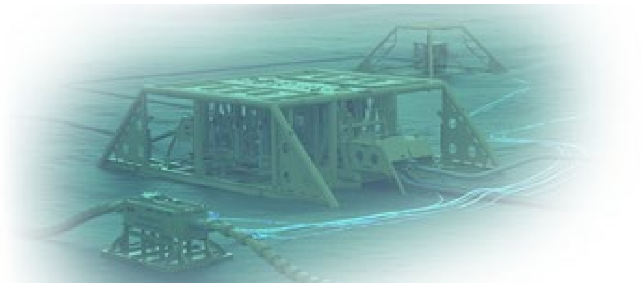
SUBPRO



sfi Centre for Research-based Innovation

NTNU – Trondheim
Norwegian University of Science and Technology

SUBPRO Symposium

Towards autonomous optimal process operations

Highlights of 8 years of Systems and Control Group

Johannes Jäschke
Department of Chemical Engineering, NTNU

Norwegian University of Science and Technology

Objective

Develop tools for automatic operation of subsea processes with minimal human intervention and supervision

- Optimal in terms of economics (short-term and medium-term production optimization)
- Keep process in safe and desired operation range (Control algorithms)
- Minimize environmental impact

Gaps addressed by SUBPRO Systems Control

1. Lack of *simplified* first-principles models for subsea processes

2. Lack of *systematic* approaches to realize optimal operation and control
   (including optimal trade-off between equipment wear and maximizing production)

3. Lack of *reliable* methods to estimate unmeasured variables

4. Lack of knowledge of how to optimally combine data and knowledge-based models

SUBPRO SYSTEM CONTROL PROJECTS

SUBPRO

Previously finalized projects

3.4 Dynamic simulation model library
Christoph Backi, Postdoc
Prof. Sigurd Skogestad

3.5 Modelling for control of subsea processes
Torstein Kristoffersen, PhD
Assoc. Prof. Christian Holden

3.6 Adaptive control of subsea processes
Sveinung J. Ohrem, PhD
Assoc. Prof. Christian Holden

3.7 Estimation of un-measured variables
Tamal Das, PhD
Assoc. Prof. Johannes Jäschke

3.9 Production optimization under uncertainty
Dinesh Krishnamoorthy, PhD
Prof. Sigurd Skogestad

3.8 Control for extending component life,
Adriaen Verheyleweghen, PhD
Assoc. Prof. Johannes Jäschke

3.7.b Enhanced virtual flow metering
Timur Bikmukhametov,
PhD
Assoc. Prof. Johannes Jäschke

3.5.b Process control algorithms
Mishiga Vallabhan, PhD
Assoc. Prof. Christian Holden

3.8.b Experimental validation of methods - Remaining Useful Life (RUL)
José Matias, Postdoc
Assoc. Prof. Johannes Jäschke

3.7.c High-accuracy virtual flow metering with machine learning and first principles models
Md Rizwan, PhD
Assoc. Prof. Christian Holden

Allyne dos Santos, associated PhD

Finalizing 2023
Defense 2024

3.9.b Field-wide production optimization
Risvan Dirza, PhD
Prof. Sigurd Skogestad

3.10 Calibration of digital twins
Halvor A. Krog, PhD from summer 2020
Assoc. Prof. Johannes Jäschke

3.5.c Energy-optimal subsea prod. and processing
Asli Karacelik, PhD (3) from September 2020,
Assoc. Prof. Christian Holden

SPINOFF: AutoPRO
- Rafael de Oliveira, PD (SC)
- Evren Turan, PhD (SC)
- Emefon Dan, PhD (RAMS)

Assoc. Prof. Johannes Jâschke/Yiliu Liu

Big-picture on Activities

SFI SUBPRO

Initial phase: 2015-2018

Main focus: Control-oriented models:

- Separators (Compact, gravity)
- Pumps
- Compressors (single/multiphase)
- Separation systems
  - Gravity, CFU, cyclones
- Production systems
  - Well, riser compressor

Later phase 2017-today

Main focus: Methods development

- Optimal autonomous operation
- Local control algorithms
- Plant-wide control approaches
- Operation with degrading variables
- Estimation of unmeasured variables, VFM

Validation in control labs: Compact separation, compressor, degradation + gas-lift

Developing control-oriented models

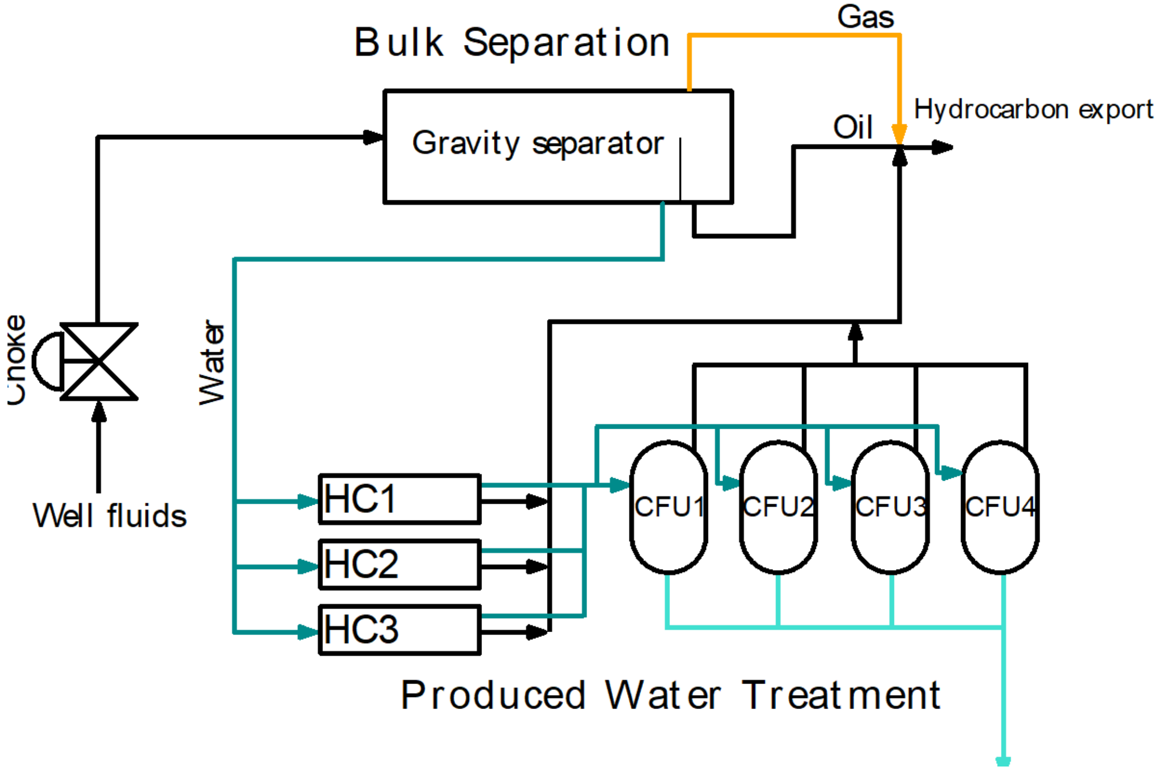
- Adresses Gap 1: Lack of *simplified* first-principles models for subsea processes

- Based on simplified first principles assumptions

- Capture specific behavior well enough for control

- Simple, fast to evaluate and optimize

- Can be easily combined to overall systems

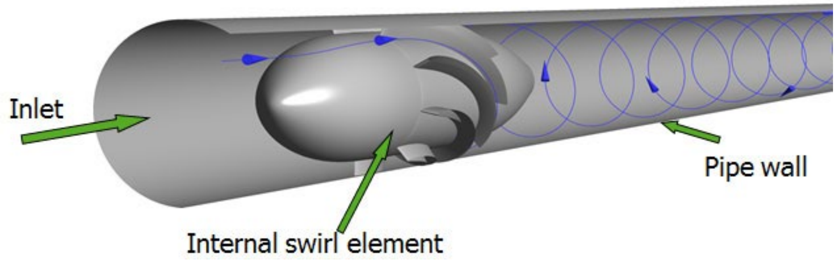


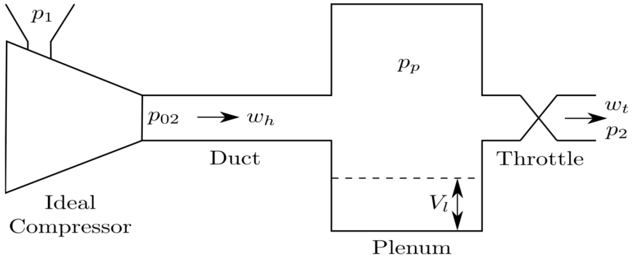
Modelling
T. Das, M. Vallabhan, C. Backi, T. Kristoffersen

- Postdoc Project: 3.4 Dynamic simulation model library
- PhD Project 3.5 Modelling for control of subsea processes
- PhD Project 3.5.b Process control algorithms
- PhD Project: 3.7 Estimation of unmeasured process variables for subsea processing systems

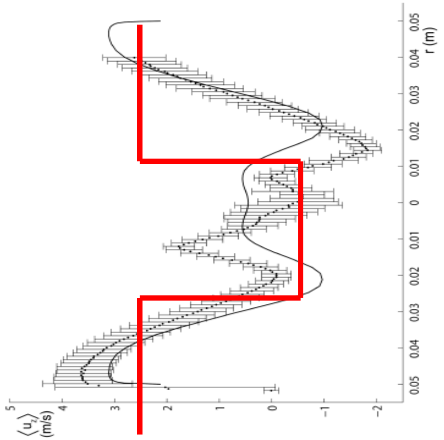


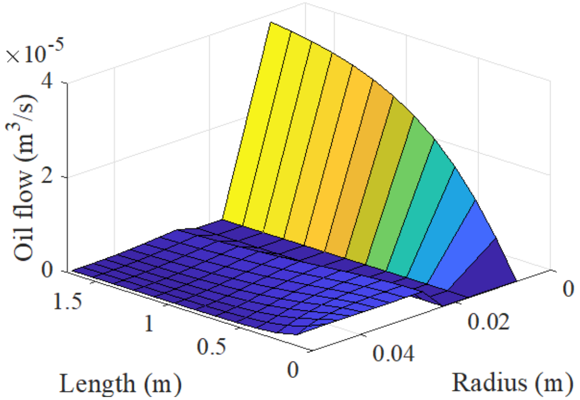

Simple models of compact separators and Wet-gas compressors (T. Das, M. Vallabhan, T. Kristoffersen)

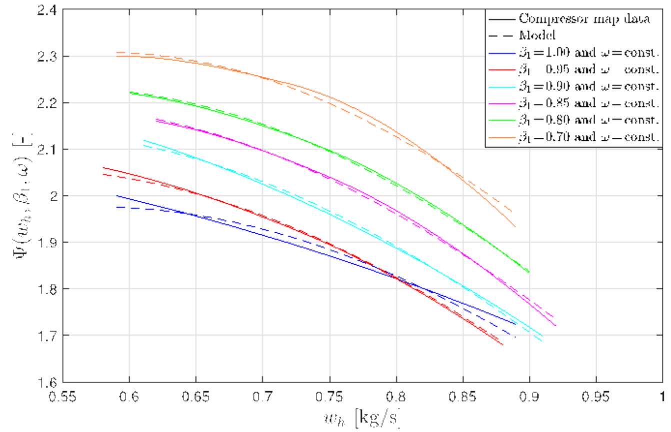




Compressor: Free volume changes with liquid fraction

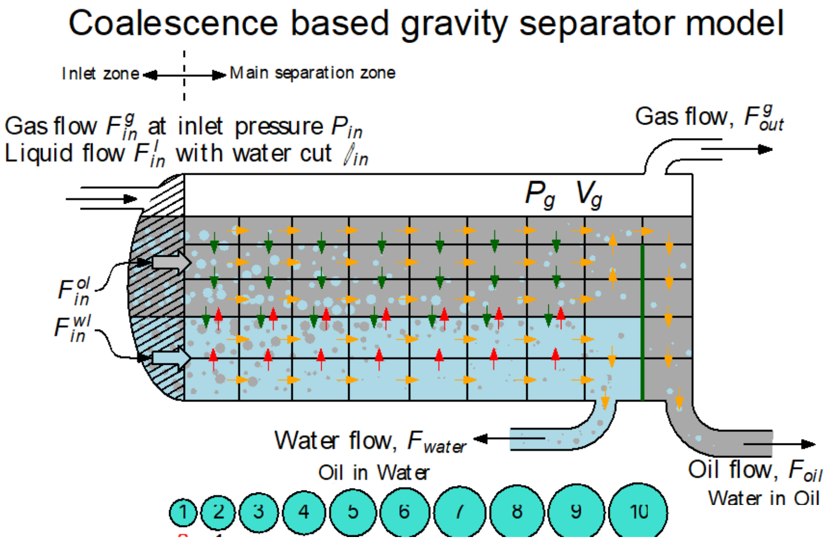




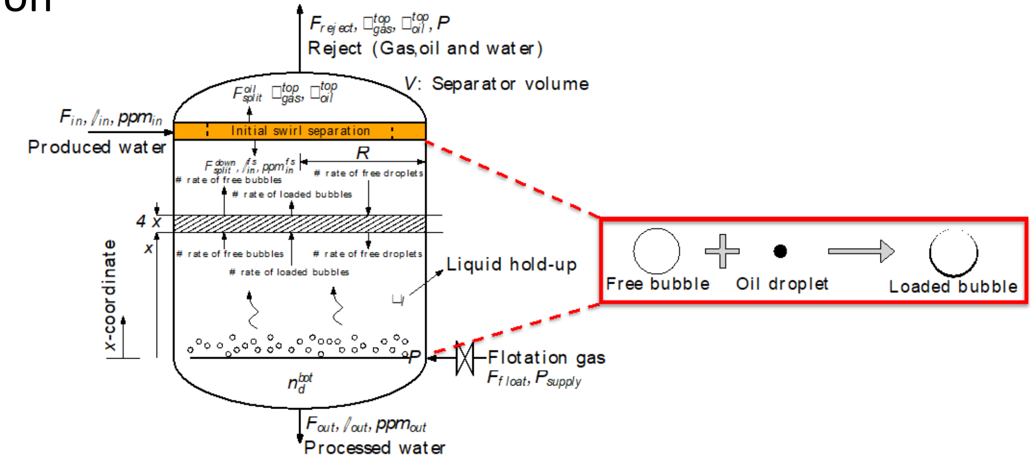


- KG, M. V., Holden, C., & Skogestad, S. (2020). A First-Principles Approach for Control-Oriented Modeling of De-oiling Hydrocyclones. *I.&ECR, 59*(42),
- Das, J Jäschke, 2018, Modeling and control of an inline deoiling hydrocyclone IFAC-PapersOnLine 51 (8), 138-143
- T. Kristoffersen, C Holden (2020) Modeling and Control of a Wet-Gas Centrifugal Compressor IEEE Trans on Contr. Sys. Tech (3), 1175-1190

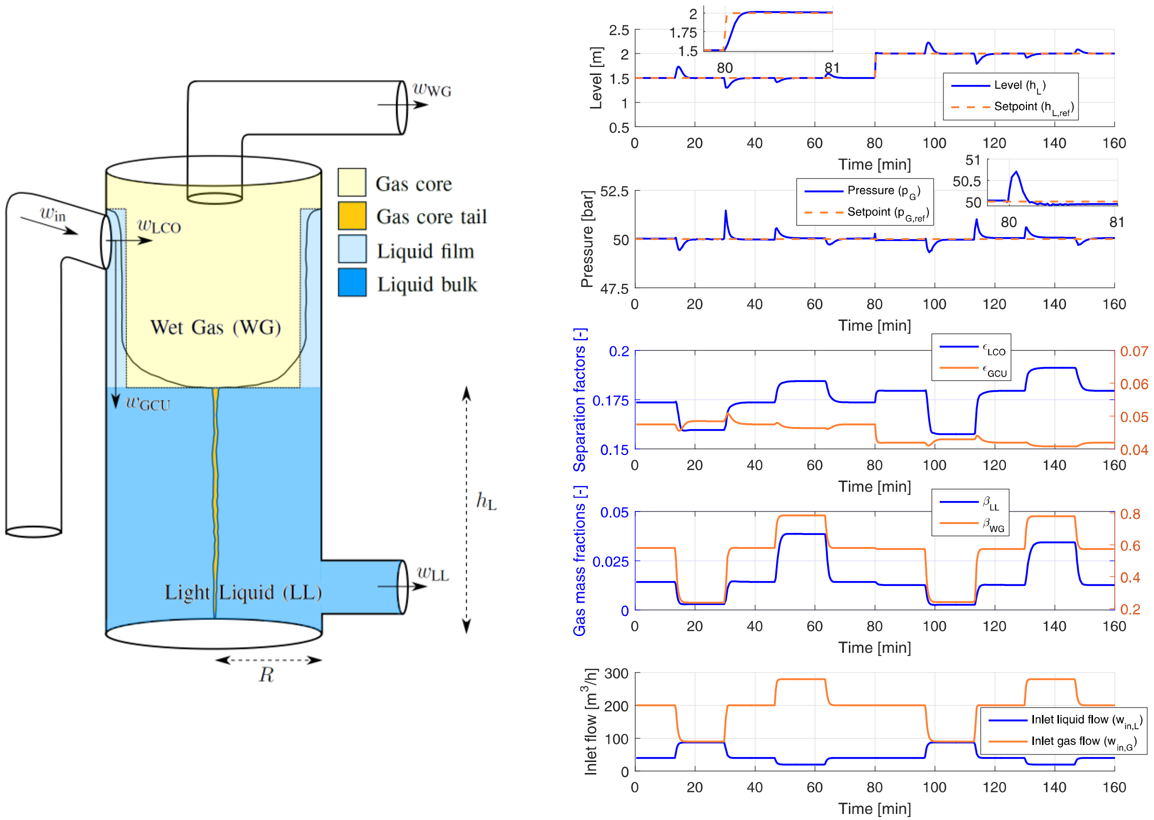
Gravity eparator models, Compact flotation and GLCC models (Das, Kristoffersen, Backi)



Flotation



Gas-Liquid Cylindrical Cyclone (GLCC)



Methods

Sveinung Ohrem

Halvor A. Krog

Asli Karacelik

Evren M. Turan

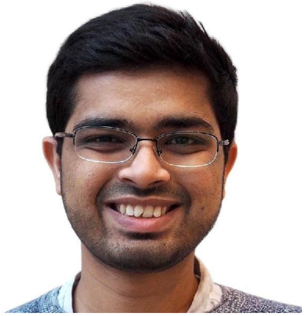
Adriaen Verheyleweghen

Jose Matias

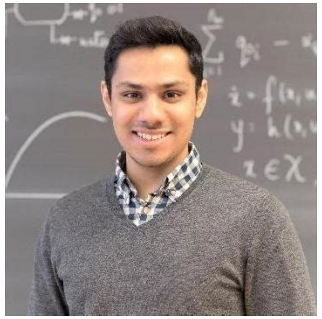
Risvan Dirza

Rafael D de Oliveira

Timur Bikmukhametov

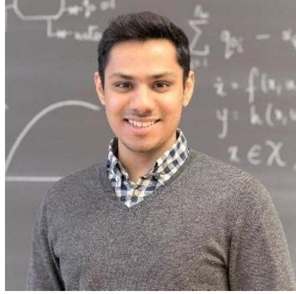


Md Rizwan



Dinesh Krishnamoorthy

Implementing production optimization

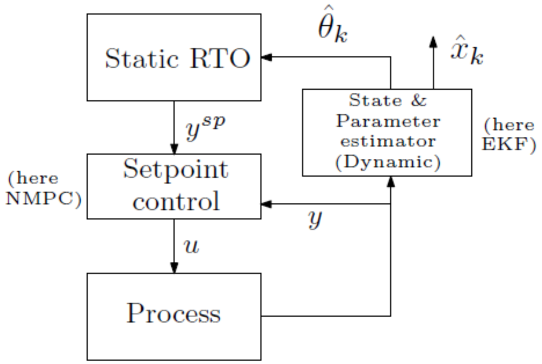


Dinesh Krishnamoorthy

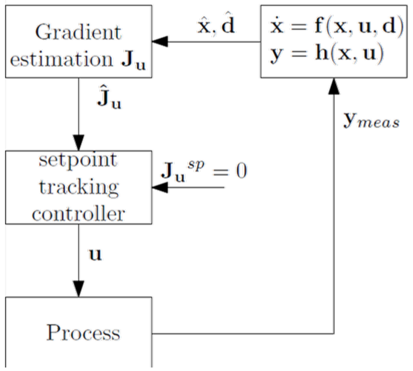
- Gap Addressed: 2. Lack of *systematic* approaches to realize optimal operation and control
- Best PhD award from NV Faculty (NTNU)
- 2020 European Federation of Chemical Engineers (EFCE) Excellence Award in Recognition of Outstanding PhD Thesis on CAPE
- Chorafas Prize

Production Optimization – different strategies

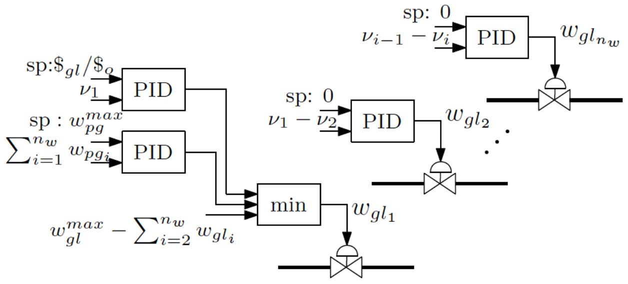
Hybrid RTO



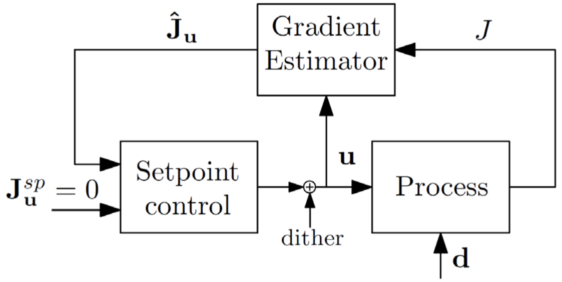
Feedback RTO



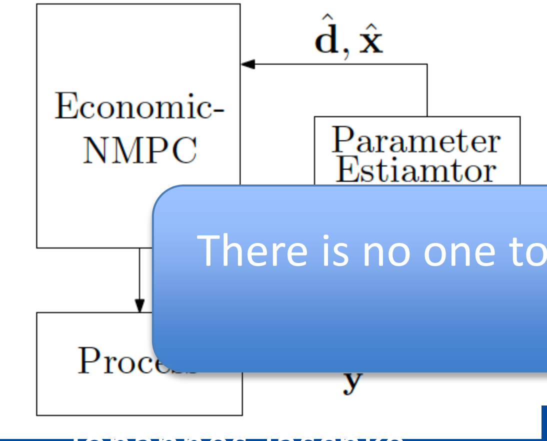
Optimization using simple controllers



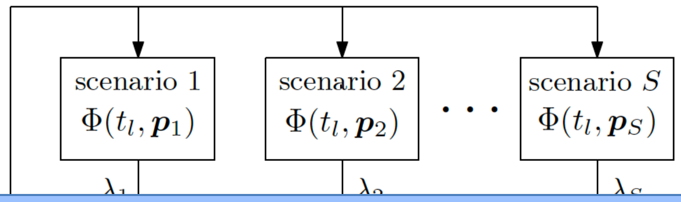
Extremum seeking control using transient measurements



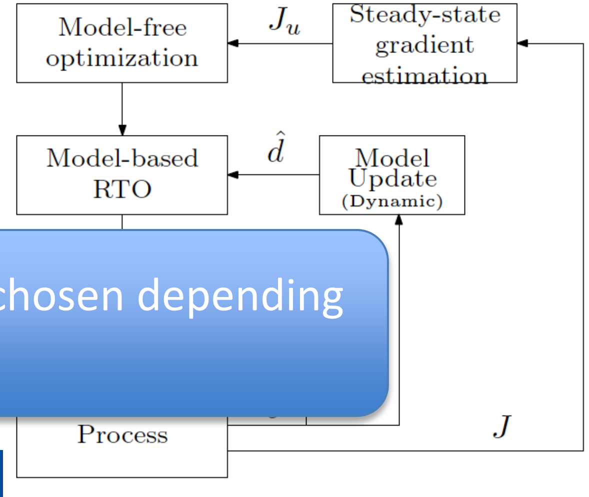
Adaptive horizon Economic MPC



Multistage Scenario Optimization



Hierarchical combination of different approaches



There is no one tool that is suitable for every problem. The method must be chosen depending on the problem.

Combining data and first principles models

Halvor A. Krog Timur Bikmukhametov

Gaps addressed:

Gap 3. Lack of *reliable* methods to estimate unmeasured variables

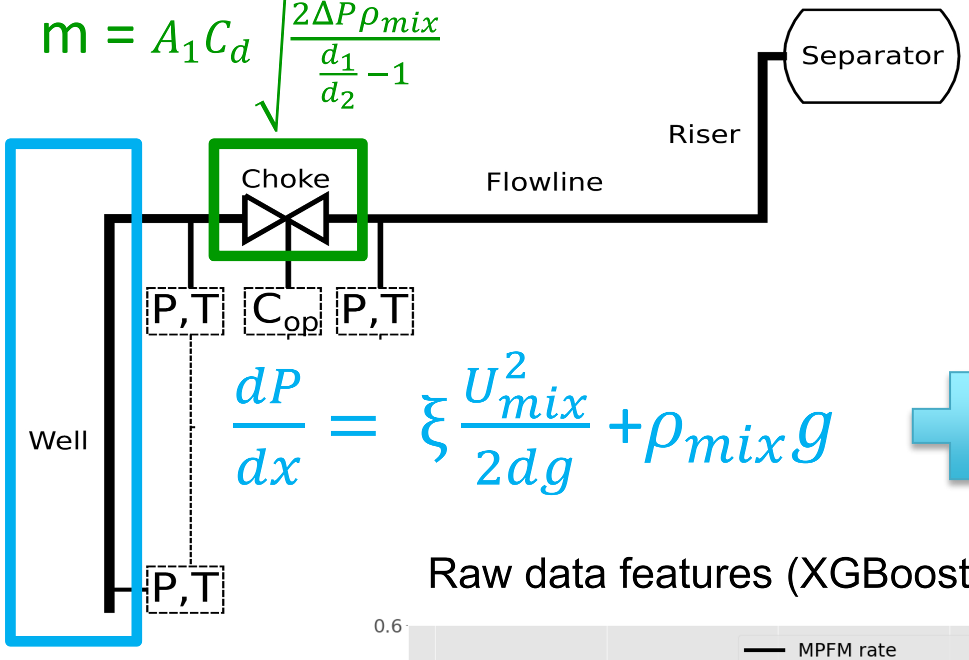
Gap 4. Lack of knowledge of how to optimally **combine data and knowledge-based models**

- Novel dynamic estimation approaches based on generalized unscented transform (Krog)
  - Innovation grant on case study with Aker Solutions, Kongsberg digital & Equinor
- Machine learning and simplified first principles (Bikmukhametov)

Hybrid models for Virtual flow metering (VFM)

Combining first principles and Machine learning

$$m = A_1 C_d \sqrt{\frac{2\Delta P \rho_{mix}}{\frac{d_1}{d_2} - 1}}$$



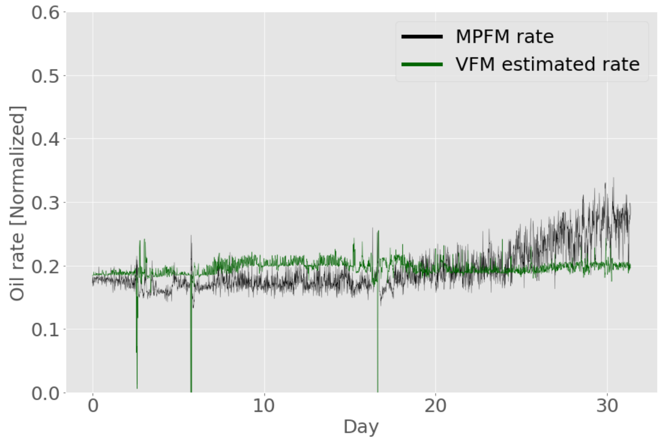
$$\frac{dP}{dx} = \xi \frac{U_{mix}^2}{2dg} + \rho_{mix} g$$

+

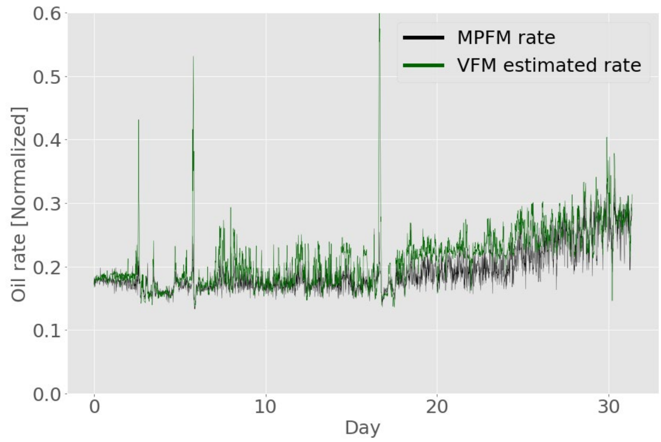
- Fluid properties
- ΔT for both sub systems

+ ML

Raw data features (XGBoost)



Tubing and choke features (XGBoost)

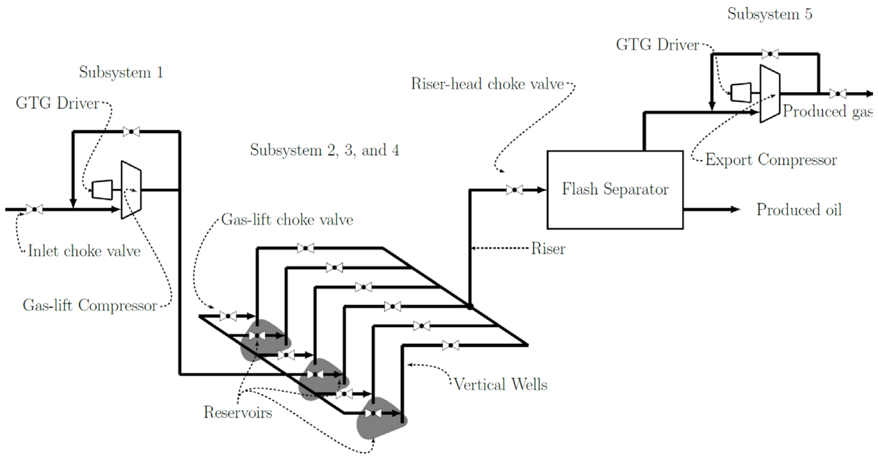


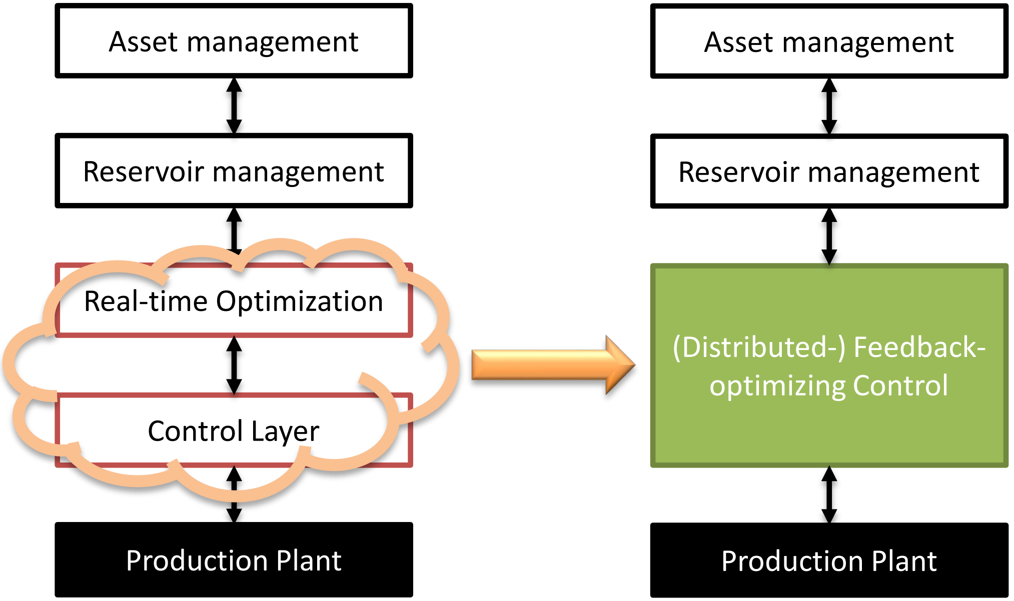
- **Well designed hybrid models are more accurate than purely data-driven models**

Field-wide Production Optimization

Gap Addressed: 2. Lack of systematic approaches to realize optimal operation and control

Risvan Dirza





Main Goal: Optimizing oil (-and) gas production in large-scale and/or complex fields from production wells to the processing facilities using simple feedback controllers (and simple model, if necessary).

Why?:

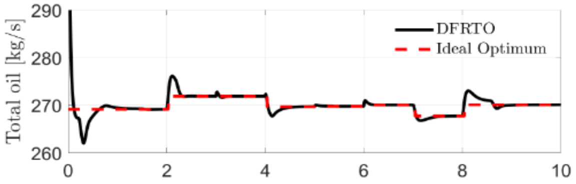
1. PID controllers, selectors etc., are proven tools in the industry for many years. Preferable by most of engineers and operators.
2. Comprehensive model development is costly and time-consuming for large-scale and/or complex system
3. Decomposing the system and constructing simplified model may lead to significant accumulated uncertainty, and creating artificial boundary -> May lead to suboptimal performance.

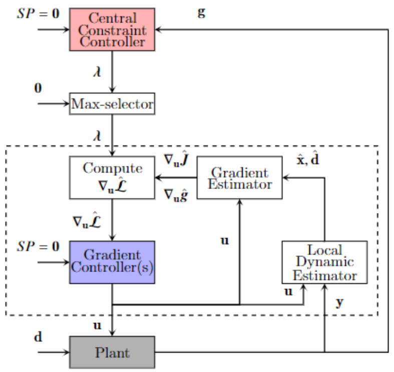
Field-wide Production Optimization

Research works

1. **Need *"automatic"* active constraint switching?**
   Consider Primal-Dual-based Control Structure

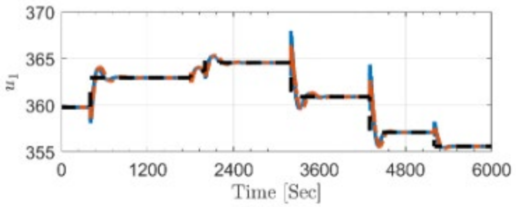
   Manuscript: [1]



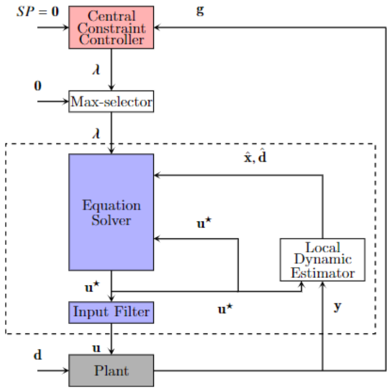


2. **Have *"highly interactive"* production system?**
   Consider Primal-Dual using RGA-based or Primal-Dual using Equation Solver

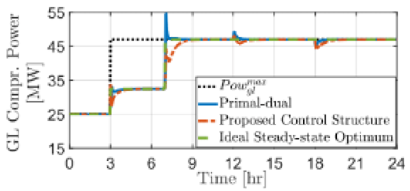
   Manuscript: In preparation

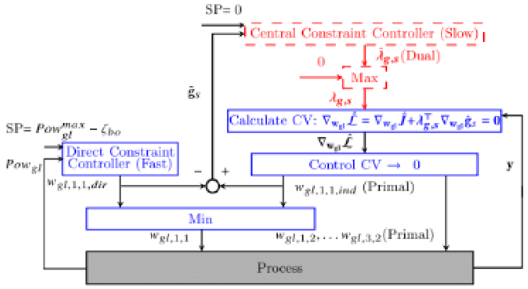


Primal-Dual with RGA-based Pairing Primal-Dual with Equation Solver Ideal Steady-state Optimal Solutions

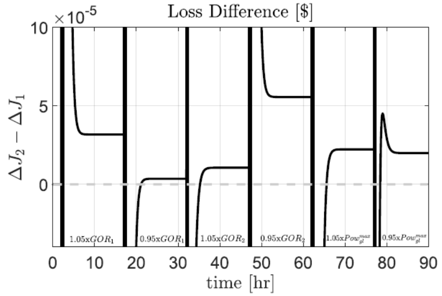


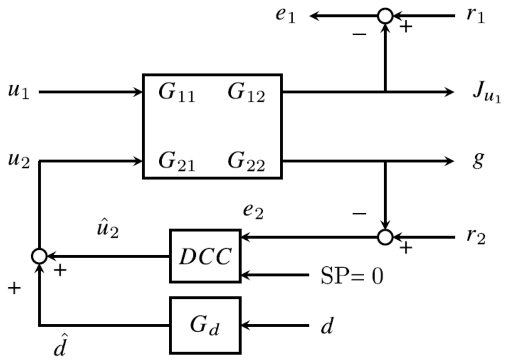
3. **Have critical/hard constraints? or want to "maximize" production plant capacity (*"reducing back-off"*) without significantly violating safety constraint?**
   Consider Primal-Dual with Direct Constraint Control (DCC)
   Manuscript: [2]





4. **How to economically pair the direct constraint control?**
   Consider Primal-Dual with DCC with Systematic Pairing
   Manuscript: [3]





[1] Dirza, R., Skogestad, S., Krishnamoorthy, D., 2021. Optimal resource allocation using distributed feedback-based real-time optimization.IFAC-PapersOnLine 54, 706–711
[2] Dirza, R., Krishnamoorthy, D., Skogestad, S., 2022. Primal-dual Feedback-optimizing Control with Direct Constraint Control. PSE 2021+ *(In press)*
[3] Dirza, R., Skogestad, S., 2022. Systematic Pairing Selection for Economic-oriented Constraint Control. ESCAPE 32 *(In press)*

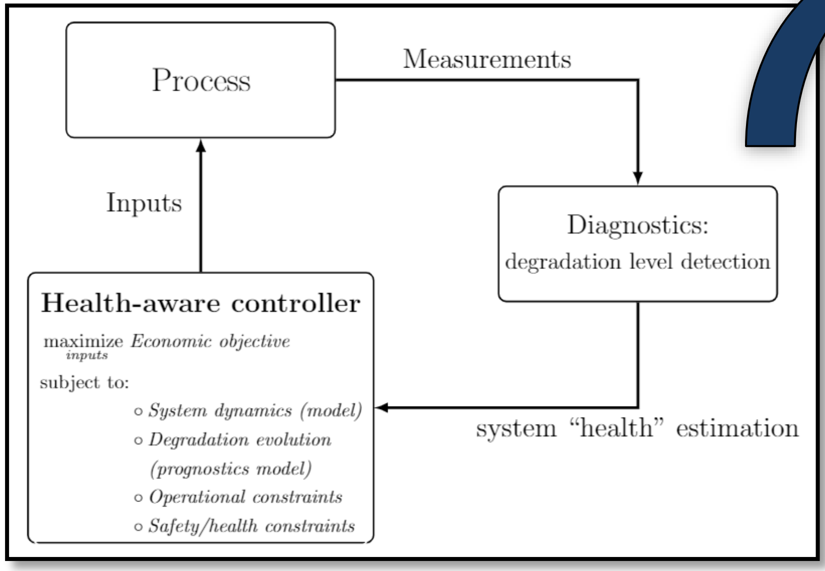
Methods for Optimizing Remaining Useful Life and Gas lift

Addresses gap 2 Lack of systematic approaches to realize optimal operation and control (including optimal trade-off between equipment wear and maximizing production)

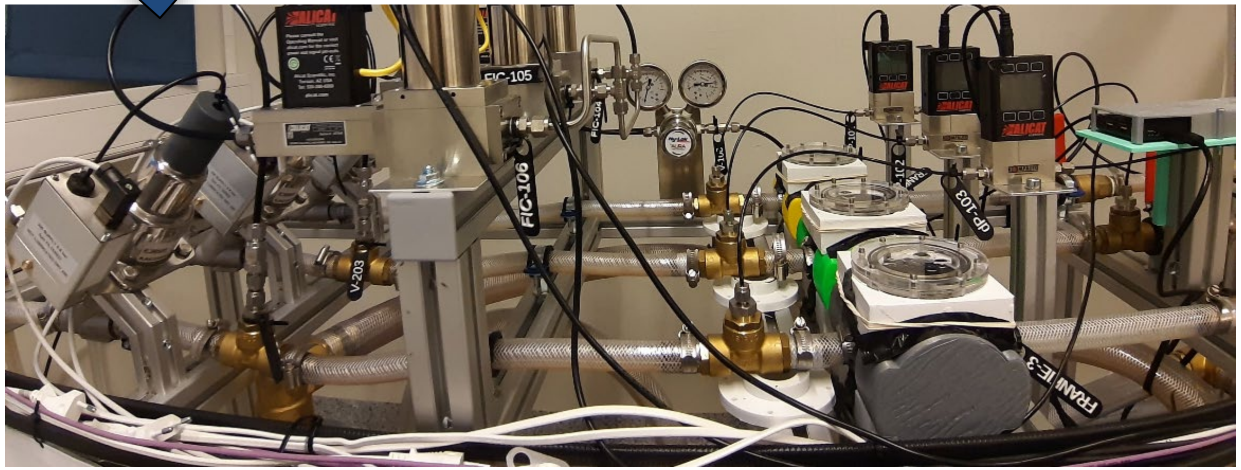
A. Verheyleweghen, J. Matias

Health-aware controller:

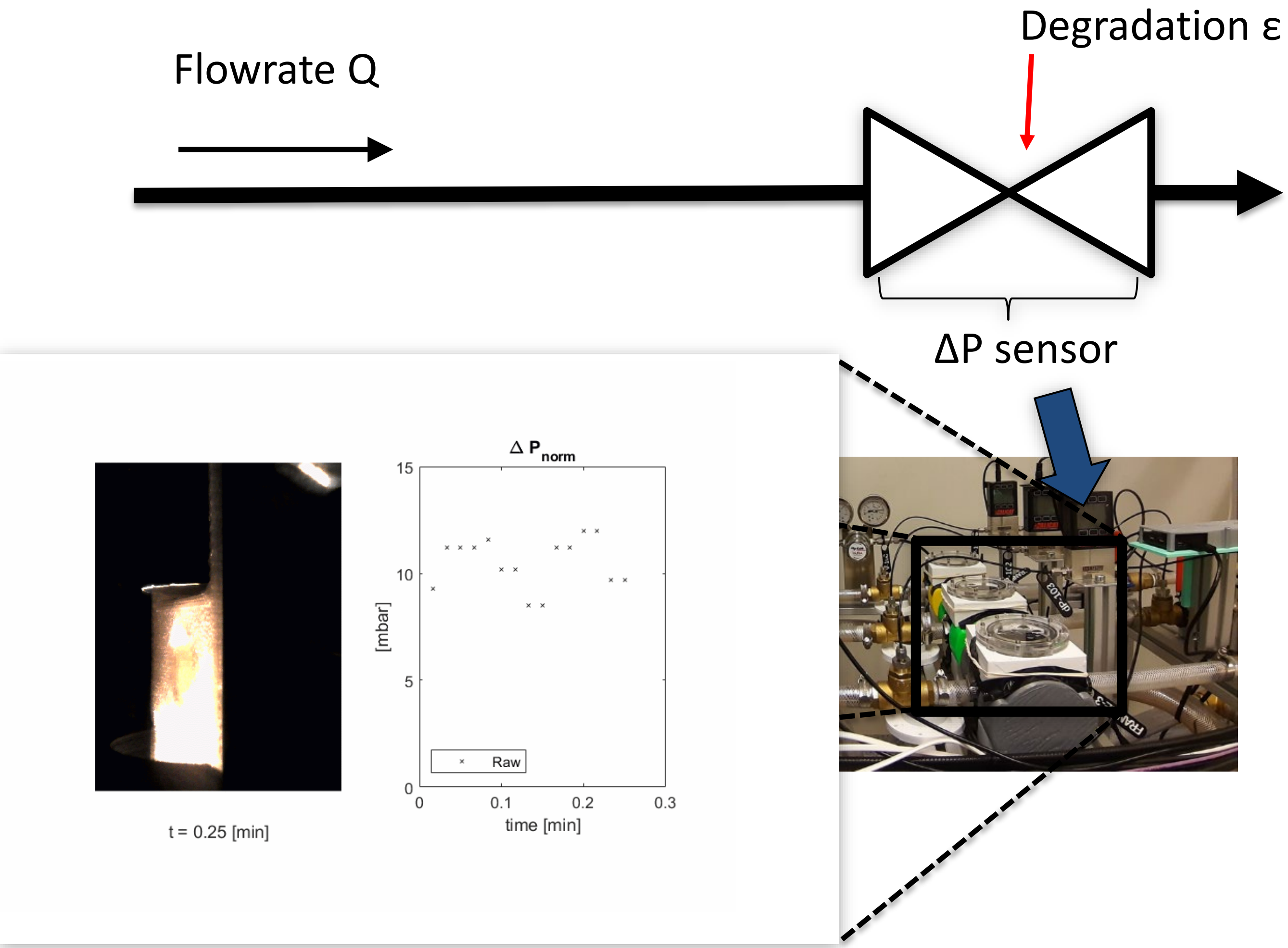
- Optimize production while ensuring Remaining Useful Life (RUL) is not exhausted before planned maintenance stop
- **Project goal:** *validate method → Erosion Rig*



Experimental validation



Validation of Methods for Optimizing Remaining Useful Life

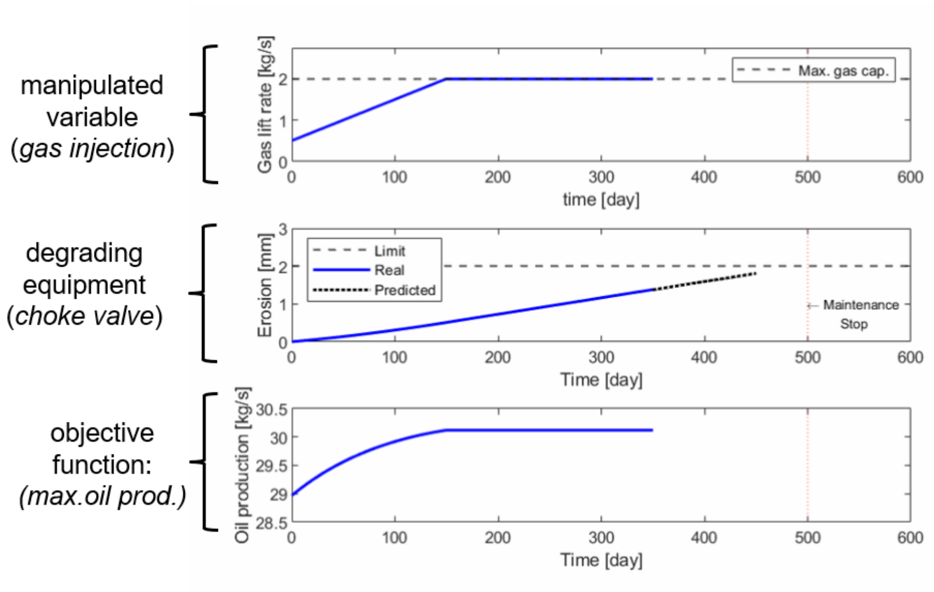


Modeling approaches:

I. Machine learning

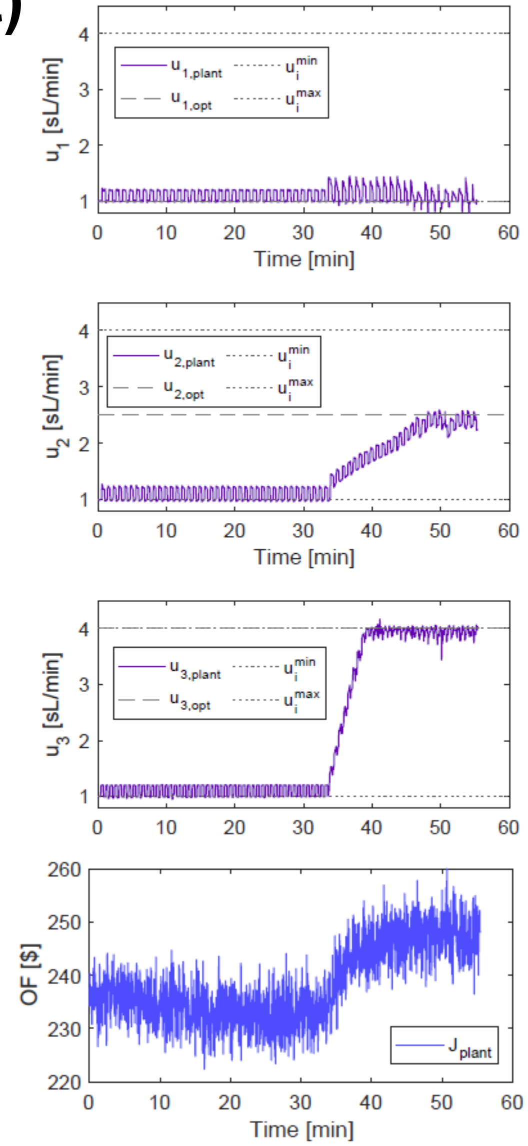
II. Stochastic process

   – Journal Paper: X. Liu, J. Matias, J. Jäschke, J. Vatn. *Gibbs sampler for noisy Transformed Gamma process: Inference and remaining useful life estimation* - Reliability Engineering & System Safety (2021)



Lab: Experimental Validation of New Control Approaches for Gas-Lift Optimization (innovation grant)

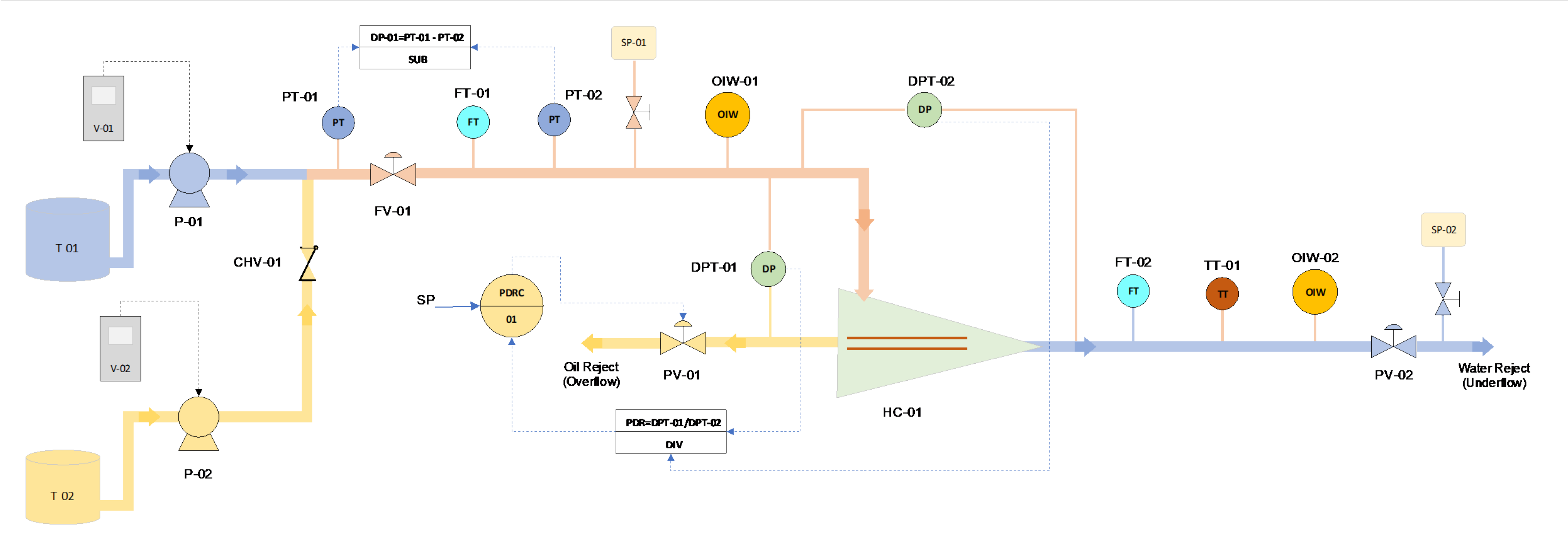
- *Implemented approaches:*
  - Steady-state RTO [1,2] [3]
  - Hybrid RTO [1,2] [3]
  - Dynamic RTO [3]
  - Extremum seeking control [4]
  - Distributed feedback RTO
  - Modifier Adaptation [5]



1. Master thesis: Julio Oliveira USP/Brazil (ongoing) – "*Otimização em tempo real aplicada em um sistema experimental de Gas Lift*"
2. Conference paper (ADCHEM 2021) – "*Real-time optimization with persistent parameter adaptation applied to experimental rig*"
3. Journal paper (submitted) – "*Steady-state Real-time Optimization Using Transient Measurements on an Experimental Rig*"
4. Master thesis: Frida Myrvang (2020) – *"Implementation of Extremum Seeking Control in an Experimenta Lab-Rig"*
5. SUBPRO summer internship and Master thesis: Maren Sofie Lia (ongoing) – "*Real-time Optimization usi simplified models*"

Compact separation Lab: flowsheet

Addressed: Gap 2. Lack of systematic approaches to realize optimal operation and control – experimental verification



Compact separation control lab

- Industrial scale hydrocyclone (eProcess Technologies)
- Flow rate up to 5 m^3/h
- 25 bar.
- Concentrations from 500 to 5000 ppm
- Adjustable droplet distributions
- Oil-in-water sensor Mirmorax
  - Measures concentration online
  - measures Dv50 online

Spin-off project AUTOPRO (Research council, Aker BP)

Develop and test methods for:

- Autonomous production optimization
- Maintenance optimization
- Diagnostics, Prognostics
- Condition-based maintenance

Rafael de Oliveira (postdoc)

- Production optimization with Degrading equipment

Evren Turan (PhD)

- Data Driven and first principles digital twin modelling

Emefon Dan (PhD)

- Condition-based maintenance optimization (RAMS group)

International collaboration
(Visits, exchange students, etc)

- USA
  - Massachussets Institute of technology (MIT)
  - Carnegie Mellon University
- Brazil
  - Univ. of Sao Paulo
  - Fed. Univ. of Rio de Janeiro
- China
  - China Ocean University

Final remarks

- Strong research in digitalization, control and optimization on a *systems level:*
  - Models
  - Production optimization
  - Produced water treatment
  - Virtual flow metering
  - Automatic control
  - Experimental validation of methods

Thank you!