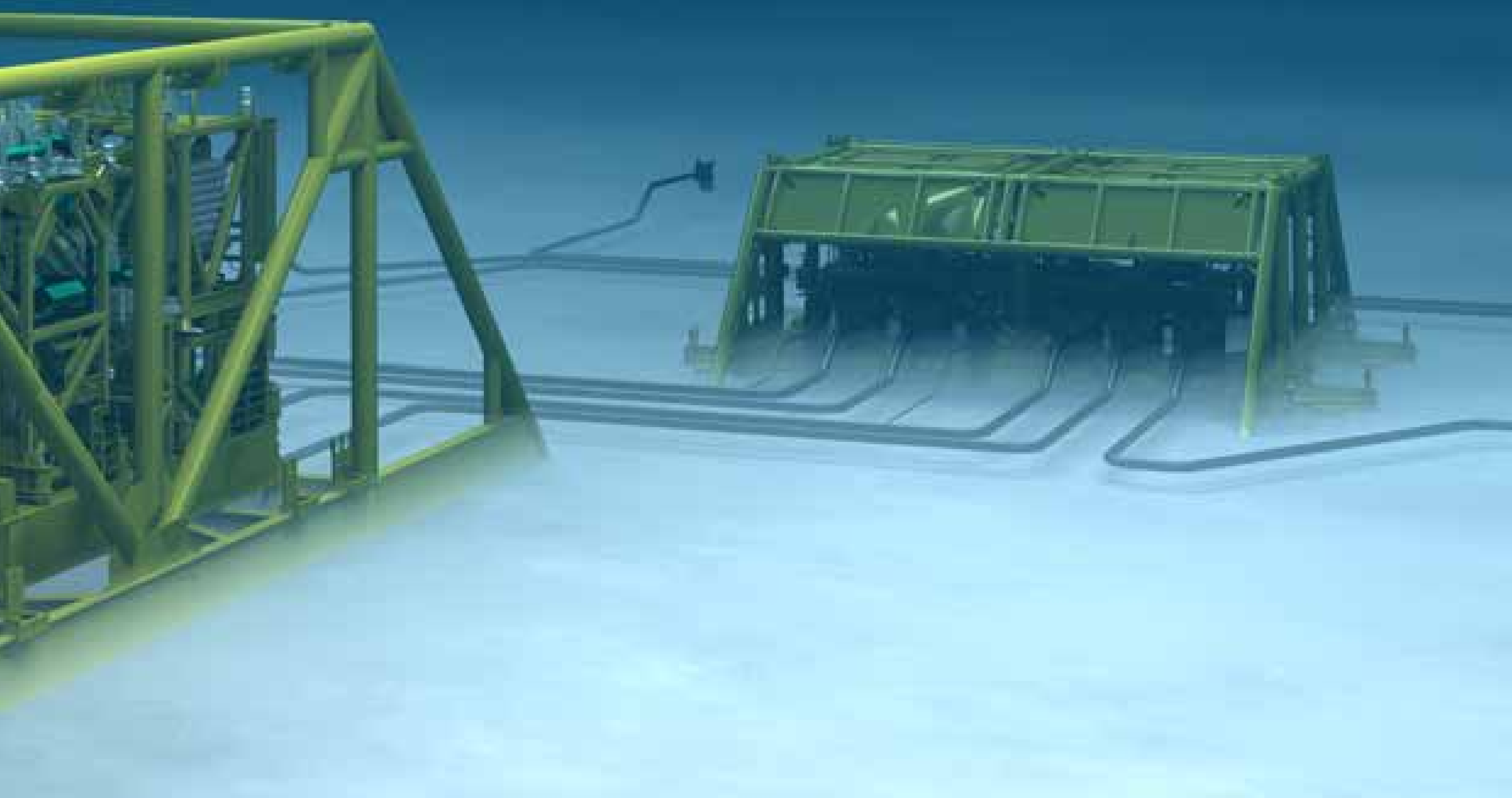

Åsgard subsea compression system, courtesy of Statoil.

People in SUBPRO

CENTRE MANAGEMENT

Prof. Sigurd Skogestad, Centre Director

Prof. Mary Ann Lundteigen, Centre co-director

Jon Lippe, Project coordinator

Gro Mogseth, Technical coordinator

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Prof. Sigbjørn Sangesland, Field architecture

Prof. Johan Sjöblom Separation - Fluid characteristics

Prof. Gisle Øye, Separation - Fluid characteristics

Ass. Prof. Hanna Knuutila, Separation process concepts

SUB PROJECT MANAGERS

Associate prof. Milan Stanko, Field devel-opment concepts, Compact separation concepts

Prof. Anne Barros, Prognostics and condition based maintenance

Associate prof. Kristofer G. Paso, Modelling of wax deposition

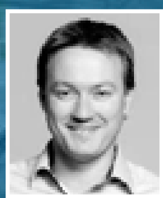
Associate prof. Brian Arthur Grimes, Modelling of coalescence

Associate prof. Liyuan Deng, Membranes for gas dehydration

Prof. Hugo Atle Jakobsen, Experiments on fluid particle breakage

Prof. Olav Egeland, Modelling and multivariable control of subsea systems

Associate prof. Christian Holden, Control of subsea processes



Associate Prof. Johannes Jäschke, Estimation of un-measureable variables, Control for extending component life

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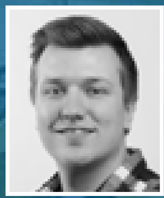
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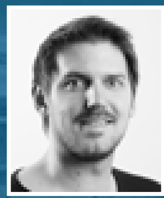
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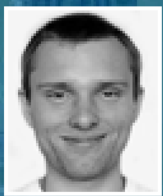
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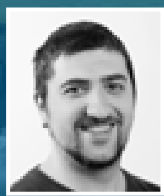
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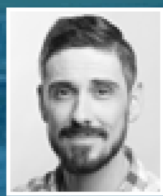
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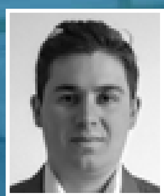
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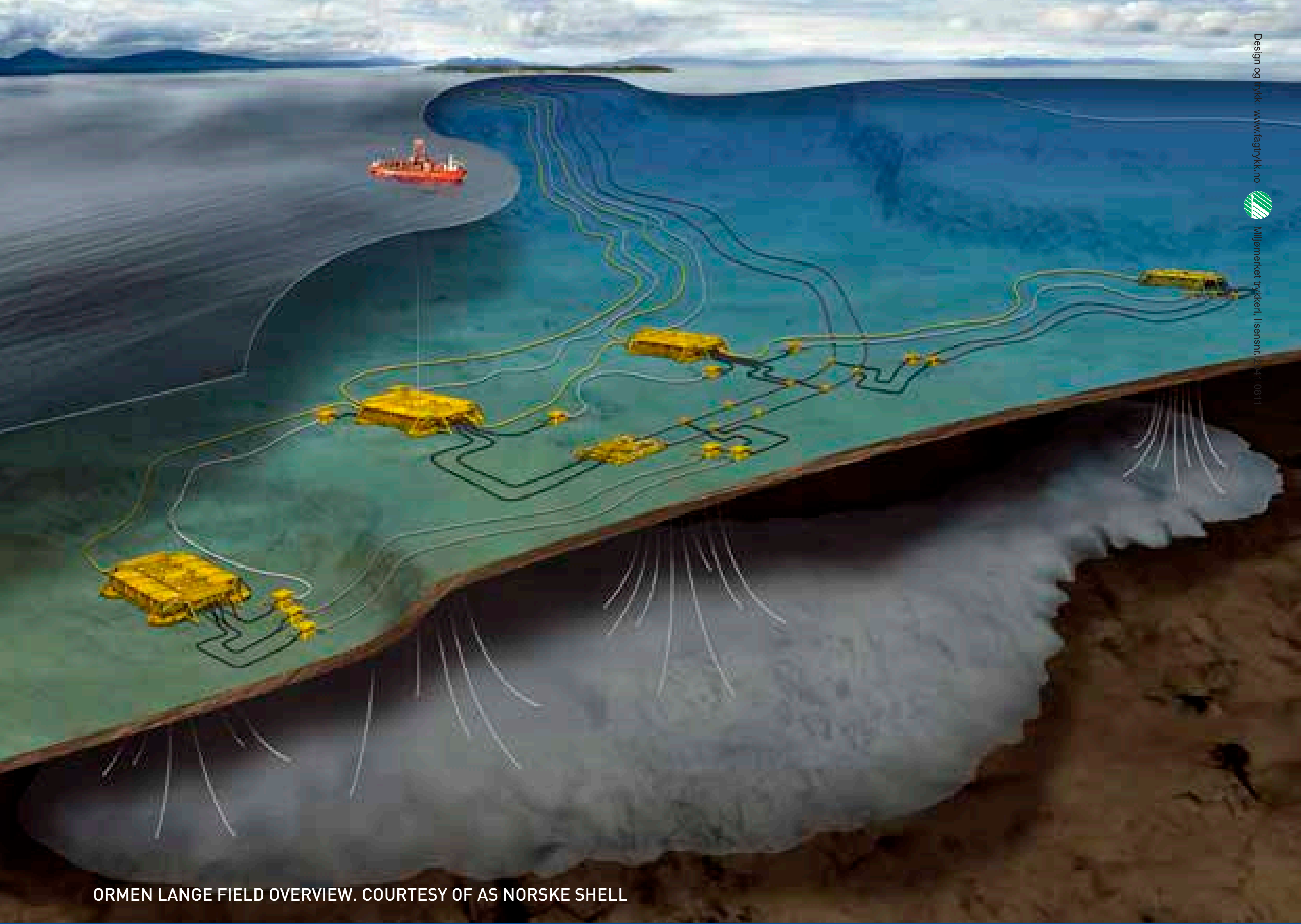

ORMEN LANGE FIELD OVERVIEW. COURTESY OF AS NORSKE SHELL

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The Research Council of Norway

SUBPRO

SUBSEA PRODUCTION AND PROCESSING

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