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Status on real-time optimization as seen both from an industrial and academic point of view

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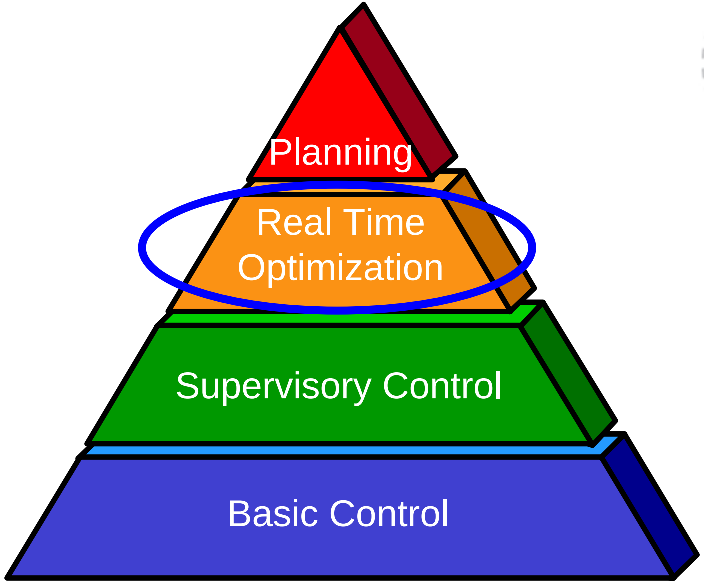
Outline

- Scope of the presentation
- Introduction to real-time optimization (RTO) scheme
- Steady-state RTO
- RTO with dynamic models
- “Simplified RTO”
- Industrial case
- Summary



What is meant by real-time optimization?

Definition [Engell, 2007]: *”a model based, upper-level control system that is operated in closed loop and provides set-points to the lower-level control systems in order to maintain the process operation as close as possible to the economic optimum*”

The interpretations of RTO are many

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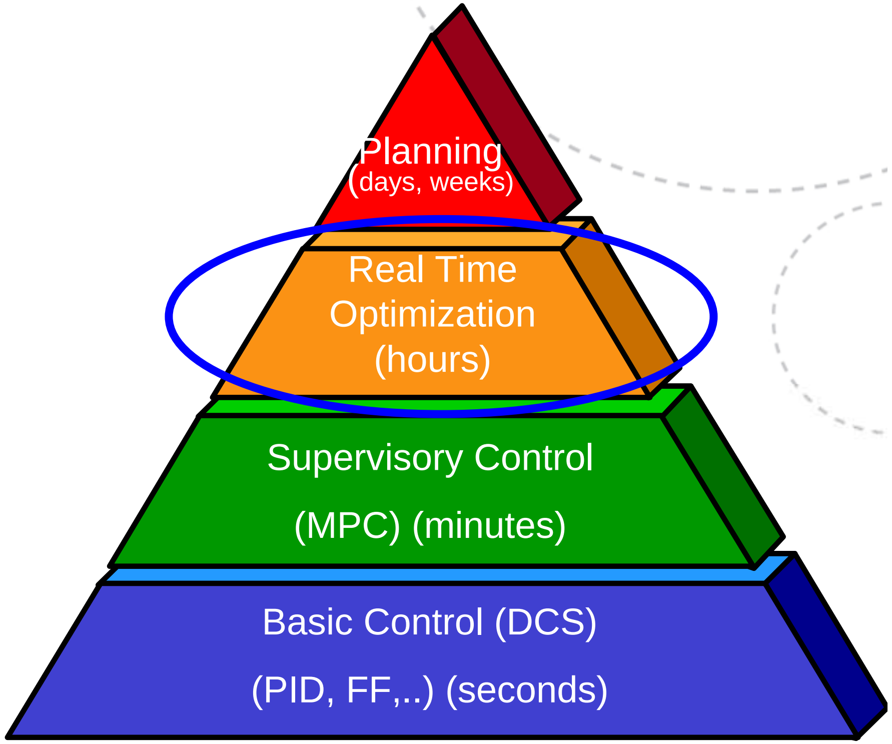
Real-time optimization (RTO)

- Objective: Economics is considered in operational decisions in terms of e.g. profit, throughput, time, energy
- Data are monitored in real-time and calculated in real-time
- Model-based approach
  - Operation decisions are calculated from a model
  - Model is updated using real-time data
- Operations decisions are implemented in plant
- Motivation: obtain market price driven economic process optimization



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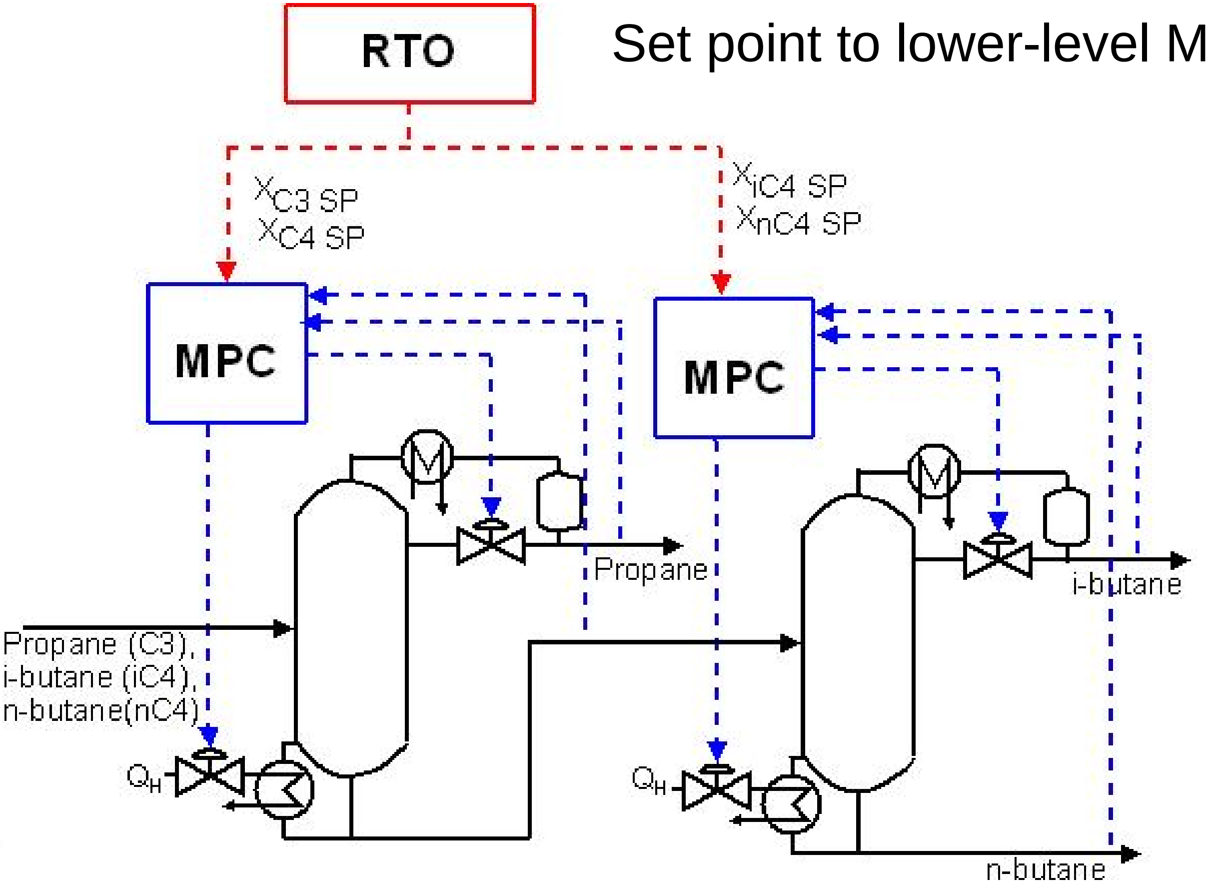
Illustrative example: RTO

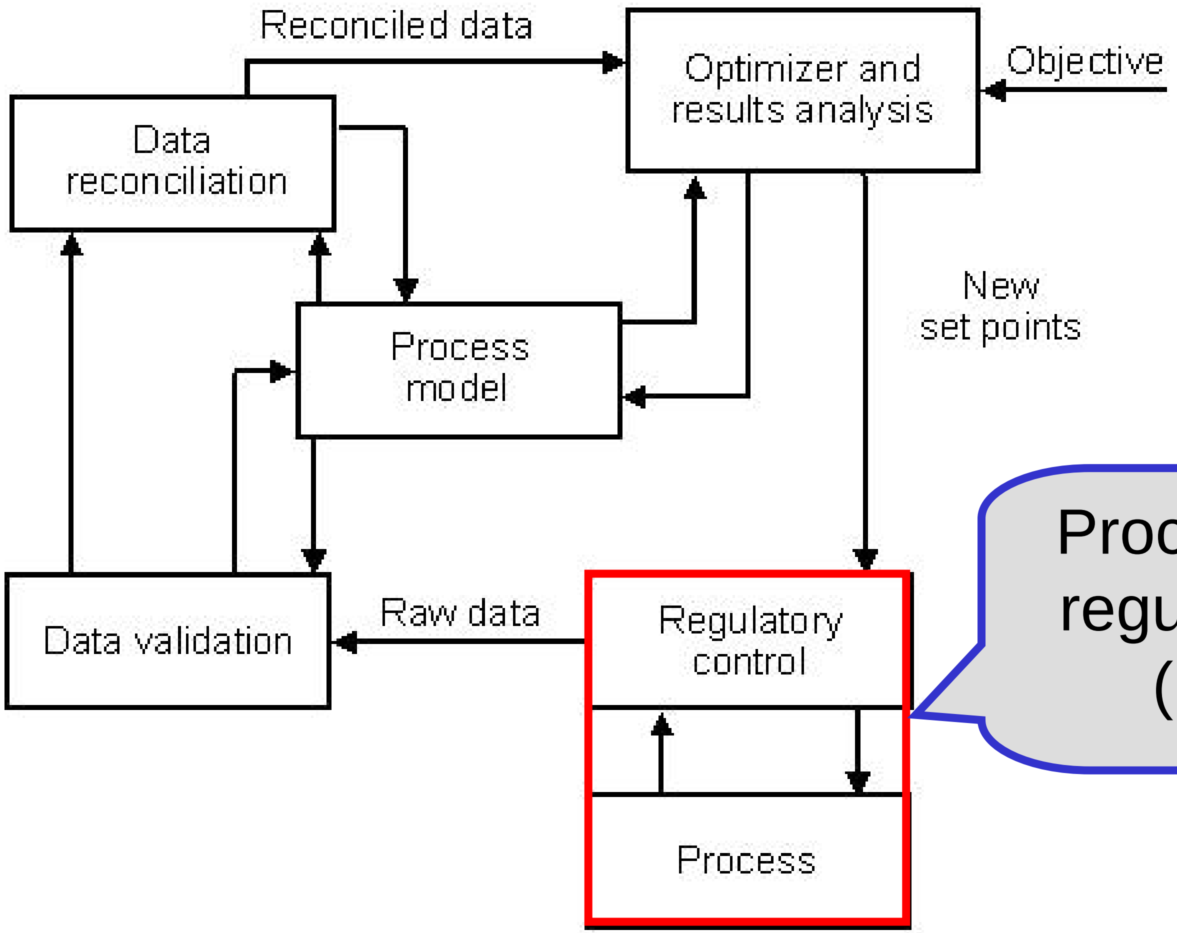
$$\text{Objective} = w_{C3} \cdot P_{C3} + w_{iC4} \cdot P_{iC4} + w_{nC4} \cdot P_{nC4} - \sum_i Q_H \cdot P_{Q_H}$$



Set point to lower-level MPC

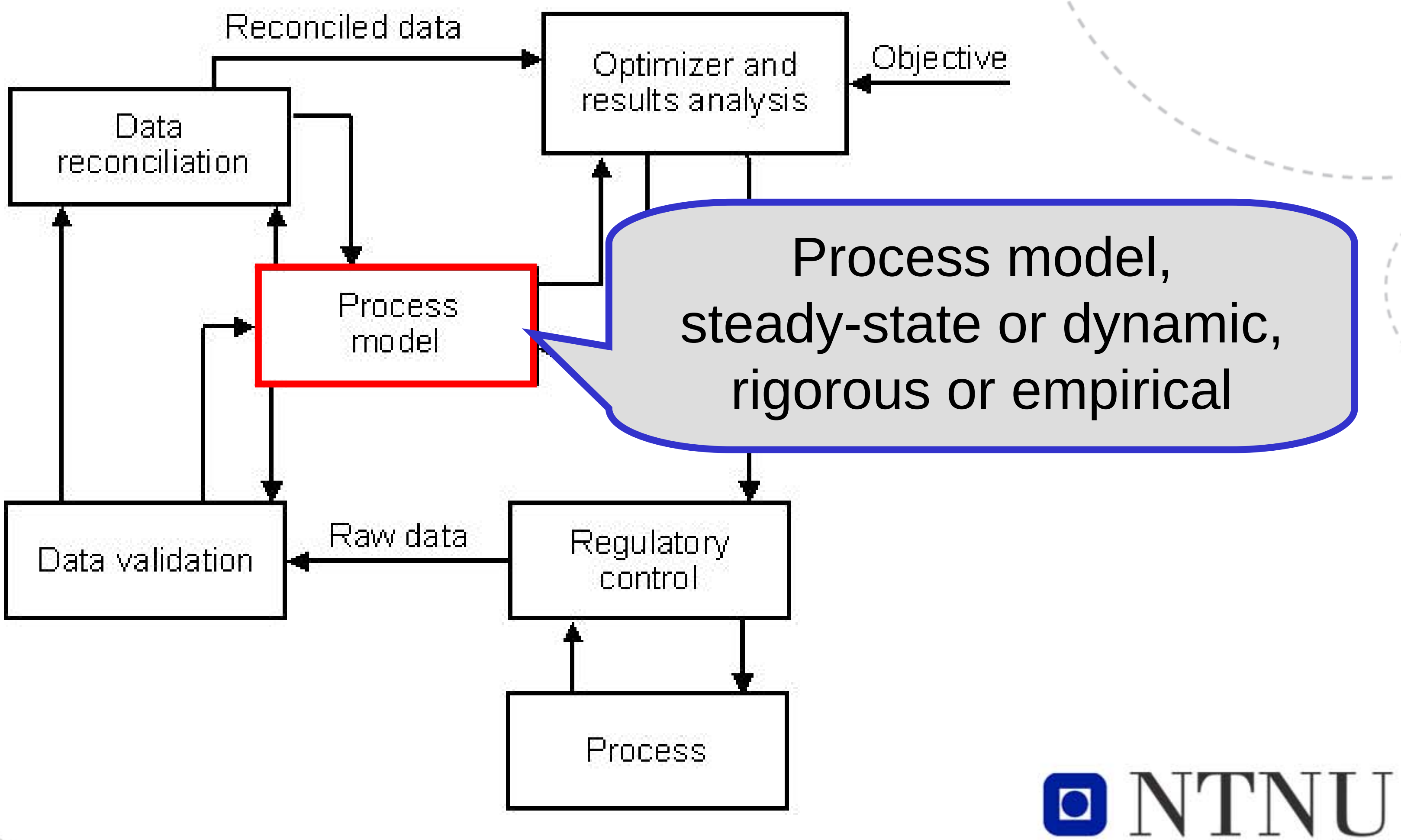
- Given feed
- RTO can affect mass flows and energy usage by changing product compositions

Scheme of RTO



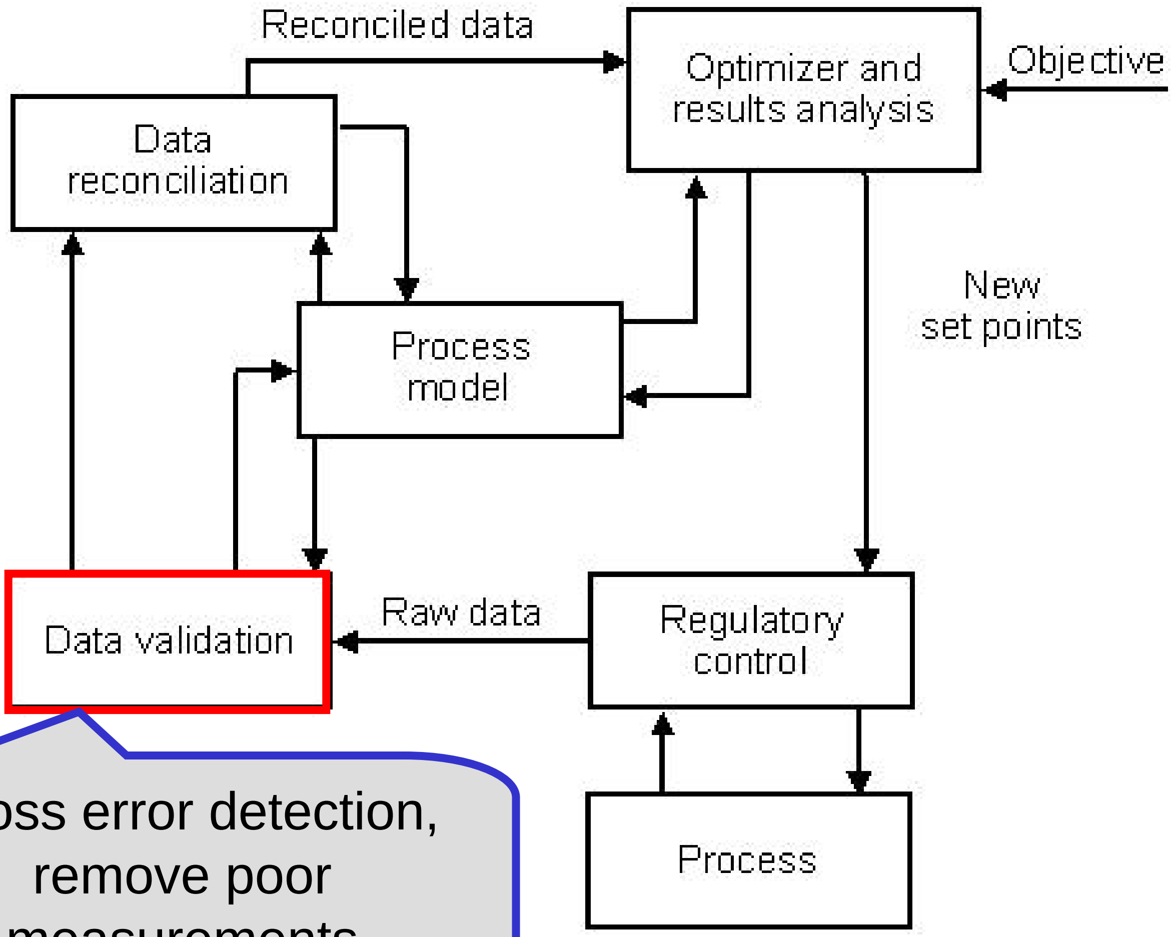
Process including regulatory control (PID, MPC)

Scheme of RTO



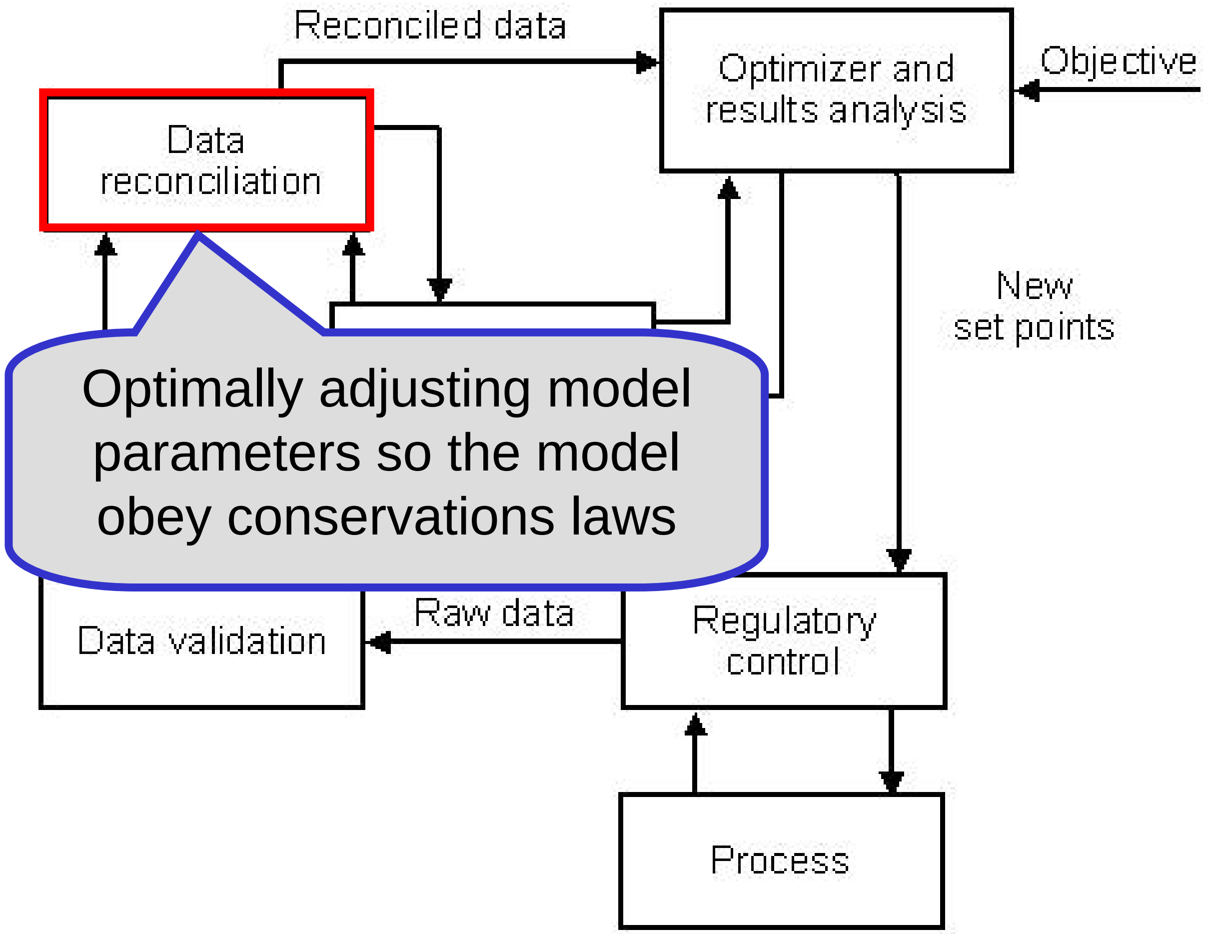
Process model, steady-state or dynamic, rigorous or empirical

Scheme of RTO



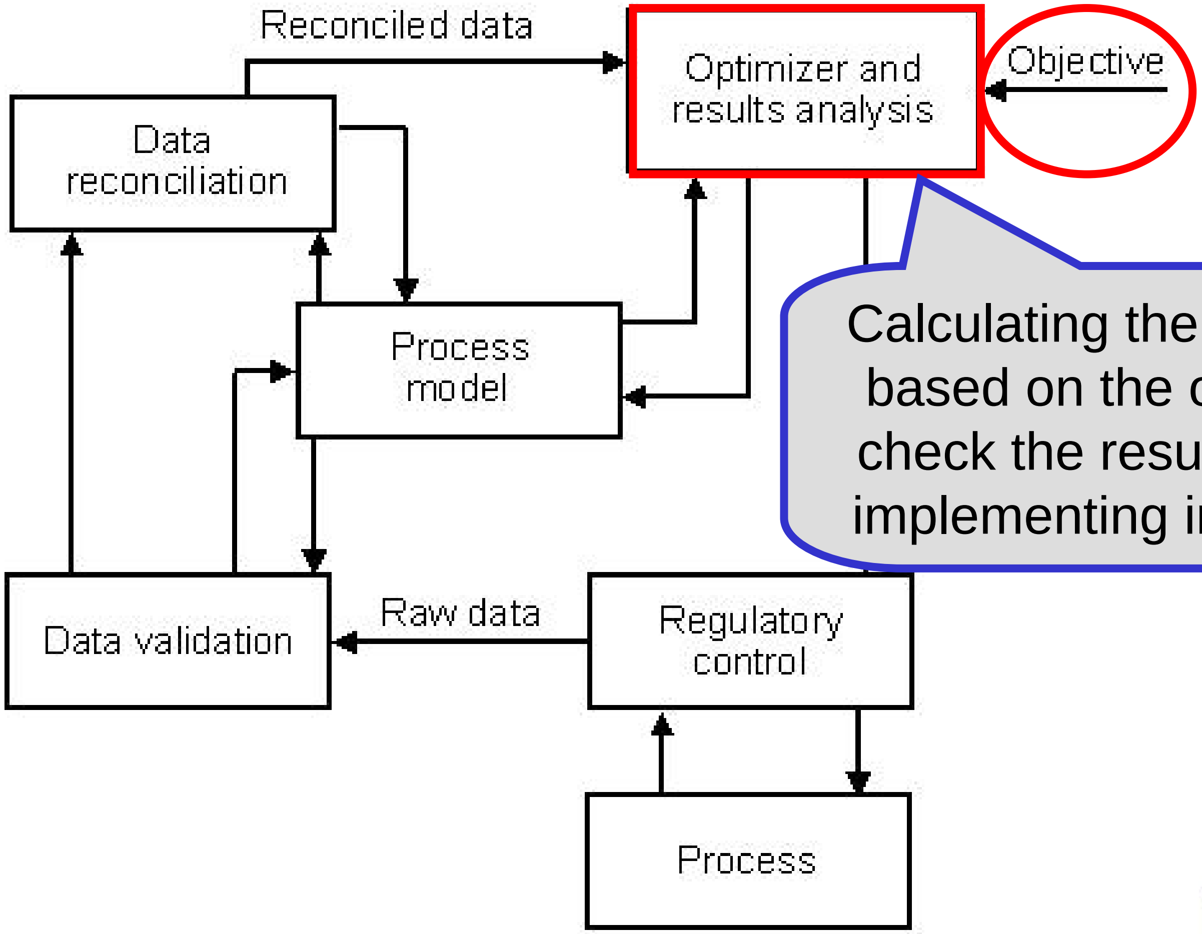
Gross error detection, remove poor measurements

Scheme of RTO



Optimally adjusting model parameters so the model obey conservations laws

Scheme of RTO



Calculating the optimum, based on the objective, check the results before implementing in process

Fundamental issue: which plants will benefit from an RTO?

- Key factors:
  - Additional adjustable optimization variables exist (degrees of freedom)
  - Profit changes significantly when optimization variables are changed
  - Disturbances occurs frequently enough for real-time adjustment to be required
  - Optimality can not be achieved by constant set points (or other standard procedures)

Forbes *et.al.*, (2006)

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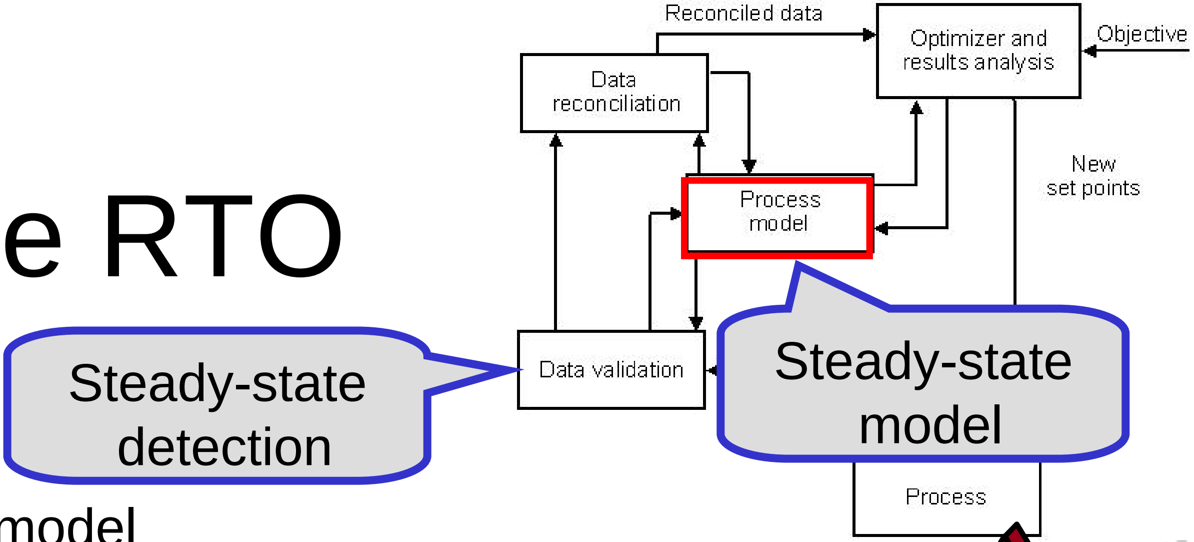
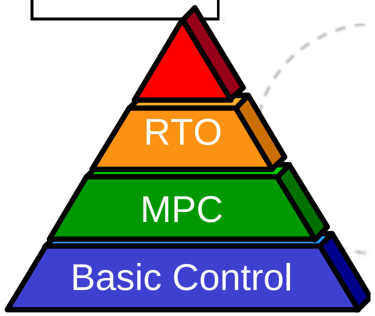
Steady-state RTO



Steady-state detection

Steady-state model



- Steady-state process model
- Steady-state detection before data reconciliation
- Hierarchical structure: clear separation of time-scale and concerns
- “Traditional” approach (Steady-state RTO combined with linear MPC)
- Well established for some processes, e.g.
  - Ethylene plants
  - Fluidized catalytic crackers (FCC)
- Commercial packages (Honeywell, AspenTech, Invensys, etc.)

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Weaknesses with steady-state RTO

- Do not handle transient plant operation
  - Continuous process with frequent changes in feed, product specifications, market disturbances, slow dynamics/long settling time
  - Continuous with frequent grade transitions
  - Batch processes
  - Cyclic operations
- Force variables to fixed set points, may not utilize all degrees of freedom
- A steady-state optimization layer and a control layer may lead to model inconsistency
- → A dynamic model can be more appropriate for the optimization task to reduce the gap between control and optimization

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Optimization = “find the target”
Control = “stay at the target”

- Steady-state RTO:
  - MPC with dynamic models to control
  - RTO with steady-state models to optimize

  } in separate layers
- Optimization with dynamic models:
  - [N]MPC with dynamic models
  - RTO with dynamic models (D-RTO)

  } what is the difference?
- No clear separation if [N]MPC consider economy (which it often does implicitly)

RTO or D-RTO or [N]MPC?

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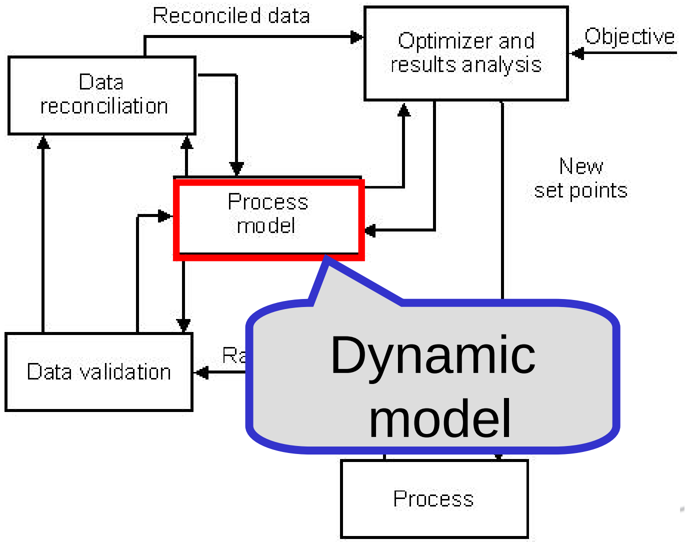
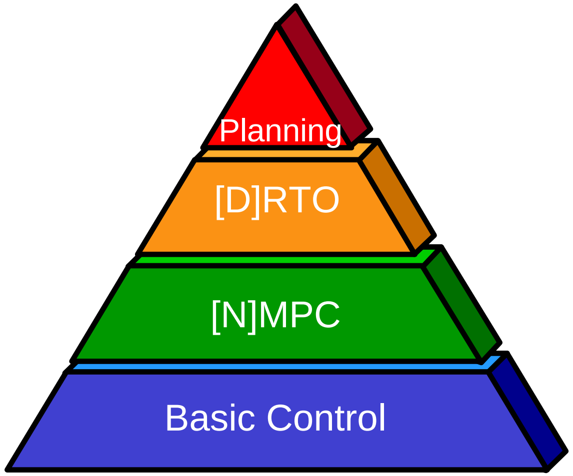
RTO with dynamic process models



Two main approaches:

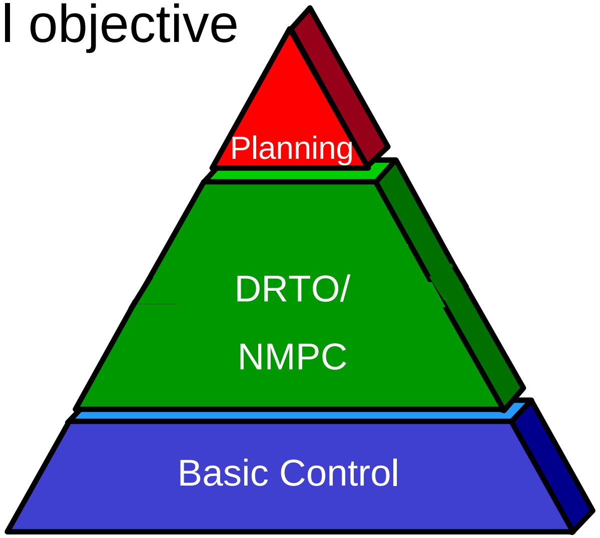
1. Two-layer structure

   Separate control and optimization in two layers

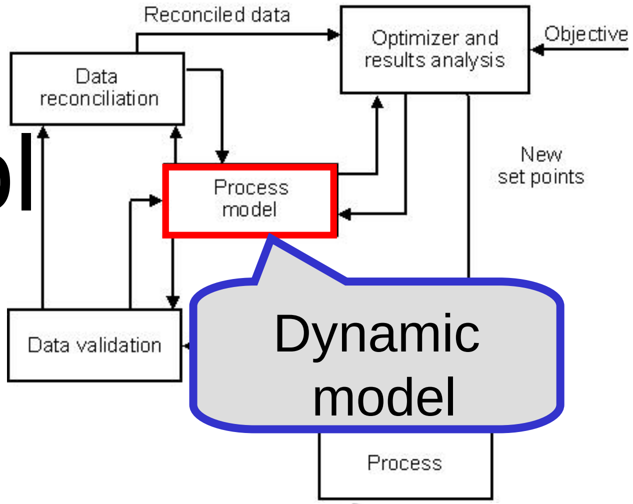


2. Direct optimization control ("1-layer approach" , "direct approach")

   Combined economical and control objective



Direct optimization control or two-layer approach?



- Kadam & Marquardt (2007): *“The acceptance of such a monolith solution [NMPC] in industry is limited” .* Arguments:
  - Direct optimization control breaks with the established time-scale decomposition in the automation hierarchy
  - More computational demanding than two-layer approach
  - More complex than two-layer approach
- Is it?
- Several NMPC with economic objective is reported, in particular in polymer industry (Bartusiak, 2007)
- For processes which needs NMPC with rigorous models, may be easier to accept a direct approach(?)
- Size dependent

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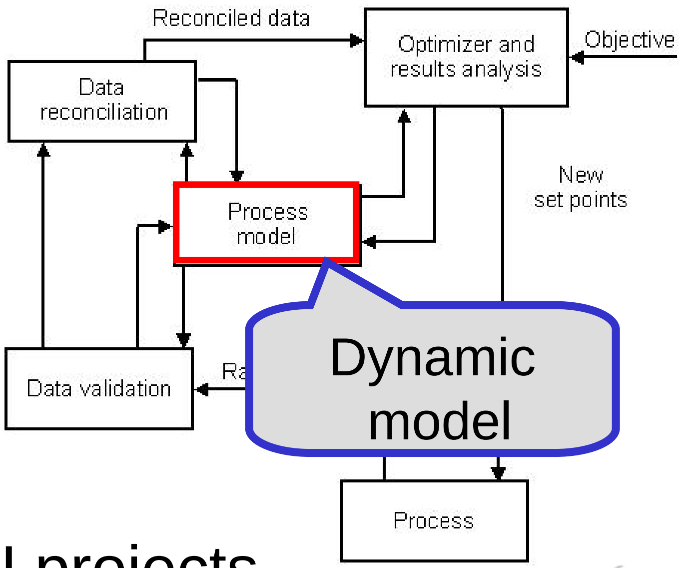
Dynamic RTO in academia



- Increasing research area, e.g the EU projects INCOOP
- One research field: how to handle larger problems:
  - Two-level strategy with a D-RTO trigger based on disturbance sensitivity analysis (Kadam et. al., 2003, extensions Kadam & Marquardt, 2007)
  - Reduced-order slow-scale dynamic model, performed at a rate slower than local-unit level MPC (Tosukhowong *et. al.*, 2004)

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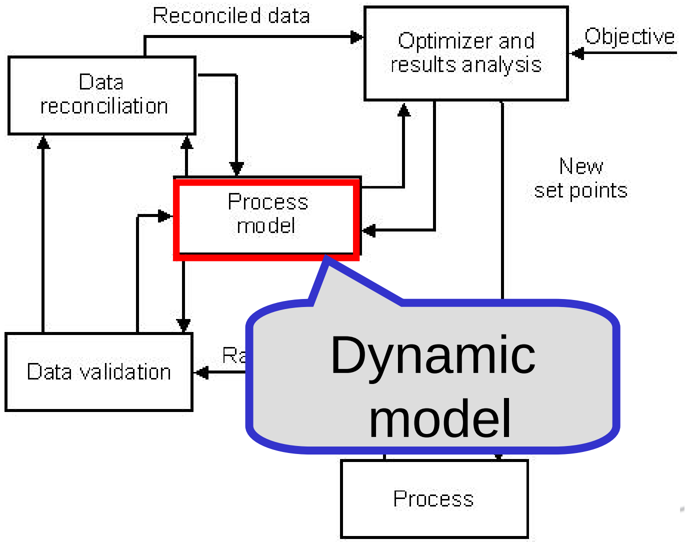
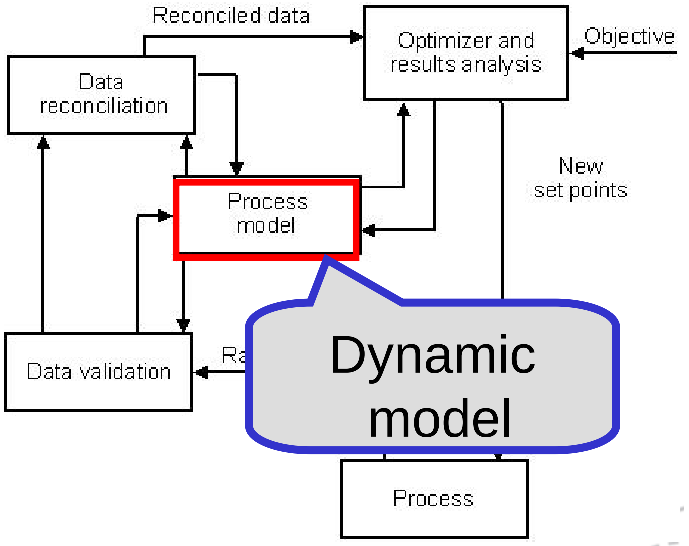
Dynamic RTO in academia II



- Reduce computational effort by
  - Model reduction techniques (review by Marquardt, 2002)
    - Model order reduction
    - Model simplification
  - Control vector parameterization (Schlegel *et. al.*, 2005)
  - Developing efficient algorithms for solving dynamic optimization problems in real-time (Biegler & Zavala, 2009)

Dynamic RTO in industry



- Commercial packages exists, e.g.
  - Honeywell Profit Bridge (webpage reports ~15 installations worldwide)
  - Ipcos Pathfinder
- Implementations reported in industry, e.g.
  - Ethylene plants (now with dynamic models, Nath & Alzein, 2000, Vettenranta et al.,2006)
  - Gas oil production (Andersen et. al, 2008)
  - Polyolefins (Bartusiak, 2007)

Some issues for further research

- Appropriate simplification of nonlinear models
- How accurate must the process model or the parameter estimates be?
- Online RTO performance monitoring and diagnostics
- Plantwide (dynamic) RTO
  - Very large scale …
  - or decentralized approach (with problem of sub-optimality)
- Optimization algorithms
  - How to handle multiple minima

Amazing method – why is it not used everywhere?

- Not available resources (people) for design, implementation and maintenance?
- Not able to identify a model .... and update the model
- Missing or poor measurements
- Etc…
- → other methods possible that requires less effort?

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”Simplified RTO”

- Model-free approaches like “Self-optimizing control” (Skogestad, 2000).
  - Find the best (=minimum loss) controlled variables to hold constant
- Off-line computations
- Constrained optimization realized by (linear) MPC

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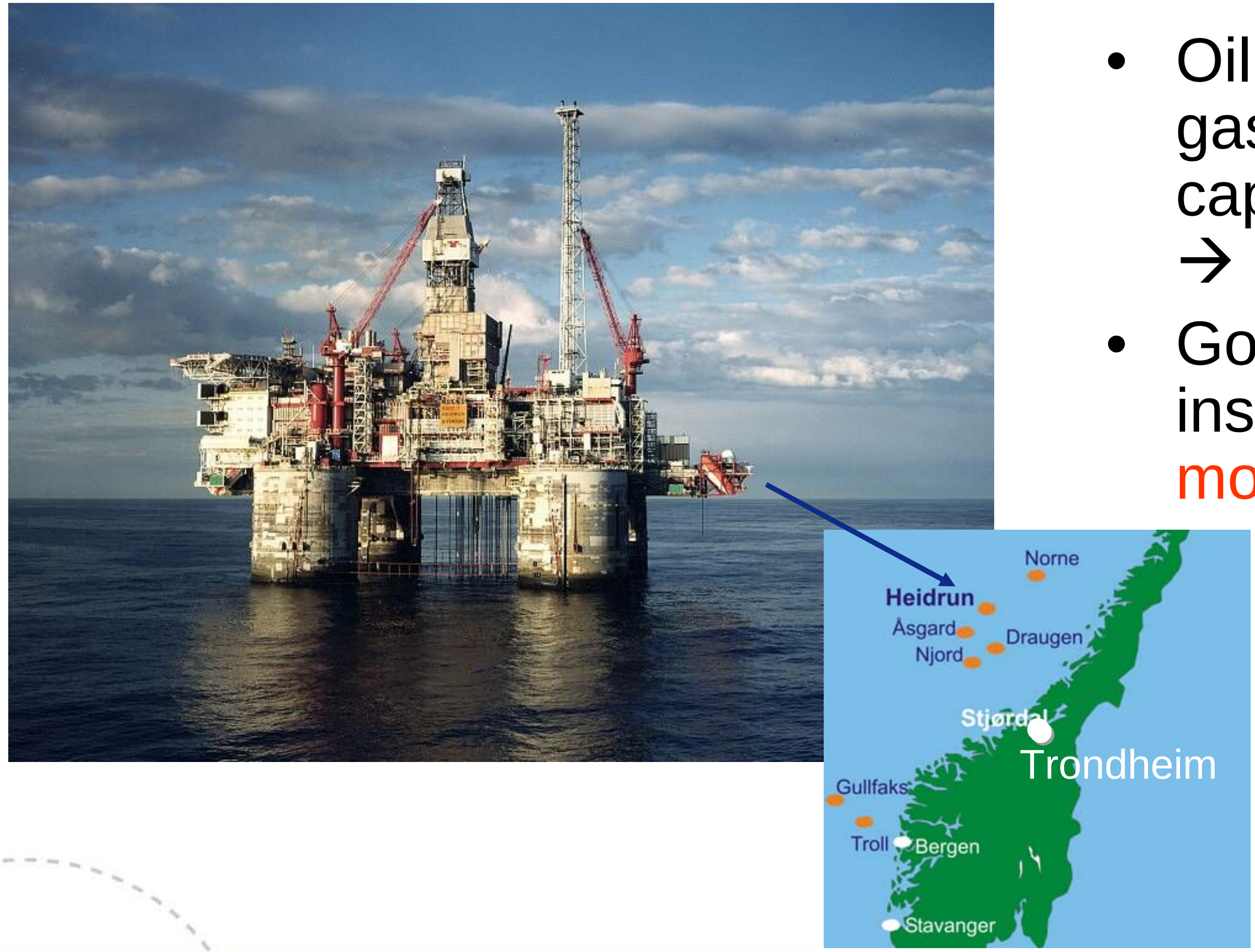
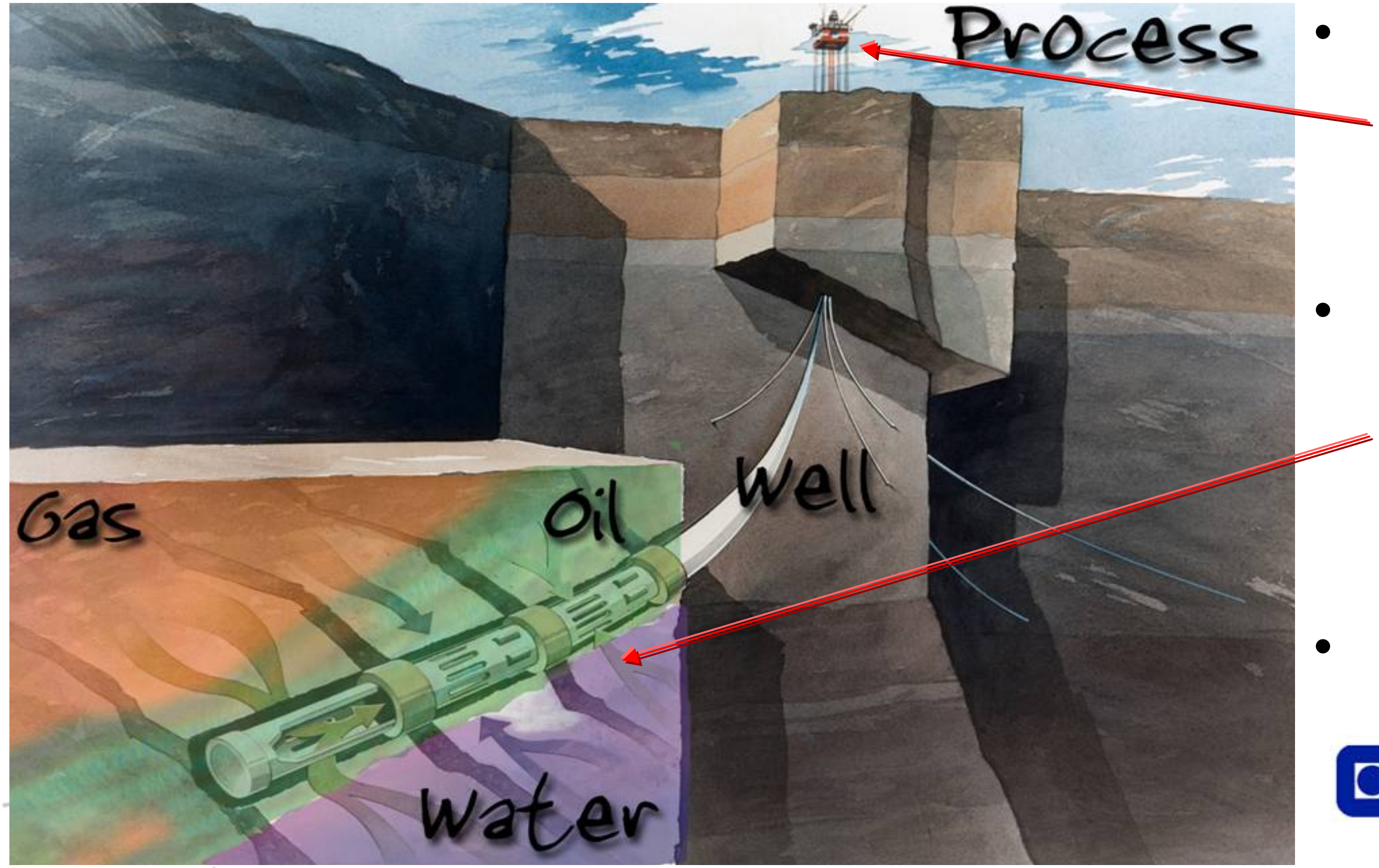
Industrial case: Maximize oil production at Heidrun field



- Oil producer with gas handling capacity constraint → active constraint
- Good well instrumentation → modelling possible

Problem formulation



- Oil producing field with gas handling constraint
- Gas-oil ratio from well depends on
  - Rate
  - Time
- Model?

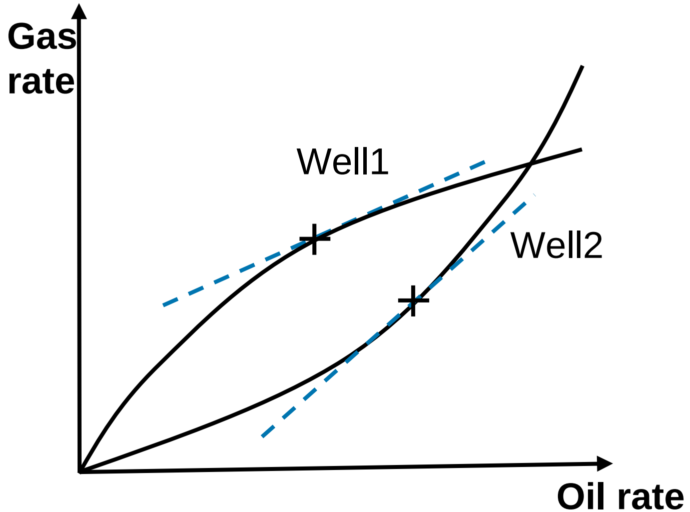
MGOR: Optimize oil & gas production

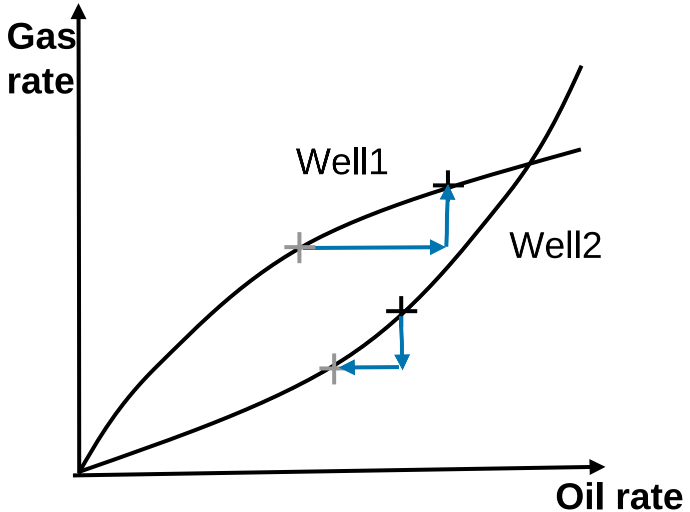
- Problem formulation

$$\max_{Q_g^i} \sum_n Q_o^n(\mathrm{Q}_\mathrm{g}^\mathrm{i}) \quad \text{s.t.} \quad \sum_n Q_g^n \le Q_g^{\max}$$

- Marginal GOR

$$MGOR = \frac{\Delta Q_{Gas}}{\Delta Q_{Oil}}$$



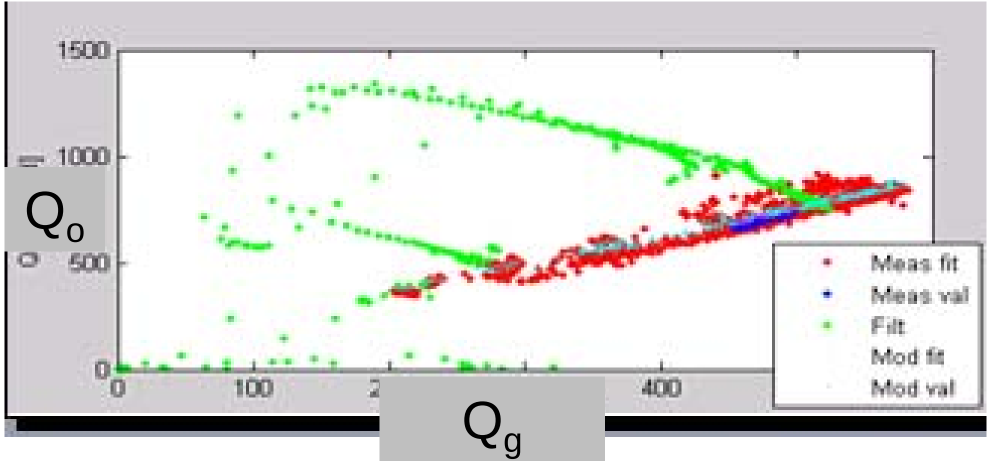


Optimal production when MGOR in all wells are equal (or on a well constraint)

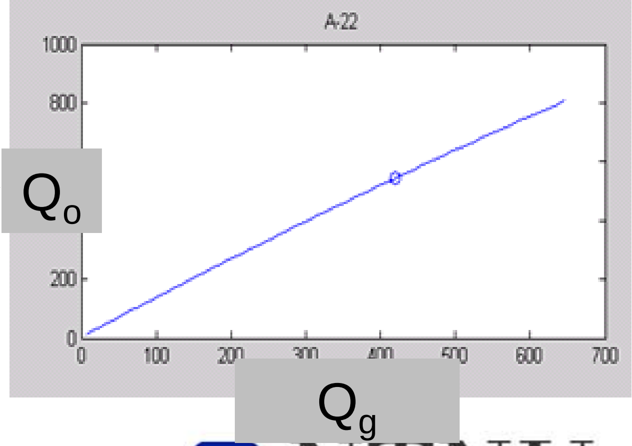
MGOR application - modelling

- Inhomogeneous reservoir, multiple producing zones, known near-well models not suitable
- Black-box dynamic oil-gas models developed based on measurements from multi-phase meters (MPM) with a dynamic and a stationary part
- Model update challenges

Oilrate vs. gasrate measurements



Model of the steady-state part



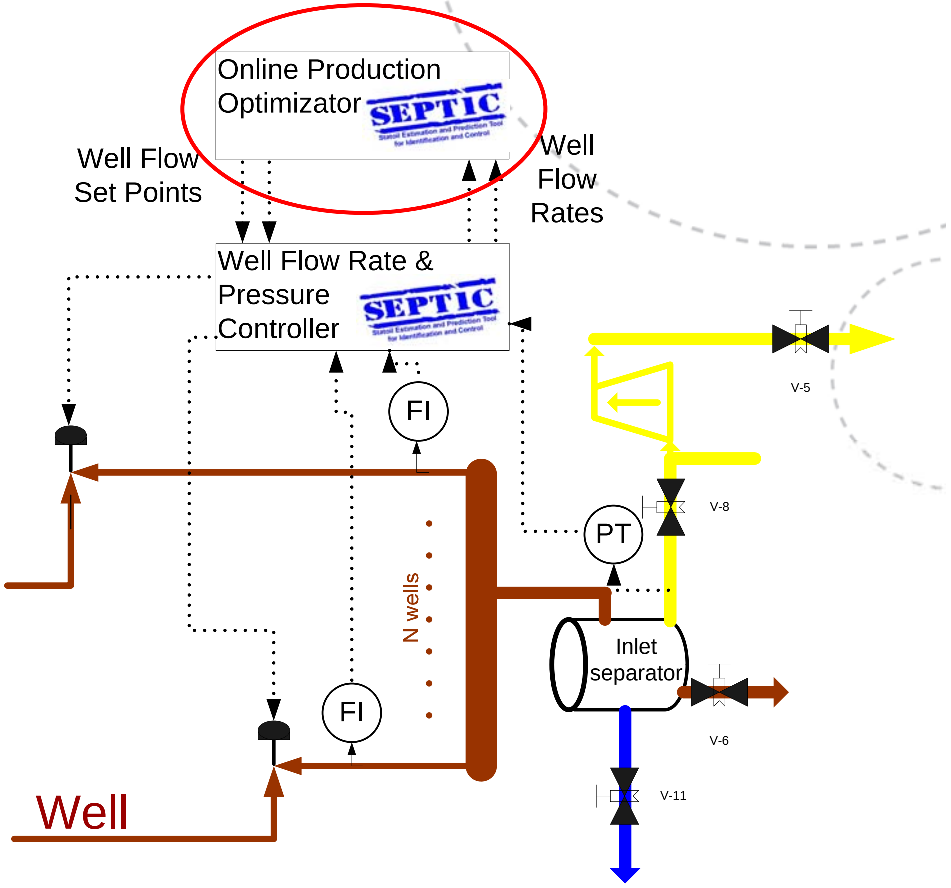
$Q_o = f(Q_g)$ to be used in optimization

MGOR application

- Objective:
  max *Oil production*
  s.t. gas constraints
- Variables: gas rate allocation between wells

- Maximize by setting a high, unreachable set point on oil rate with lower priority than constraints

- → Obtain "RTO" with experimental models and solved with MPC



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Summary

- Two main trends:

1. RTO with dynamic models
    - Extensive research
    - Technology used in industry
2. “Simplified RTO” as a competitive approach
    - Favorable if model-free approach is possible
    - MPC with a simplified objective function

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