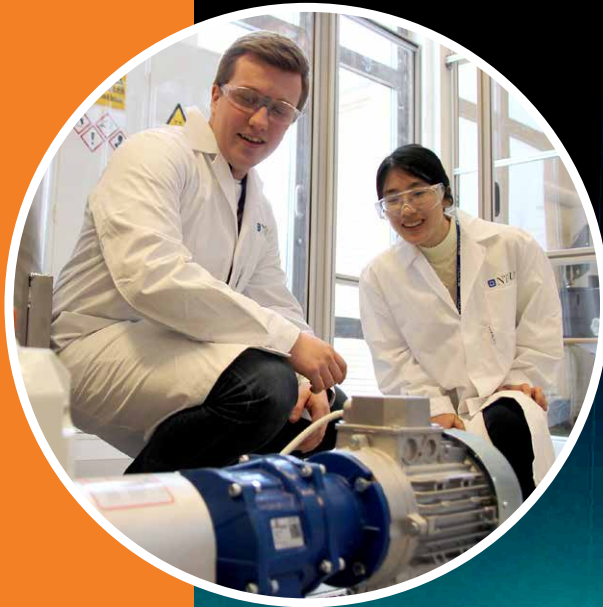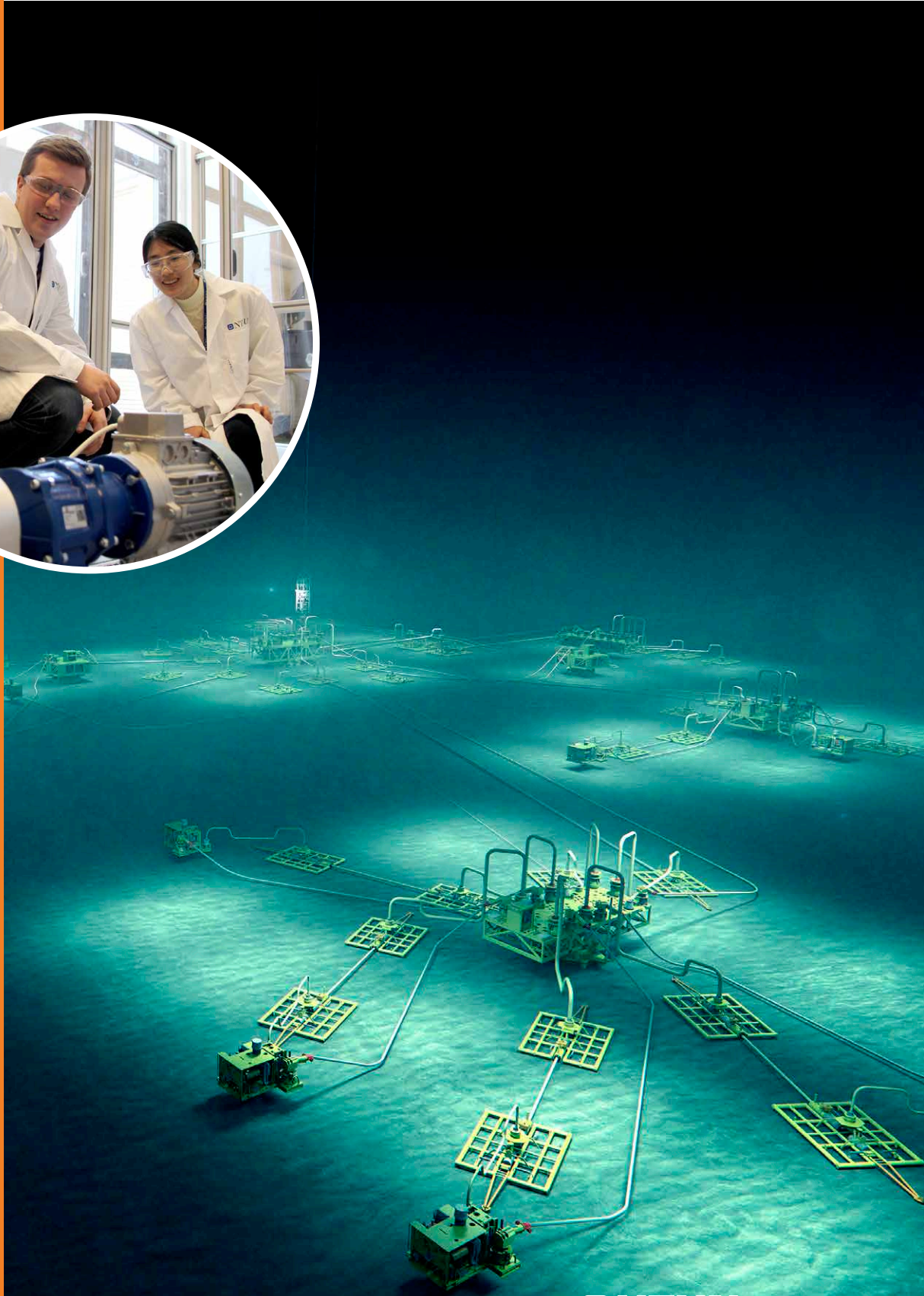# SUBPRO

SUBSEA PRODUCTION AND PROCESSING

Annual Report 2015

NTNU
Norwegian University of
Science and Technology

SUBPRO VISION

Become a global leader for research based innovation in subsea production and processing, through a partnership between NTNU and major industrial players in the field.

OUR GOAL

To provide:
- 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 candidates

Front page and 2nd page background illustration:
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THOUGHTS FROM SUBPRO DIRECTORS

Prof. Sigurd Skogestad
Centre director

"Norway is in the forefront internationally on subsea technology. To keep this lead, we want to improve the fundamental knowledge in selected areas and provide new ideas and talent for the industry."
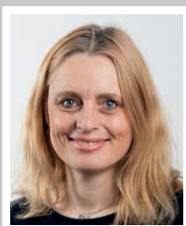
Prof. Mary Ann Lundteigen
Centre co-director

"The subsea oil and gas industry has created many interesting jobs and contributed to highly innovative solutions over several decades. Despite the current economic situation in the oil and gas industry, we strongly believe that the subsea sector will be a vital industry for many years to come, contributing to the economy of the society. The SUBPRO centre will support this trend by providing long term knowledge development for this industry."

PARTNERS

Shell

ENGIE

ABB

Statoil

NTNU — Norwegian University of Science and Technology

Lundin Norway

AkerSolutions

DNV·GL

The Research Council of Norway

EXPECTATIONS TO SUBPRO FROM THE INDUSTRY

Audun Faanes,
Chairman of the SUBPRO board,
Leading Engineer Subsea Technology, Statoil

What is the motivation for your company to join the SUBPRO Centre as an industry partner?
"Subsea technology is important for Statoil with more than 500 subsea wells in operation and subsea field development considered in several upcoming projects. Åsgard Subsea Compression demonstrates a large potential for subsea processing. New solutions are required to reduce costs and develop new subsea concepts. The SUBPRO Centre is considered as an important contributor in this picture through cross disciplinary collaboration between internationally high level academic groups at NTNU and central players in the industry".

What is your expectation for the outcome of the Centre?
"We expect the centre to provide new fundamental understanding, knowledge, methods and tools to be applied in Statoil's technology development, field development and operations directly or through products and services from the vendors. Education of high level master and PhD candidates with knowledge and skills within this field of expertise will be an important part of this."

Hervé Valla,
Head of Innovation & Technology, Aker Solutions

What is the motivation for your company to join the SUBPRO Centre as an industry partner and what is your expectation for the outcome of the Centre?
"SUBPRO's innovation potential lies in having parties that normally do not collaborate, work together on mapping needs and carrying out joint research and development, all in order to make individual technologies work together as a system."

EXPECTATIONS TO SUBPRO FROM NTNU

Anne Borg,
Dean of the Faculty of Natural Sciences and Technology, NTNU

Ingvald Strømmen,
Dean of the Faculty of Engineering Science and Technology, NTNU

What is the motivation for NTNU to host the SUBPRO Centre as an academic partner?
"Novel and efficient methodology in the oil and gas industry taking advantage of subsea production and processing infrastructure is essential for the development of new, demanding oil and gas fields. This is the major objective of SUBPRO. The role of NTNU in this context is to develop basic scientific knowledge relevant for the industry and to pave the ground for innovations in the field, through the research activities. Most significantly, the centre will educate PhD and MSc candidates within this important research area for Norway. In 2015 a large number of talented PhD students and postdocs were recruited, a very good starting point for the centre."

What is your expectation for the outcome of the Centre?
"Reaching the goals of centre requires an interdisciplinary approach. Therefore, SUBPRO is a joint effort between several research groups at two faculties at NTNU, Faculty of Natural Sciences and Technology, serving as host, and Faculty of Engineering Science and Technology. A further strong point of the centre is the close collaboration with the industrial partners ensuring the societal relevance of the scientific activities as well as of the master of engineering programs in the field at the university. We are looking forward to see scientific achievements, as well as implementation of the research-based knowledge into innovative solutions for the industry in the years to come."

THE RESEARCH COUNCIL OF NORWAY

Expectations to Centres for Research-based Innovation (SFI)

"The purpose of the Centres for Research-based Innovation (SFI) is to build up and strengthen Norwegian research groups that work in close collaboration with partners from innovative industry and innovative public enterprises."
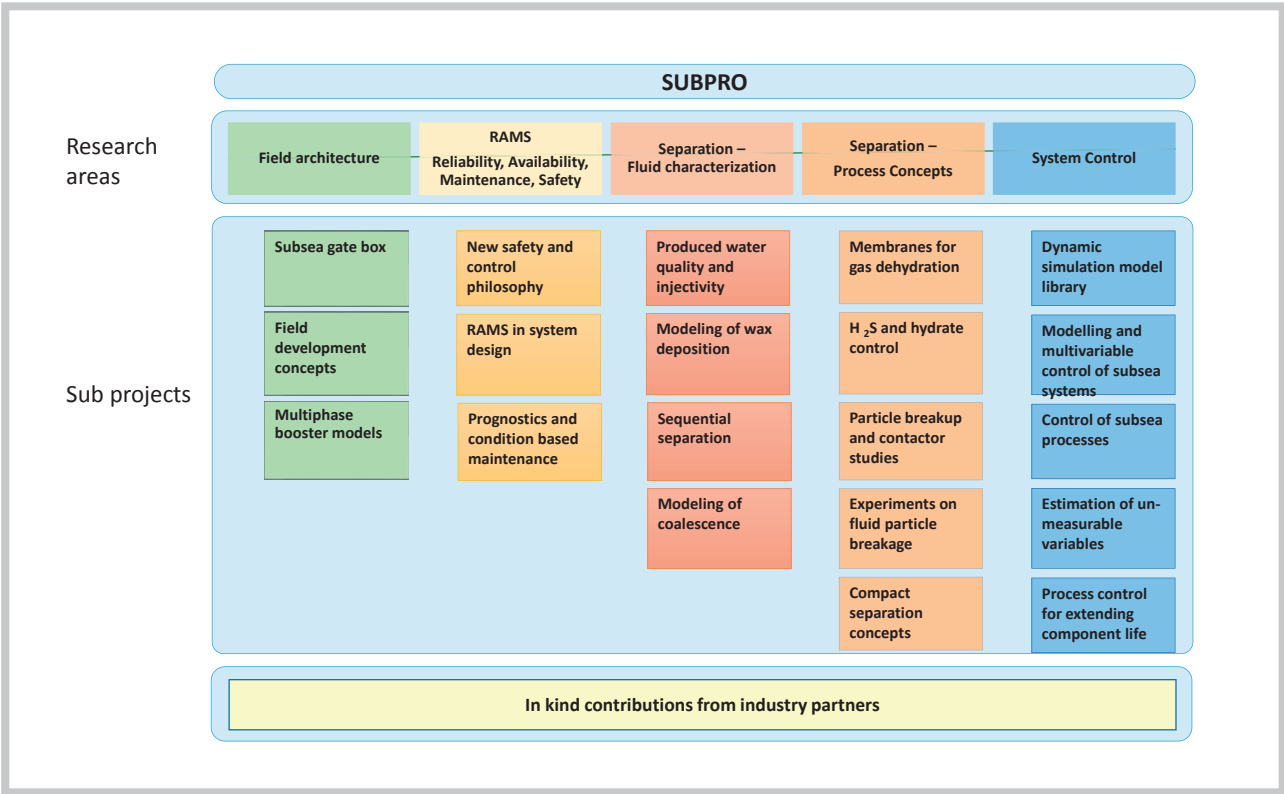
PROJECT STRUCTURE

SUBPRO				

Research areas

Field architecture	RAMS Reliability, Availability, Maintenance, Safety	Separation – Fluid characterization	Separation – Process Concepts	System Control

Sub 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 multivariable control of subsea systems
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 un-measurable variables
			Compact separation concepts	Process control for extending component life

In kind contributions from industry partners

Figure 1. SUBPRO is organised in 5 research areas and 20 sub projects

FIELD ARCHITECTURE

This research area covers the development of methods, systems elements and production process configuration 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 *(Figure 2)*.

Research area manager,
Prof. Sigbjørn Sangesland

Specific industrial challenges and goals:
• Increase field production by enabling a "smart" synthesis of the diversified wells potential, constraints, and recovery targets.
• Employ "near the source" seabed separation and boosting whenever this improves the recovery, reduces the transport costs or prolongs the economic life of the field.
• Shorten the schedule and reduce the costs of design, construction, installation and commissioning of subsea systems. This implies system simplifications, elimination of unnecessary functionalities, industry wide standardisation, simplification of sub-system interfaces to enable modularisation and cheapest adaptation to changing production conditions.
• 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
• Minimize energy dissipation in well control choking by transferring well control functionality to a compact separator.

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

• Case 1 – Gas field
  - Low Gas to Oil Ratio (GOR) (prioritised)
  - High GOR (currently not prioritised)
• 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 have been initiated as a part of the research area Field architecture:

- Subsea gate box
- Field development concepts
- Multiphase booster models

Figure 2. Subsea field architecture © 2015 Aker Solutions

Subsea gate box

Project manager Prof. Sigbjørn Sangesland

Postdoc, Mariana Diaz

Co-supervisor, Professor Emeritus Michael Golan

Co-supervisor, Associate prof. Milan Stanko

Postdoc, Jesús De Andrade

Different wells in a subsea field have different production capacities, production constraints and production targets dictated by the reservoir depletion strategy. Therefore, they are subject to individual management and control. However, commingling the production streams of the individual wells, creates a strong interdependence of the flow rates and production pressures of the individual wells. The results of this interdependency is that the yield of the integrated system is, most often, considerably sub-optimal.

This project explores new facilities and system configurations to achieve efficient and optimal management of the integrated system over the entire life of the field.

A central element of the project is the concept development of a modular and multi-functional assembly to allow easy re-routing of well streams and a quick and easy deployment of separation and boosting capability to a single well, to a group of wells or to the entire cluster.

This subsea assembly named Subsea gate box is configured as a template that accommodates individual well modules and compartments, containing proper process equipment (Figure 3). The process equipment may include separators, pumps, compressors, control valves and/or flow meters, according to the characteristics of the well stream. A task in the early phase of the project (Figure 4), will be to identify the leading technology in the market that suits best to a compact and modular solution. The project deliverables will include a description of the state-of-the-art subsea process technology, feasibility analysis of the Subsea gate box and performance analysis of business cases designed for both conventional and low-energy oil fields.
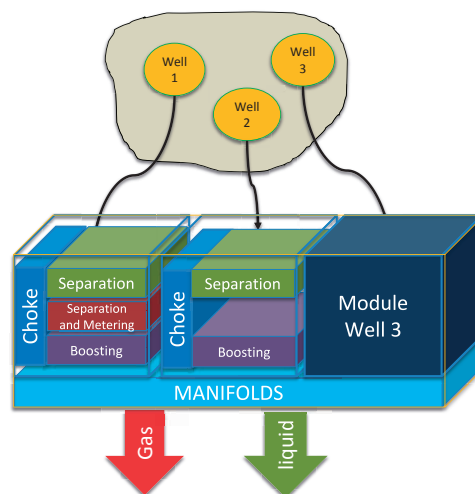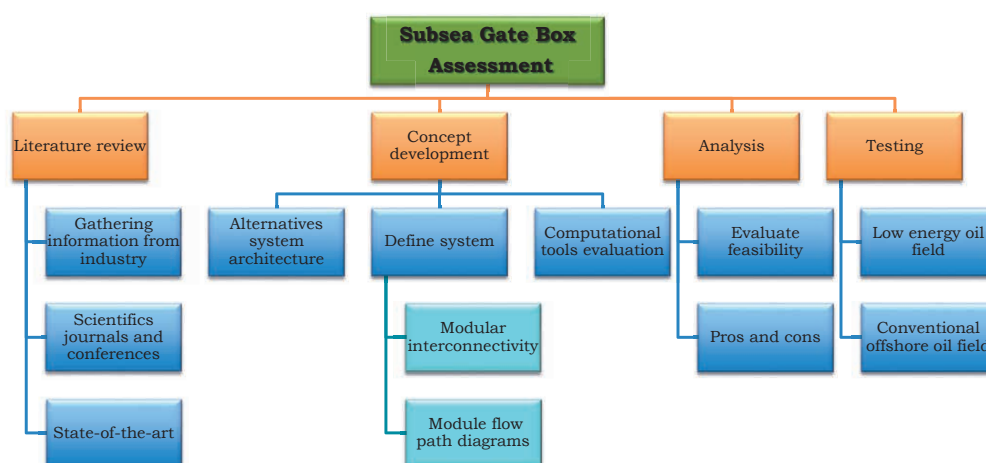

Figure 3. Subsea Gate Box concept sketch

Figure 4. Subsea Gate Box project activities

Field development concepts

Project manager and main
PhD supervisor, Associate
Prof. Milan Stanko

PhD candidate,
Diana Gonzalez

Co-Supervisor, Prof.
Sigbjørn Sangesland

Co-Supervisor, Prof.
Emeritus Michael Golan

Over the last years, the world energy demand has increased exponentially, bringing the necessity of developing hydrocarbon production systems in remote areas e.g. remote arctic fields, deep and ultra-deep water offshore fields and low energy reservoirs. However, the development and operation of such type of fields is challenging due to the safety and environmental risks, weather season limitations, complex logistics, low sea temperatures, requirements for energy consumption, high investments costs etc. The main objective of this project is 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 transport distances taking into account flow assurance.

A thorough literature review will be performed including consultations with the industrial partners to determine which field architecture concepts should be analysed and considered for low energy remote offshore fields. There will be a strong focus in new technologies and tendencies in subsea processing and boosting. Some examples are:

- Production to floater and transportation to shore (traditional)
- Subsea separation and transportation to shore (reinjection of gas and water)
- Multiphase boosting and transportation to shore
- Subsea to beach

The research will be divided into two main activities *(Figure 5)*, the first consists of identifying one or several ideal field architectures for the development of a remote oil reservoir with low energy. The second activity consists of analysing and evaluating flow assurance issues in these ideal field architectures.

The first activity will be carried out evaluating two main aspects for each field architecture concept; the economics, taking into account capital expenditures (drilling costs, equipment cost, installation costs etc.) and operating expenditures (maintenance, intervention, flow assurance measures etc.) and an operational evaluation, where the production profile of each field architecture will be computed and evaluated. The input and advice for the calculations and simulations from the industrial partners will be taken into account to keep the analysis as realistic as possible. The project will develop Integrated asset models (digital field) for the selected concepts and will use realistic models with built in commercial software if possible. This allows running simulations until end of asset life.

For the second activity, flow assurance issues will be addressed. Here, the operational challenges and technological bottlenecks of the current technologies will be analysed and new enabling technologies will be explored and analysed.
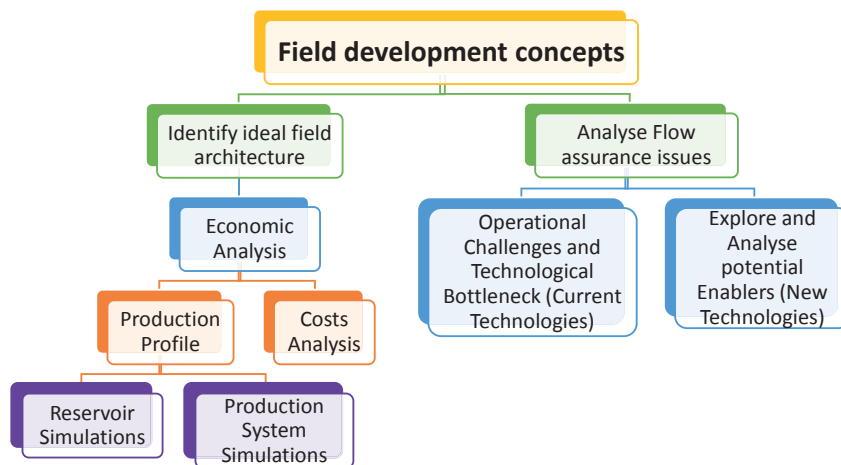

Figure 5. Field development concepts activities

Multiphase booster models

Project manager and main
PhD supervisor, Prof.
Sigbjørn Sangesland

PhD Candidate,
Gilberto Nunez

Co-Supervisor, Postdoc
Jesus De Andrade

Co-Supervisor, Prof.
emeritus Michael Golan

Subsea multiphase boosting offers several advantages in field development for both greenfield and brownfield projects. Furthermore, it seems to be a key enabler for development of remote fields. Currently several subsea boosting technologies are commercially available and have been successfully installed and tested in fields around the world. However, for the early phases in the assessment of a subsea field, models are required for an appropriate selection of available technologies, including preliminary calculations of flow and discharge pressure capabilities and power requirements. At this stage, uncertainty level is very high and therefore accurate models are not required. Simplified models coupled with process simulators and other commercial tools will be sufficient. Simplified models will also enable an integrated modelling of the field and production optimisation in the conceptual design phase. Nevertheless, detailed performance prediction models of multiphase boosters is also required under changing conditions in the field lifetime (e.g. flow rates, fluid properties, gas void fraction) *(Figure 6)*. This calls for an increased understanding of thermodynamics and fluid dynamics phenomena in multiphase boosters. Therefore, the main goal in this project is the development of numerical models for prediction of multiphase booster performance. In the first phase of the project, the main goal is the development of a simplified and robust model for currently available technologies for subsea multiphase boosting. Subsequently, the focus will be a detailed study of thermodynamic and fluid dynamics phenomena in multiphase boosters. Finally, the comprehensive study of multiphase behaviour of pumps and compressors will aid the development of more accurate proxy-models for performance prediction. After discussion with the industrial partners, it has been decided to focus on one specific type of booster (Semi-axial impeller).
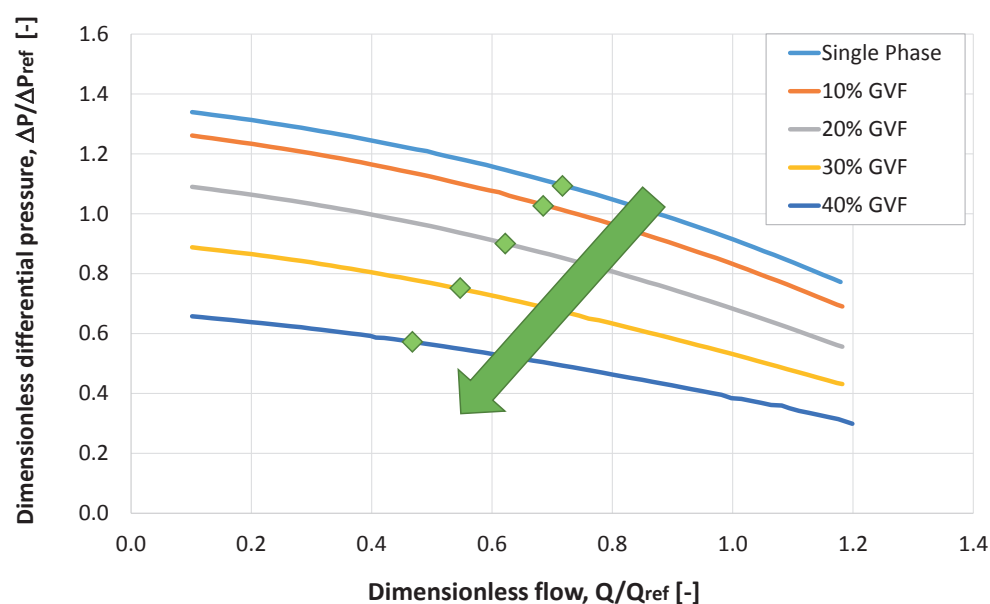

Figure 6. Example of changing multiphase pump performance due to different gas void fraction (GVF)

RELIABILITY, AVAILABILITY, MAINTENANCE AND SAFETY (RAMS)

Many of the future developments in subsea require adaption of new technology and new ways of operation. Safe operation is paramount, but more focus is placed on achieving high safety and availability level with more cost efficient solutions. Topside design principles and philosophies are often modified for subsea use (to ensure well proven design), but future field development will require tailor-made solutions for subsea conditions. Reliability, availability, maintenance and safety (RAMS) are four important properties of systems that need to be specified and included in the evaluation of design alternatives. For the RAMS research area, the overall aim is to develop new knowledge, methods and tools to support decision-making about RAMS in design as well as in operation. In the first three years of SUBPRO, the focus is on developing:

Research area manager,
Prof. Mary Ann Lundteigen

• A new philosophy for subsea safety and control systems
• A new framework and models to support the specification and evaluation of subsea solutions in an early design phase
• New models and methods for prognostics-based maintenance planning of subsea systems

New safety and control philosophy

Project manager, Prof. Mary Ann Lundteigen

Postdoc, HyungJu Kim

Co-supervisor, Associate Prof. Christian Holden,

The main objective in this project is to develop a new control and safety philosophy for subsea systems. The new philosophy aims to overcome some of the challenges of implementing such systems with basis in standards developed for topside conditions, and to ensure that the subsea safety risks and subsea operating environment are fully captured. It is a need to reduce complexity of systems and their interaction, while maintaining a high integrity of critical functions.

The first year of the project focuses on detailing the challenges of existing subsea control and safety systems, identifying subsea risks associated with different subsea field architectures and locations, and investigating industry practise on the application of risk acceptance criteria for safety and asset protection functions. We have seen

a significant interest from industry partners on this topic. One issue already identified during the interaction is the opportunity to learn from recent subsea processing installations, like Åsgard subsea compression. During the first half year of the project, industry partners have contributed with specific input in dedicated workshops and reports, both on understanding challenges but also on framing conditions for future field developments. This insight will be used to propose, with support from industry, some preliminary (and conceptual) alternative architectures. These alternatives will be discussed, iterated, and evaluated against regulatory requirements and subsea risk conditions. An outcome of the project is new knowledge and new principles that may be further adapted into new or existing standards on subsea design and operation.
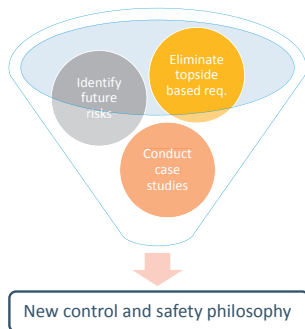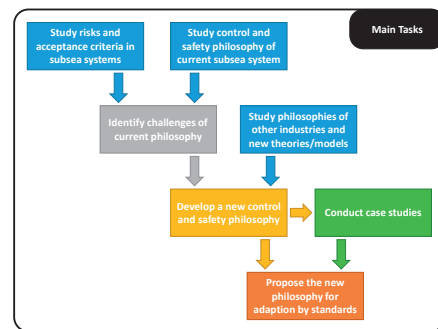

Figure 7. Key steps towards new philosophy

Figure 8. Main tasks of subproject

RAMS in system design

Project manager and main PhD supervisor, Prof. Mary Ann Lundteigen

PhD candidate, Juntao Zhang

Co-supervisor, Associate Prof. Yiliu Liu

The objective of this project is to redesign reliability and availability assessments so that they are more suited to support decision-making in early design phases. Today, the assessments are often carried out too late to have an impact on system architecture. It is paramount to frame assessments so that all relevant factors of importance to reliability and availability are captured, including e.g. weight and modularization and location of components.

The first phase of the project focuses on understanding in more detail the industrial status and challenges on the use of reliability and availability assessments for qualification of new technology. Industry partners have already shared some of their specific challenges in workshops and reports, and their input has been used to confirm, but also narrow, the research focus. Two research topics have been circled out as being the most important: (i) How should RAMS requirements be formulated to give suitable balanced functional as well as non-functional (e.g. construction and weight) requirements and constraints, and (ii) what is a suitable RAMS model to support early design evaluations. In collaboration with industry partners, we have identified two other sub-projects as case studies for the research: The Subsea gate box system (described in the research area Field architecture) and the Membrane system (described in the research area Separation process concepts).

| Study the overall industrial gap and status | Study the overall industrial gap and status | Study the overall industrial gap and status | → | Status & gap analysis |

Confirm information in discussion with industry partners

| Identify the most important subsea factors | Develop new framework of RAMS formulation and allocation | Develop model-based RAMS verification framework | → | Publications & presentations |

Acquire comments and feedback from industry partners

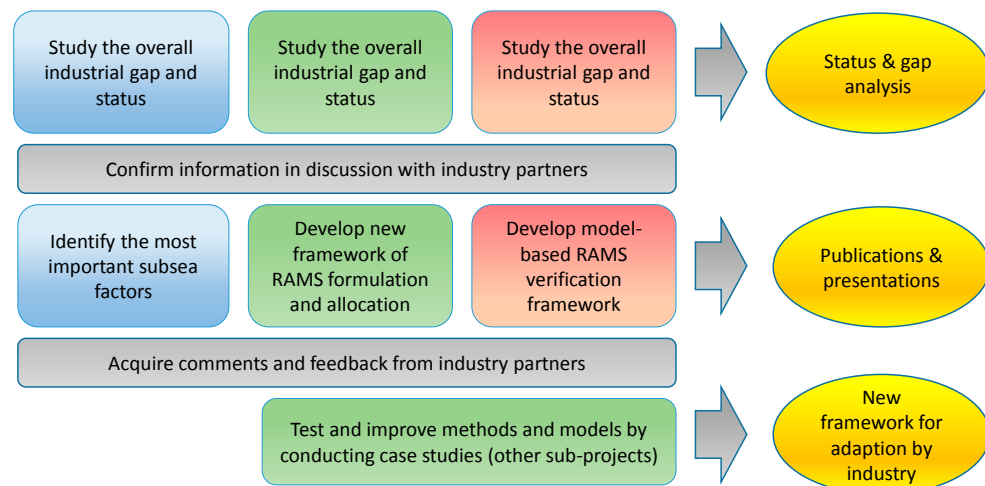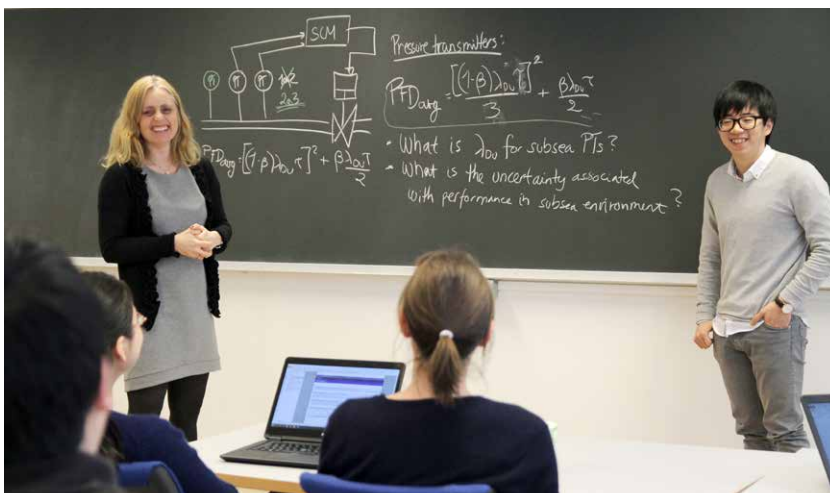| Test and improve methods and models by conducting case studies (other sub-projects) | → | New framework for adaption by industry |

Figure 9. Main tasks of the subproject

RAMS discussions in the NTNU team

Prognostics and conditionbased maintenance

Project manager and main
PhD supervisor,
Prof. Anne Barros

PhD candidate, Yun Zhang

Co-supervisor,
Prof. Antoine Rauzy

The objective of this project is to develop a mathe-matical and algorithmic framework to optimize the maintenance, inspection and reconfigurations of subsea systems. Optimization may concern the design phase (the number and locations of spare units and sensors to monitor degradation processes) and the operation phase (the number and the frequency of maintenance operations, the maintenance/reconfiguration decisions made during these operations given degradation indicators at hand).

During the first year, a literature survey on condition-based maintenance of topside systems and on subsea systems (mainly gap analysis) is performed and a theoretical framework to build generic models is investigated. This framework relies on i) stochastic processes and new model-ling methods for degradation and maintenance, ii) high level modelling languages to address complex systems and integrate different models, iii) optimization techniques. The industry partners were deeply involved to define studied cases of interest for condition monitoring and maintenance optimisation. During the second phase of the project we will have access to a database (off-shore subsea systems) provided by Statoil in order to improve the use of condition monitoring for decision making in operation. In the project, we have identified strong common interests and possible collaborations with sub-project "Control for extending component life".
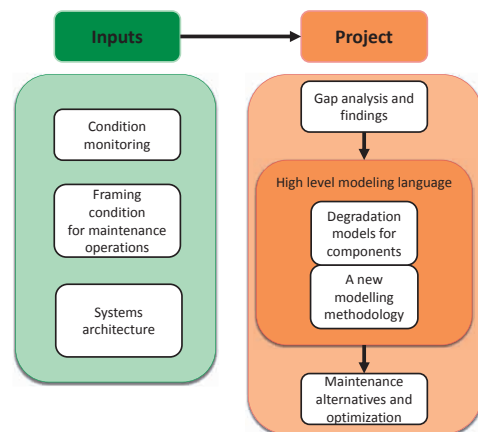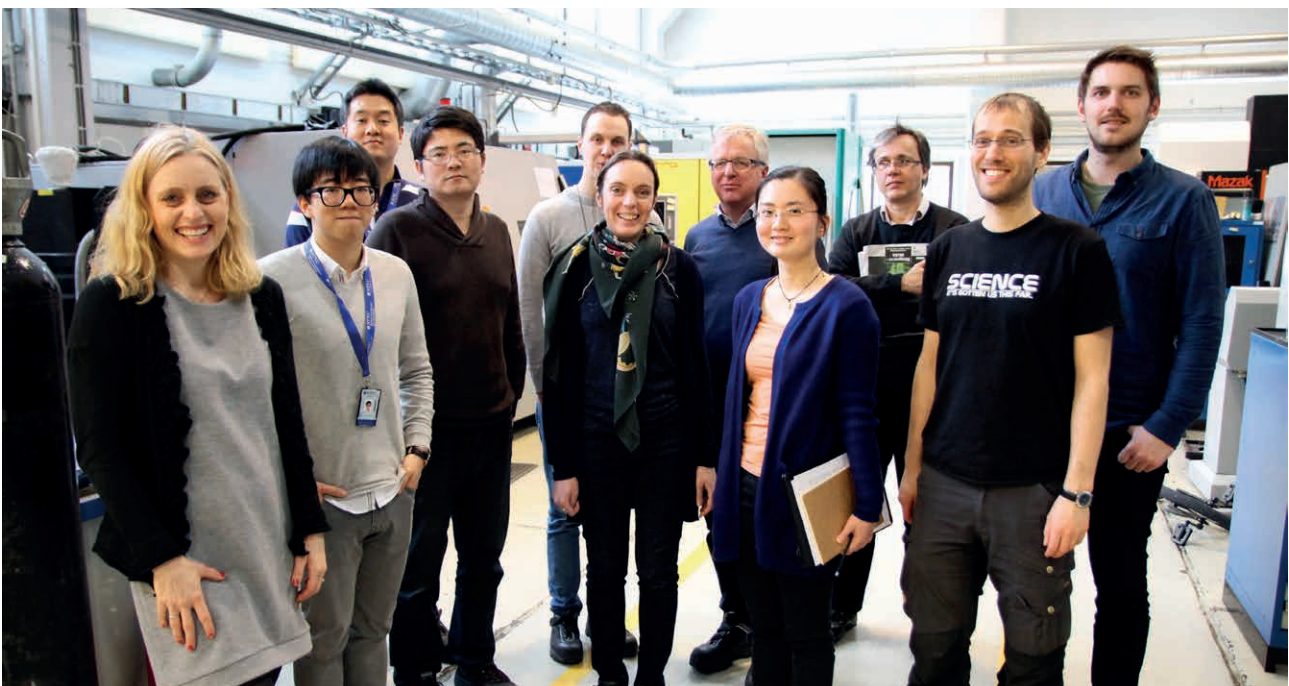

Figure 10. Main tasks of the subproject

The SUBPRO/RAMS research team

SEPARATION – FLUID CHARACTERIZATION

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. In order to optimise these processes, proper fluid characterization and fundamental understanding of the underlying phenomena, like flocculation, coalescence, precipitation, sedimentation and creaming, is required. The overall goal is to develop new methods for advanced fluid characterization at conditions relevant for subsea processing. During the first three years of SUBPRO, the focus is on developing:

Research area manager, Prof. Johan Sjöblom

Research area co-manager, Prof. Gisle Øye

- methods for studying oil drop and gas bubble coalescence at elevated temperature and pressure in order to facilitate design of subsea water treatment systems
- experimental and simulation methods for predicting build-up and ageing of wax deposits
- sequential separation as an approach for investigating the quality of the oil and water phases at different separation stages
- a new coalescence model

Produced water quality and injectivity

Project manager and PhD supervisor Prof. Gisle Øye

PhD student, Marcin Dudek

A major challenge during subsea processing is treatment of produced water. Dispersed oil and solids must be separated from the water so that it reaches sufficient quality to be reinjected into reservoirs or eventually discharged to sea. Merging (coalescence) between oil drops or between oil drops and gas bubbles is a central phenomenon that will promote the separation. In this project, the objective is to study how the chemical composition of crude oil and water influence the route to drop-drop and drop-bubble coalescence (see Figure 11) at elevated pressure and temperature. A new microfluidic setup is built for this purpose. The fundamental knowledge of the produced water fluids gained in the project can be applied in design of subsea water treatment systems for reliable water management. The project will be carried out in close collaboration with Aker Solutions, ENGIE, Lundin Norway and Statoil.
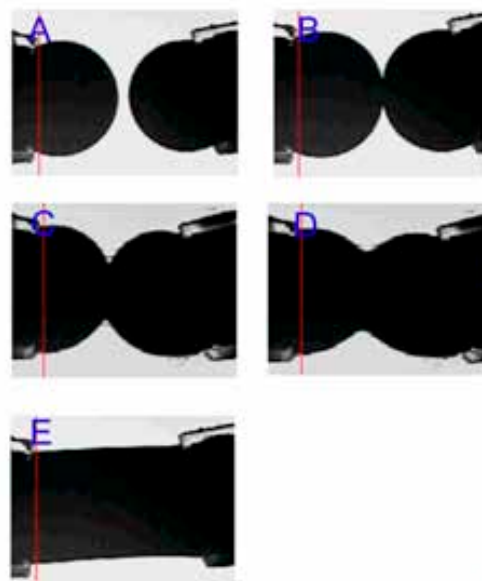

Figure 11. The route to coalescence between two oil drops (determined by a drop-bubble micropipette setup)
A) Drops approaching
B) Thinning of the aqueous film between the drops
C) Breakage of the thin film
D) Merging of drops
E) Completely merged drops

Modelling of wax deposition

Project manager and PhD supervisor, Associate Prof. Kristofer Paso

PhD candidate, Jost Ruwold

Paraffin wax deposition may occur in subsea production systems. Paraffin wax deposition occurs because of wax crystal precipitation as waxy crude oil is cooled during pipeline transportation and subsea processing. When warm waxy crude oil flows past a cold surface, thermal gradients drive deposition of paraffin wax on the cold surface. Build-up of wax deposits in a pipeline results in reduced cross-sectional flow area in the pipeline, restricting fluid flow. At extended tie-back distances, wax deposition may become a more severe problem due to greater thermal losses.

A new simulation model is under development to provide improved forecasts of wax deposition rates applicable to extended tie-backs and sub-sea processing units where the bulk fluid temperature drops below the wax appearance temperature (WAT). The simulator will predict the build-up of wax deposits as well as aging of wax deposits. The simulator will provide predictions for untreated fluids as well as fluids treated with polymeric wax inhibitors.

A cold finger apparatus is used to experimentally measure wax deposition rates. A cold finger device will be used which matches the shear rate conditions present in the sub-sea production system. Figure 12 shows a cartoon of the cold finger device, which provides improved matching of heat transfer, mass transfer and momentum transfer conditions in comparison to traditional cold finger designs. The development of the wax deposition simulator will be informed by the experimental wax deposition measurements.
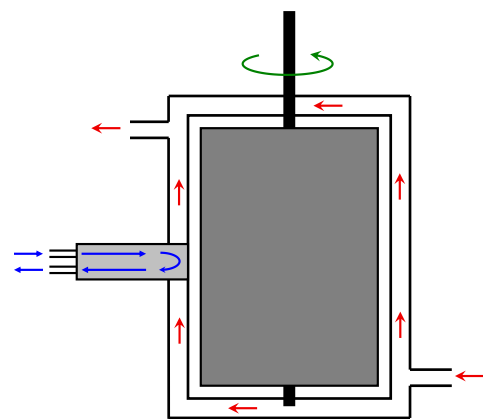

Figure 12. The coldfinger apparatus, with cold and hot water flows labelled with blue and red arrows.

Sequential separation

Project manager and PhD supervisor, Prof. Johan Sjöblom

PhD candidate, Are Bertheussen

Researcher, Dr. Sebastien Charles Simon

The main topic to be studied in the sequential separation subproject is the quality of the water and oil phases from several separation stages, with a focus on the water quality. Adding additional subsea oil polishing steps as described in the "All subsea" and "Subsea Factory" visions entails a more complex separation system for both phases. The composition and properties of the well stream will change over the lifetime of the installation, which also affects the water and oil quality at different separation stages. To predict how inlet conditions will affect the oil and water quality at the different stages of the separation, more knowledge is needed about the compounds that affect the separation. The compounds of interest in this subproject are the indigenous polar crude oil compounds which display surface active properties, focusing on the resin fraction. This mostly entails acidic molecules like naphthenic acids or basic molecules like pyridines. These compounds partition themselves between the oil and water and affect the emulsion stability by adsorbing at the oil-water interface. We will study the partitioning kinetics of acids and bases of different sizes, and how parameters like pH and water cut affect the partitioning.

Modelling of coalescence

Project Manager,
Associate Prof. Brian
Grimes

Postdoc, Aleksandar
Mehandzhiyski

Coalescence (merging between particles, oil drops or similar in a hydrocarbon flow) is crucial for separation and transport of hydro-carbons. The main ob-jective of the project is to obtain a new semi-em-pirical expression of coa-lescence time (time for two particles to merge). Coalescence time in general is an important equation in both simple and complex separation and transport models. With a new expression for the coalescence time, the effects of petro-sur-factant chemistry can be taken into account. To wit a molecular dynamics, simulations will be performed to capture the molecular effects and to obtain a relation with a film drainage model via an expression for the disjoining pressure. Thus, the project employs multiscale modelling in order to solve more accurately a problem on the process scale, namely the coalescence and separation of water and oil.

SEPARATION PROCESS CONCEPTS

Research area manager,
Associate Prof. Hanna
Knuutila

One of the goals of subsea processing is to reduce the need for topside processing and for some fields to move all the needed gas and liquid processing subsea. The first case, partial subsea processing, could be a concept where the gas is treated to pipeline specifications directly and the further oil stabilization and chemical treatment is 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.

The process equipment used topside today, like different absorbers for water and sour gases are not suitable for subsea application. There is need for developing 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 intervals without maintenance or intervention. In the first three years of SUBPRO, the focus is on following concepts:

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

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

15

Membranes for gas dehydration

Project manager and main
PhD supervisor, Associate
Prof. Liyuan Deng

Co-supervisor, Prof.
Magne Hillestad

PhD candidate,
Kristin Dalane

One of the main process-ing steps in natural gas processing is dehydration. This has been identified by our industry partners as a major challenge, in order to prevent hydrate for-mation, slug flow, corro-sion and erosion in pipes and process equipment.

The objective for this project is to evaluate a new membrane process design for subsea natural gas dehydration *(Figure 13)* to reach pipeline transport specifications. To evaluate the membrane dehy-dration process, modelling and process simula-tion will be conducted. The two membrane mod-ules will be modelled and verified before they are implemented into the simulation tool HYSYS for an overall process design evaluation and optimi-zation. With a verified and optimized process sim-ulation model a feasibility study of the membrane dehydration process can be reported. In a later stage, there will be a need for verification of mod-els through experimental testing.

With subsea dehydration, no water will be present in downstream gas pipelines and process equip-ment, which gives several advantages: Prob-lems connected to multiphase transport will be removed and there is no need for other mitigation techniques as continuous injection of preven-tion chemicals like Mono-ethylene glycol (MEG). In addition, dehydration in an earlier processing stage will reduce the cost and complexity of the downstream equipment.

Figure 13. Preliminary process design for closed loop membrane dehydration with glycol. Water from wet natural gas is absorbed by glycol in a membrane contactor, and glycol is regenerated with pervapora-tion where the water is removed from the rich glycol.

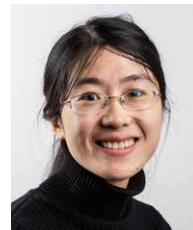# H_2S and hydrate control, particle breakup/contactor studies

Project manager and PhD
supervisor, Associate
Prof. Hanna Knuutila

PhD candidate, Eirini
Skylogianni

Co-supervisor, Prof. Emeritus
Hallvard Fjøsne Svendsen

Postdoc, Jing Shi

used for hydrate control in the well flowlines, giving in total 3 different chemical systems with separate absorption and regen-eration equipment. Simplifying the chemical systems or mov-ing equipment and process ele-ments subsea could be a way to ensure better energy efficiency and utilization of the resources.

Pipelines used to transport produced gas have quality restrictions related to content of water, CO_2, H_2S and heavy hydrocarbons. If these requirements cannot be met by the well flow, separation is re-quired either topside or subsea. Today on a typical platform, water is removed by Triethylene glycol while CO_2 and H_2S is removed by amine processes. In addition to this, Mono-ethylene glycol (MEG) is

The objective of this project is to develop a regenerative process where hydrate formation is controlled and H_2S is removed. Since this would be a regenerative process, significantly higher concentrations of H_2S could be treated than what normally is the case with e.g. triazine. The work will contain both modelling and experimental studies.

A new regenerative process will allow production from wells with high H$_2$S concentration directly to transport line.

Experiments on fluid particle breakage and contactor studies
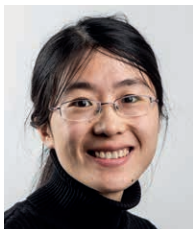
Project manager and
main PhD supervisor,
Prof. Hugo A. Jakobsen

PhD candidate,
Eirik Helno Herø

Co-supervisor,
Dr. Jannike Solsvik

Postdoc, Jing Shi

In order to facilitate subsea boosting and transportation, phase separation of the hydrocarbon flow subsea is often required. Phase separation efficiency is severely dependent on the distribution of the fluid particles size. The fluid particle size is determined by equilibrium between various mechanisms of fluid particle breakage and coalescence (particle merging). These mechanisms depend on system properties, surface chemistry, operating conditions, and flow phenomena. The current understanding and ability to predict these processes is still immature and further research is needed. In this project emphasis is placed on fundamental investigations of the fluid particle breakage mechanisms.

A new experimental equipment for investigation of single fluid particle breakage under controlled flow conditions has been designed, based on a literature survey, and is currently under construction. The novel part is the analysis section in which more uniform turbulence dissipation rate level is produced due to an enlarged wall roughness. It is noted that only the drops moving in the centre part of the tube will be considered to avoid wall effects as the dissipation rate profile will have maxima close to the walls. The experimental setup is sketched in Figure 14.

The main aim is to perform experiments to determine breakage frequency (breakage time and breakage probability), number of daughter particles created in breakage events, and size distribution of daughter particles created in breakage events.
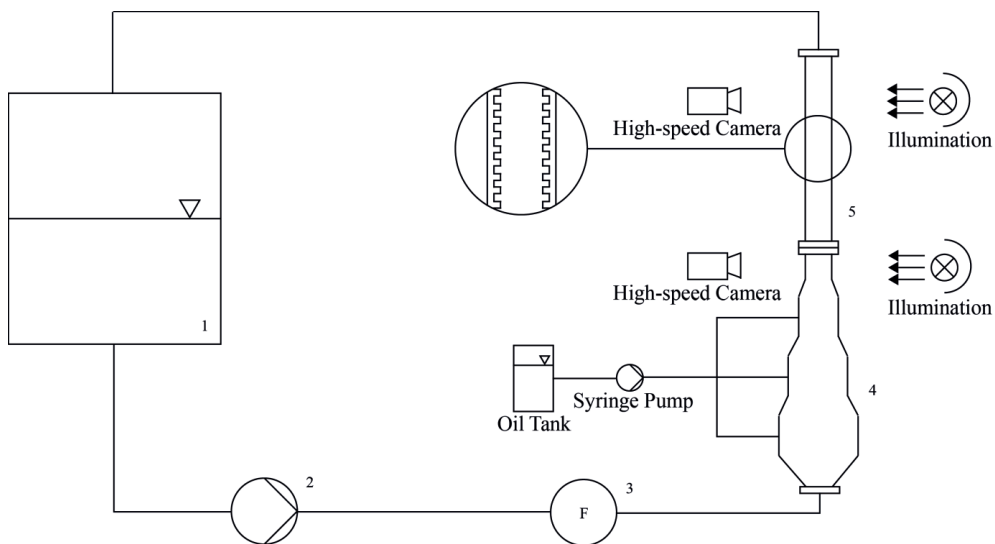

Figure 14. Simplified flow diagram of the experimental set-up. 1) water/oil storage tank, 2) pump, 3) flow meter/controller, 4) droplet generation section, 5) breakage analysis channel.
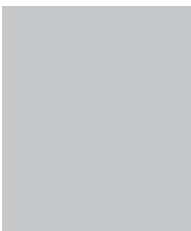
17

Compact separation concepts

Project manager and main
PhD supervisor, Associate
Prof. Milan Stanko

Co-supervisor,
Prof. Sigbjørn Sangesland

Co-supervisor, Prof.
Emeritus Michael Golan

PhD candidate, hiring in
process

The main objective of this project is to perform an experimental and numerical evaluation of primary separation techniques for oil and water flows with potential for subsea implementation. The techniques to be analysed should be robust, effective and have low energy requirements.

At an early stage, the research will perform a systematic evaluation of existing systems and methods for subsea separation using input from existing projects and from industrial partners. Afterwards a screening and pre-evaluation of new

separation concepts and ideas worth pursuing will be performed. There are two concepts analysed previously at NTNU that might be looked into: separation in spiral conduit and separation in an inclined pipe using distributed tapping.

At a later stage, the research will select the most promising concept to develop further (in agreement with the industrial partners) and will perform experimental measurements and numerical simulations to determine separation performance.

Status: The project will start mid-2016, due to limited availability of qualified PhD candidates in the first announcement round.

The originally proposed work plan has been revised, considering the delay. The laboratory facilities have been planned and prepared at the end of 2015.
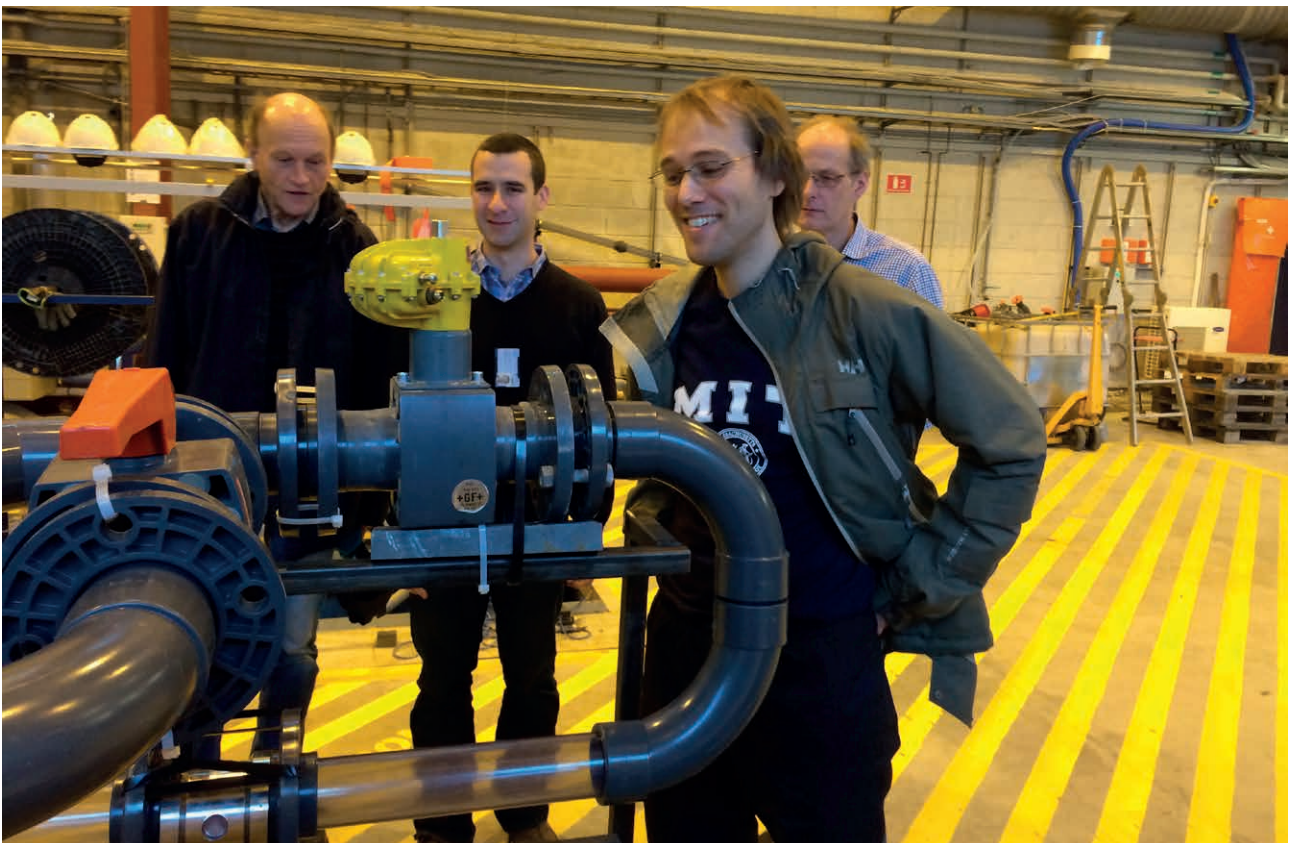
Separator rig, NTNU.

SYSTEM CONTROL

Research area manager,
Prof. Sigurd Skogestad

The operation of most subsea installations today require very little automatic (feedback) control action. However, to recover hydrocarbons also under increasingly challenging reservoir conditions, the subsea installations may contain one or several modules for separation, pumping and boosting. As the subsea processes become more complex, also more advanced control and monitoring solutions are required to operate these safely and optimally.

The research area Systems Control covers the development of new methods and tools related to safe and optimal operation of such complex subsea processes. In particular, it focuses on the development of:

• Models
  - Models designed for process control purposes
  - Modelling techniques for subsea process control purposes

• Methods
  - Control and optimal operation strategies for subsea processes

- State and parameter estimation methods for estimating unmeasured process conditions

The main application focus of the research area Systems Control is on subsea separation processes. In addition, other processes, such as pumping or compression may be included. The goal is to develop tools and methods that are simple and robust enough for use in real subsea applications.

Sub-projects of Systems control
The research area Systems Control consists of five sub-projects:
• Dynamic simulation model library
• Modelling and multivariable control of subsea systems
• Control of subsea processes
• Estimation of un-measureable variables
• Control for extending component life

Dynamic simulation model library

Project manager,
Prof. Sigurd Skogestad

Postdoc, Christoph Backi

In the area of subsea processing and production there is a big need for simple, yet efficient mathematical models describing complex phenomena and behaviours of different equipment. These models can be used for example for conceptual design of subsea processes and dynamic simulation of (interconnected) equipment as well as model-based controller design and the test of control structures in an overall (high level) setup. A major part of the subproject will be to coordinate model development performed in the other activities in System control area and to cooperate with other subprojects, such as for example "Multiphase booster models" in the Field architecture area. These modelling activities will cover equipment in the whole chain from reservoir to the product export. The biggest area is thereby the modelling of separators such as phase splitters, gravity separators, cylindrical cyclones and in-line (swirl) separators. Furthermore, the large area of boosting devices, such as compressors (dry- and wet-gas) as well as pumps (single- and multi-phase),

can be investigated, although this is not a main research area in the SUBPRO project. In addition, heat transfer phenomena and heat exchangers, membranes as well as valves/chokes and pipes are potential areas for modelling activities. Furthermore, the choice of a simulation environment / programming language is crucial in order to test and verify the obtained mathematical models. In the first stage, the models will be designed and tested in the tools MATLAB/SIMULINK. However, also Modelica will be used, in cooperation with Statoil. At later stages, it should be possible to implement the mathematical models in commercial software, such as OLGA. This can possibly be achieved by interconnecting different simulation environments, for example MATLAB with OLGA, in order to test sophisticated control structures.

The ultimate goal will be to build a model library for subsea processes including models for the most crucial equipment mentioned above, but also for novel control structures based on the obtained models.

Modelling and multivariable control of subsea systems

Project manager and main
PhD supervisor, Prof. Olav
Egeland

PhD candidate, Torstein
Thode Kristoffersen

Co- supervisor, Associate
Prof. Christian Holden

Co-supervisor,
Prof. Sigurd Skogestad

Traditionally, the big and easily available oil fields offshore producing from a topside processing plant have already been developed. The oil and gas industry now focuses on increased oil and gas recovery from brownfields and on development of smaller oil and gas greenfields. Subsea process-ing will be a key factor both for increasing oil and gas recovery on existing fields and for making new, smaller oil and gas fields economically feasible.

Subsea processing plants are small compared to topside processing plants and have fast dynamics and strong interaction between units. This fast dynamics poses challenges with transients and modelling which are important for analysis and design of online multivariable control and optimi-zation. The control oriented models need to be fast and sufficiently accurate to describe the physical properties of the subsea processing plant. Thus, the objective of this subproject is to create stand-ardised models for a complete subsea processing plant, analyze and improve interacting control loops and design a multivariable control structure to utilize the strong interactions and fast dynamics

to handle transients and optimize production, e.g. linear/nonlinear Model Predictive Control. An important research objective will be to find the minimum buffer volume necessary to sufficiently control the process and handle transients with multivariable control.

The models to be developed will start from recent separation technology, (e.g. the CompactSep separation system developed by Statoil in collab-oration with Chevron, Petrobras, Total and FMC) and extend with boosting and cooling, including actuator dynamics, processing time delay and transmission of signals and power. An intension is that the modelling work should result in a general framework for standardized modelling of subsea processing plants. A laboratory of several microcontrollers is to be constructed and run with various parts of the complete control model of compact subsea process to study the effect of increased time delay subsea. During the modelling work, focus will be given to numerical solutions of the models for the simulation to be fast enough.
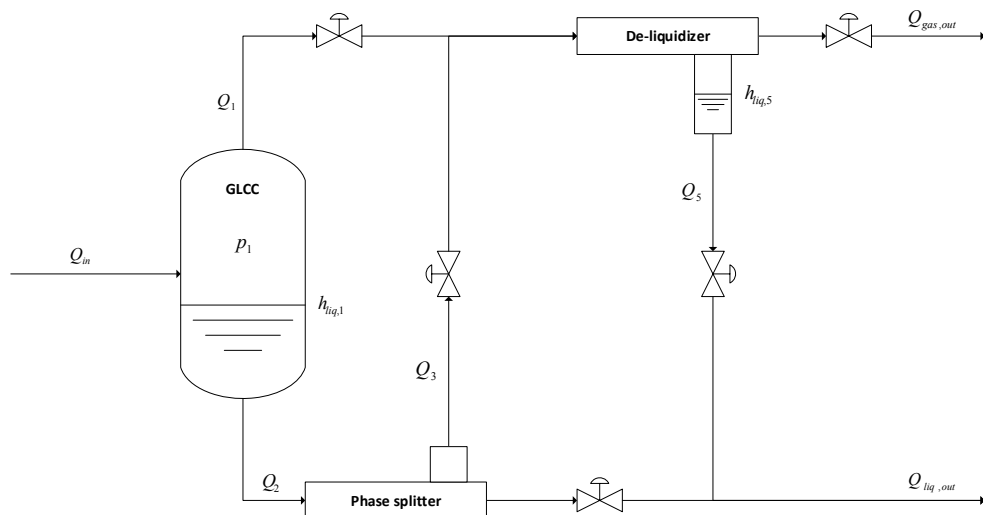

Figure 15. CompactSep, an example of a separation system to be modelled. Patented separation process by Statoil. Picture from presentation at the 22nd Mediterranean Conference on Control and Automation 2014.

Control of subsea processes

Project manager and
main PhD supervisor,
Associate Prof. Christian
Holden

PhD candidate,
Sveinung Johan Ohrem

Co-supervisor,
Prof. Olav Egeland

Co-Supervisor,
Prof. Sigurd Skogestad

Most processes in the oil and gas industry, whether subsea or topside, are in need of some sort of control. Many variables like liquid level, pressure and flow rate are influencing the quality of the product and the operators need to be able to manipulate these variables. While some of this manipulation can be performed manually, some require, or can be significantly improved by, automatic control. Operators can choose a set point for operation and the control system ensures that the variable converges to, or at least stays close to, this set point, including taking into account safety margins and hardware constraints. Design of the automatic control systems is challenging, both scientifically and practically, due to the complex behaviour frequently seen in subsea processes. Designing these advanced automatic control algorithms is the goal of this subproject.

In this subproject, we will investigate control of several hydrocyclone separators in series to improve the quality of produced water, dampen slugs in risers to prevent overloading topside equipment, control compact flotation units for separation of oil and water, and other related topics. The research topics are chosen based on suggestions from our industry partners. A traditional control system would need continuous, expensive and time-consuming re-tuning by specially trained personnel to cope with the complexities and uncertain behaviour. Control may even be impossible. The advanced control algorithms we will design as a part of this project will be able to handle the complexities and uncertainties in a truly autonomous manner and obviate the need for re-tuning. We believe advanced control methods, like non-linear and adaptive control, provide the most suited approach for subsea processes.

To validate the developed methods and improve the quality of research, we are building a small-scale separation laboratory that will include hydrocyclones, bulk separation, coalescing pumps and other compact separation systems. Our industry partners are very interested in improving the control algorithms used in a hydrocyclone separation system. Phase 1 of the laboratory, which is planned for construction in 2016, will predominately focus on hydrocyclones.
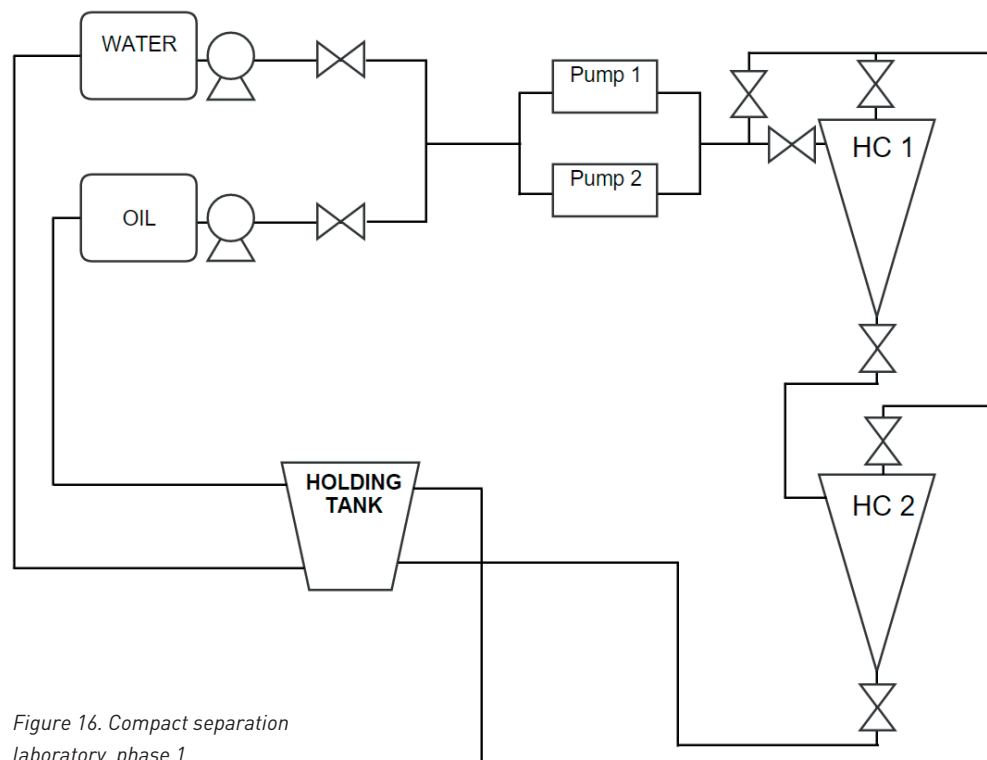

Figure 16. Compact separation laboratory, phase 1.

Estimation of un-measurable variables

Project manager and PhD supervisor, Associate Prof. Johannes Jäschke

PhD student, Tamal Das

In subsea oil and gas production, many important variables are not measured due to lack of reliable qualified sensors. Some of these variables are, however, essential for process control, monitoring and safety, and may further be used to plan interventions. State and parameter estimation are powerful tools 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 oil concentration in water outlet of the separator. For estimation, we will use state-of-the-art estimation methods, such as moving horizon estimation, Bayesian estimation, extended Kalman filtering etc. Estimation algorithms, if needed, would be tweaked to cater for specific applications, such as online estimation and control.
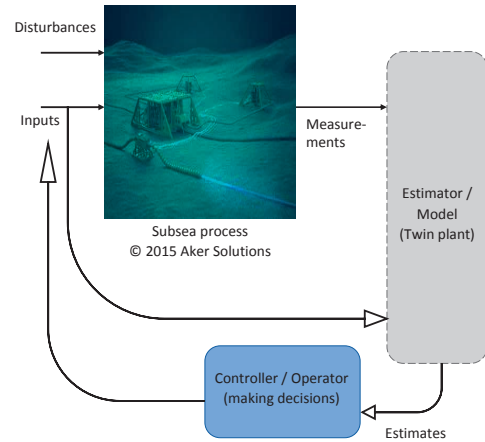
Figure 17:The measurements and the inputs to the plant are used in the estimation block to estimate unmeasured process variables

Control for extending component life

Project manager and PhD supervisor, Associate Prof. Johannes Jäschke

PhD student, Adriaen Verheyleweghen

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 (ROV). 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 process control to find the optimal back-off from the constraints. The goal is to ensure that the RUL (Remaining useful life) of the equipment is not exceeded before the next planned maintenance stop, while maximizing production. We will develop computer models and algorithms to solve this problem.
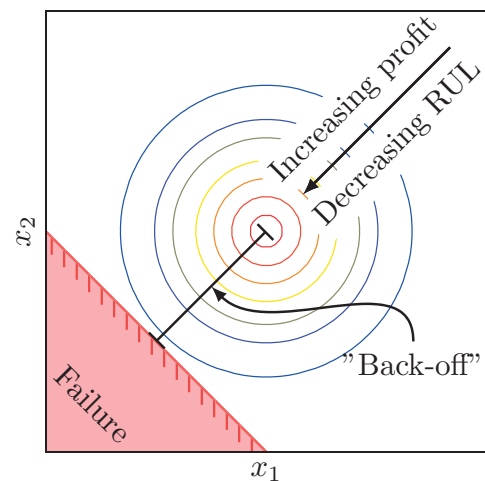

Figure 18. Illustration of constraint back-off. Here the RUL is dependent on two operational variables, x_1 and x_2, but there will typically be more dimensions in a real situation.

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.

Aker Solutions has supplied the following in kind deliverables in 2015:
- Subsea system engineering course for PhD's and Postdocs in SUBPRO
- Technical report providing information related to the following sub projects:

- Multiphase booster models
- Produced water quality and injectivity
- Membranes for gas dehydration
- New safety and control philosophy
- Estimation of un-measurable variables
- Control for extending component life

The report is used by the R&D activities in SUBPRO as a part of the current technology mapping.
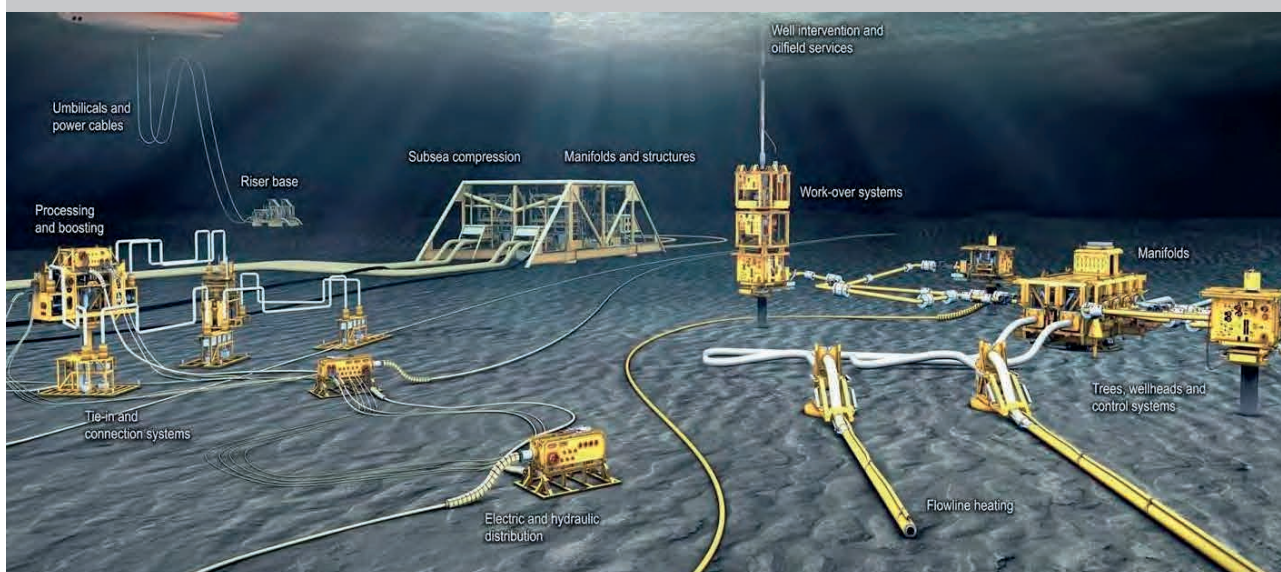
Figure 19 Illustration of subsea system components, from Subsea system engineering course © 2015 Aker Solutions

Subsea field and FPSO © 2015 Aker Solutions   *Subsea fieldinstallation* © 2015 Aker Solutions
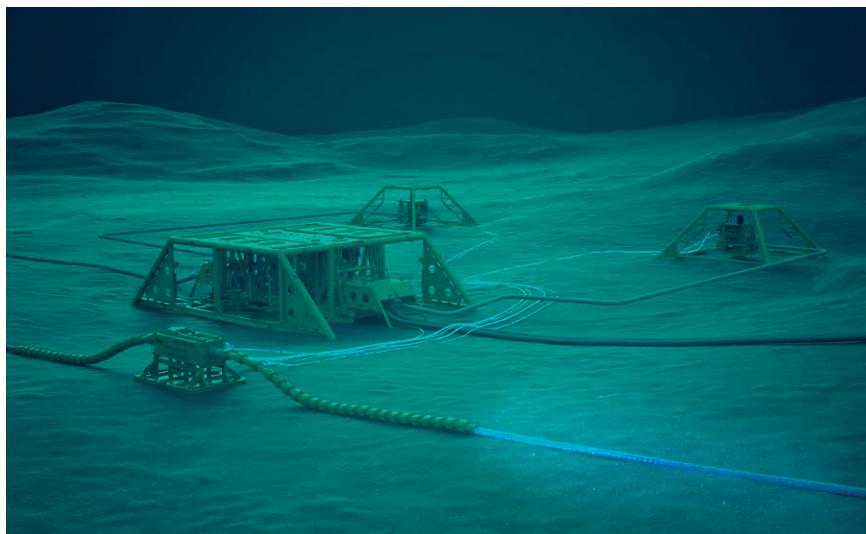
EDUCATION

PHD CANDIDATES AND POSTDOCTORAL SCHOLARS
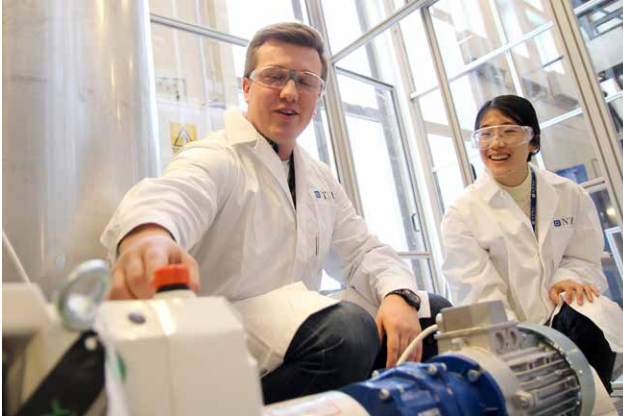
SUBPRO will educate 30 PhD candidates and 9 Postdoctoral scholars through the coming 8 years. 20 of these have started their projects during the fall 2015 or spring 2016. The candidates will gain a unique competence in the field of subsea production and processing, both from an academic and industrial perspective. They will be highly relevant personnel for positions in the industry and academia.

RESEARCH OPPORTUNITIES IN SUBPRO AND DEPLOYMENT OF FUTURE KNOWLEDGE

Are Bertheussen PhD candidate, Sequential separation

What opportunities do you see as a PhD candidate in SUBPRO?
"Being a PhD student in SUBPRO has given me the opportunity to delve into the field of subsea technology. Although the main topic of my PhD is quite narrow, as PhD topics often are, the SUBPRO project provides us with a broader understanding of the background and status of the new and exciting subsea technology field through lectures, company excursions and colloquiums."

What kind of work do think could be relevant for deploying the knowledge from your PhD project?
"The knowledge accumulated through my PhD period could be relevant for further research into subsea oil and water separation, especially working towards the envisioned Subsea Factory and All Subsea concepts."

Christoph Backi
Postdoctoral scholar,
Dynamic simulation model
library

What opportunities do you see as a Postdoctoral scholar in SUBPRO?
"SUBPRO is characterized by an interdisciplinary working environment consisting of people from both academia and industry. The researchers have their expertise in a broad variety of scientific fields. This and the complexity of the overall scope of the project divided into many sub-tasks make cooperation challenging and interesting at the same time."

What kind of work do think could be relevant for deploying the knowledge from your Postdoctoral project?
"As a Postdoctoral Fellow, I am assigned to my own subproject within SUBPRO. Collaboration with PhD students in my research area, with researchers in neighboring areas and with the industrial partners are crucial in order to solve the given tasks efficiently and employ the knowledge and methods obtained in the subproject to industrial applications."

Kristin Dalane PhD
candidate, Membranes
for gas dehydration

What opportunities do you see as a PhD candidate in SUBPRO?
"As a PhD in SUBPRO I get the great opportunity to learn more about subsea processing in general in addition to get into depth of one specific part. To work in a multidisciplinary project towards a common goal is very inspiring and motivating, as it covers different knowledge giving good foundation for discussion and problem solving. SUBPRO's high focus towards the goal in addition to the interest from the industry gives a large driving force for the research."

What kind of work do think could be relevant for deploying the knowledge from your PhD project?
"During a PhD project, in addition to becoming a specialist in one topic, you learn how to be a researcher and how to solve difficult problems, which is a valuable knowledge for future work life."

Mariana Diaz
Postdoctoral scholar,
Subsea gate box

What opportunities do you see as a Postdoctoral scholar in SUBPRO?
"As a Postdoc in SUBPRO, I am looking forward to carrying out a research project in close collaboration with the industry, in order to address my investigation to actual necessities and propose novel solutions with the potential to be applied in future developments. I think the industry–academy partnership within the SUBRO framework will allow developing new and fresh ideas with a strong background both conceptual and technical.

I expect to have the opportunity to learn about the different technology available within subsea field development, as well as on the different stages of the subsea production process. I wish to have a closer interaction with the active partners of the industry, increase my professional networking and explore different knowledge areas related to other subprojects of SUBPRO."

What kind of work do think could be relevant for deploying the knowledge from your Postdoctoral project?
"The knowledge developed during the Postdoc period will be highly relevant for planning and strategy layout of new field developments or for the incorporation of new resources to existing facilities. The expertise to be acquired may be appropriate for roles such as research consultancy, research and development, production technology among others areas."

What opportunities do you see as a PhD candidate in SUBPRO?
"Being part of the team to deliver solutions to real industries' needs is inspiring, I have the opportunities to deepen my understanding of condition and prognostic based maintenance, with the chance to see diverse ideas, experience and approaches to problems under the framework of the big project."

What kind of work do think could be relevant for deploying the knowledge from your PhD project?
"The outcomes of this PhD study is not limited to a specific industry branch. As of today, there is a growing need for RAMS expertise in a wide range of industries and organizations like O&G, transportation, aerospace, defense etc. The knowledge, skills and philosophy obtained from the project assist me to identify and solve challenges lying in the interface of theoretical and practical areas."

Yun Zhang
PhD candidate,
Prognostics and condition
based maintenance

MSC CANDIDATES

In the academic year 2015/2016 NTNU/SUBPRO is educating 30 Master students with specialization in subsea production and processing.

EXPERTS IN TEAMWORK VILLAGE – CHALLENGES IN SUBSEA PRODUCTION AND PROCESSING

In the spring term 2016, 30 Master students from NTNU with background from engineering and natural science are participating in the course "Experts in Teamwork Village". They work with interdisciplinary projects in the following fields, under supervision of professors and industry personnel who are involved in SUBPRO:

- Arctic field development
- Real time risk management for subsea systems
- Liquid-Liquid separation technology: Modelling with respect to control design, instrumentation and disturbance handling
- Managing the safety of subsea production and processing systems
- Subsea production system for low CO_2 emission

ORGANISATION
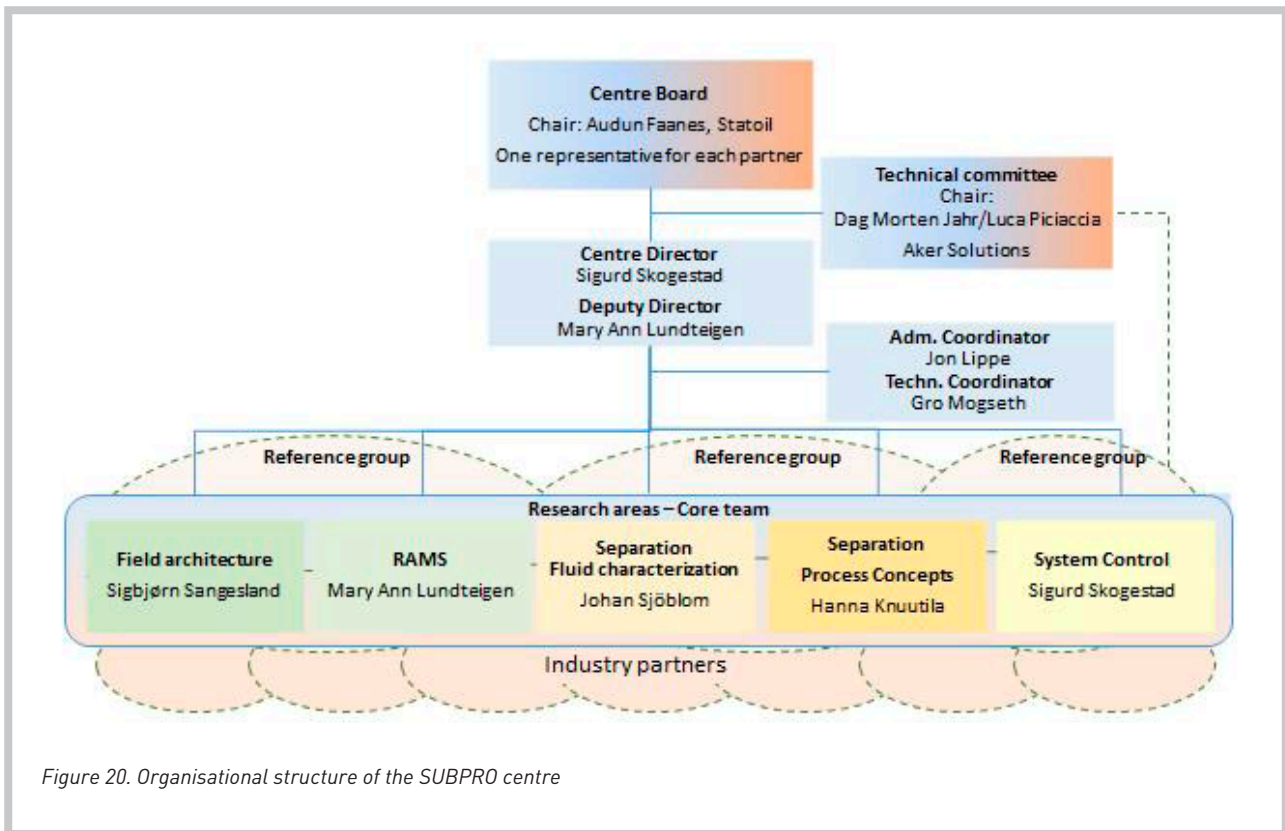
Figure 20. Organisational structure of the SUBPRO centre

CENTRE BOARD

Audun Faanes, Statoil
Chair of the board

Tone Schanke-
Jørgensen, Lundin Norway

Tom Steinskog
ENGIE

Torolf Hæhre
Shell

Anne Borg
NTNU

Kjartan Pedersen
Aker Solutions

Frank Børre Pedersen
DNV GL

Katrine Hilmen
ABB

Sigurd Skogestad
NTNU, Centre director
Secretary of the Centre
board

Kimberly C. Mayes
Research Council of
Norway, Observer

TECHNICAL COMMITTEE

Dag Morten Jahr, Aker Solutions, Chair of the Technical committee spring 2016

Luca Piciaccia, Aker Solutions, Chair of the Technical committee fall 2015

The Technical committee is responsible for monitoring the scientific quality and industrial relevance of the Centre activities and for giving advice to the Centre board about technical matters.

The committee consists of 2-3 technical representatives from each industry partner and the research area managers and project managers from NTNU

REFERENCE GROUPS

SUBPRO has established three reference groups for the following areas:
- Field architecture and RAMS (Reliability, Availability, Maintenance and Safety)
- Separation
- System control

The reference groups provide technical advice to the projects, discuss possible applications of expected project results and help establishing direct cooperation between the projects and the industry partners. Business cases are used to adapt the research to realistic challenges of existing and new types of fields around the world. In the reference groups, PhD candidates, Postdocs and researchers meet people from the industry and get direct feedback to ongoing work.

The first reference group meeting in Trondheim in September 2015 discussed working plans for the coming three years and established sub groups for the different research areas.

KNOWLEDGE TRANSFER TO THE INDUSTRY

SUBPRO applies several mechanisms for knowledge transfer from research to the industry partners:
- Reference group meetings
- Technical workshops
- Training seminars
- Electronic information sharing system for reports, publications and other technical documentation
- Informal communication and collaboration between researchers and industry partner personnel

INTERNATIONAL COLLABORATION

SUBPRO aims at establishing cooperation with advanced universities in the field. Discussions with potential instutu-tions have been initiated during 2015.
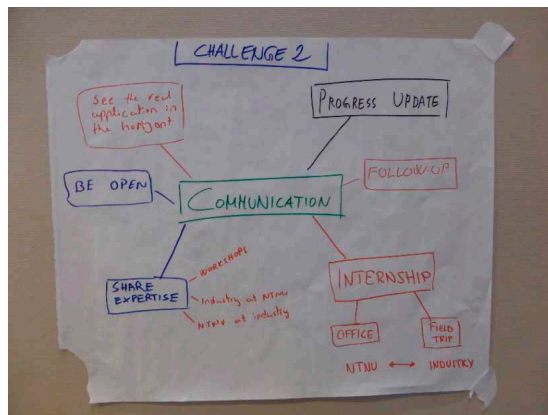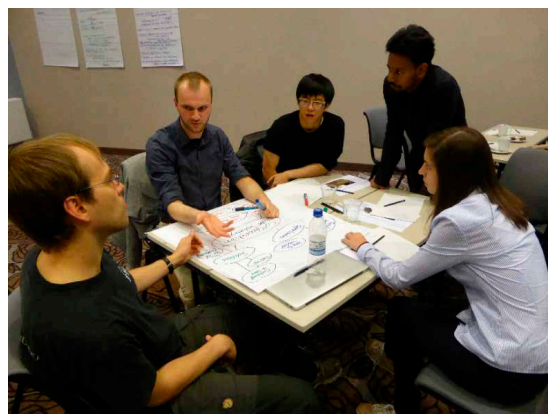
HSE

SUBPRO is engaged in extensive laboratory activities and field work as a part of the R&D projects. SUBPRO follows NTNU's system for HSE in all activities. All experiments at NTNU and field trips outside NTNU are subject to thorough risk analysis prior to execution, and SUBPRO personnel receive systematic HSE training and are drilled in reporting and analysis of unexpected events.

KEY FIGURES FOR SUBPRO

Project duration	August 2015 – August 2023*		
Total annual costs	33 mill. NOK		
Personnel	The whole project period	Hired as of March 2016	Female percentage
PhD candidates	30	15	30 %
Postdoctoral scholars	9	5	40 %
Professors involved at NTNU	20	20	20 %
Other researchers	5	5	40 %
MSc students (per year)	30	30	20 %
Total		**75**	**25 %**

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

CROSS DISCIPLINE COLLABORATION

The field of subsea production and processing is a multi-discipline area, containing elements of Chemical engineering, Petroleum engineering, RAMS and System control. SUBPRO provides a unique opportunity to combine such disciplines across the organisation both at NTNU and the industry partners, to find new and original solutions. Emphasis is put on communication between projects, through co-location of PhD candidates, PhD colloquia, team building and electronic collaborative environments.

COOPERATION WITH OTHER INITIATIVES FOR SUBSEA R&D AND INNOVATION

SUBPRO has cooperated actively with other R&D/ innovation initiatives in the subsea field during 2015. The centre was presented at the UTC Underwater Technology Conference in Bergen, on the Subsea Valley Conference in Oslo, on the DNV GL Summer surf subsea technology seminar in Oslo and at a NCEI seminar in Trondheim during 2015.

RESEARCHERS IN THE SUBPRO CENTRE

CENTRE MANAGEMENT

Prof. Sigurd Skogestad, Centre director

Prof. Mary Ann Lundteigen, Centre co-director

Jon Lippe, Project coordinator

Gro Mogseth, Technical coordinator

RESEARCH AREA MANAGERS/CORE TEAM

Prof. Sigbjørn Sangesland, Field architecture

Prof. Mary Ann Lundteigen, RAMS

Prof. Johan Sjöblom Separation - Fluid characteristics

Prof. Gisle Øye, Separation - Fluid characteristics
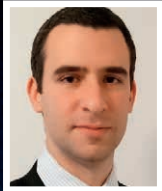
Ass. Prof. Hanna Knuutila, Separation process concepts

Prof. Sigurd Skogestad, System control

SUB PROJECT MANAGERS

Prof. Sigbjørn Sangesland, Subsea gate box, Multiphase booster models

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

Prof. Mary Ann Lundteigen, New safety and control philosophy, RAMS in system design

Prof. Anne Barros, Prognostics and condition based maintenance

Prof. Gisle Øye, Produced water quality and injectivity

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

Prof. Johan Sjöblom, Sequential Separation

Associate prof. Brian Arthur Grimes, Modelling of coalescence

Associate prof. Liyuan Deng, Membranes for gas dehydration

Associate prof. Hanna Knuutila, H2S and hydrate control. Particle breakup and contactor studies

Prof. Hugo Atle Jakobsen, Experiments on fluid particle breakage

Prof. Sigurd Skogestad, Dynamic simulation model library

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

Gro Mogseth, In kind contribution from industry partners
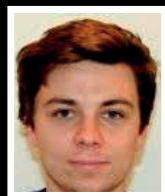
PHD CANDIDATES

Diana Gonzales

Gilberto Nunez

Juntao Zhang

Yun Zhang

Marcin Dudek

Jost Ruwoldt

Are Bertheussen

Kristin Dalane

Eirini Skylogianni
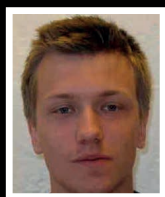
Eirik Helno Herø

Torstein Thode Kristoffersen

Sveinung Johan Ohrem

Tamal Das

Adriaen Verheyleweghen

POSTDOCTORAL SCHOLARS
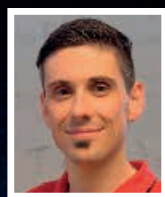
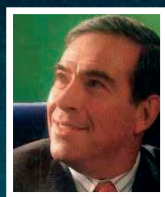**Mariana Diaz**

HyungJu Kim

Jing Shi

Aleksandar Yordanov Mehandzhiyski

Christoph Josef Backi

RESEARCHERS AND CO-SUPERVISORS

Prof. emeritus Michael Golan

Postdoc Jesus de Andrade

Associate prof. Yiliu Liu

Prof. Antoine Rauzy

Researcher Sebastien Charles Simon

Prof. Magne Hillestad

Prof. Emeritus Hallvard Fjøsne Svendsen

Postdoc Jannike Solsvik

Researcher Esmaeil Jahanshahi

SUBPRO
Subsea production and processing

PARTNERS

Shell

ENGIE

ABB

Statoil

NTNU
Norwegian University of
Science and Technology

Lundin
Norway

AkerSolutions™

DNV·GL

The Research Council
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