NTNU

Innovation and Creativity

DESIGN OF PLANTWIDE CONTROL SYSTEMS WITH FOCUS ON MAXIMIZING THROUGHPUT

Elvira Marie B. Aske

Department of Chemical Engineering
Norwegian University of Science and Technology

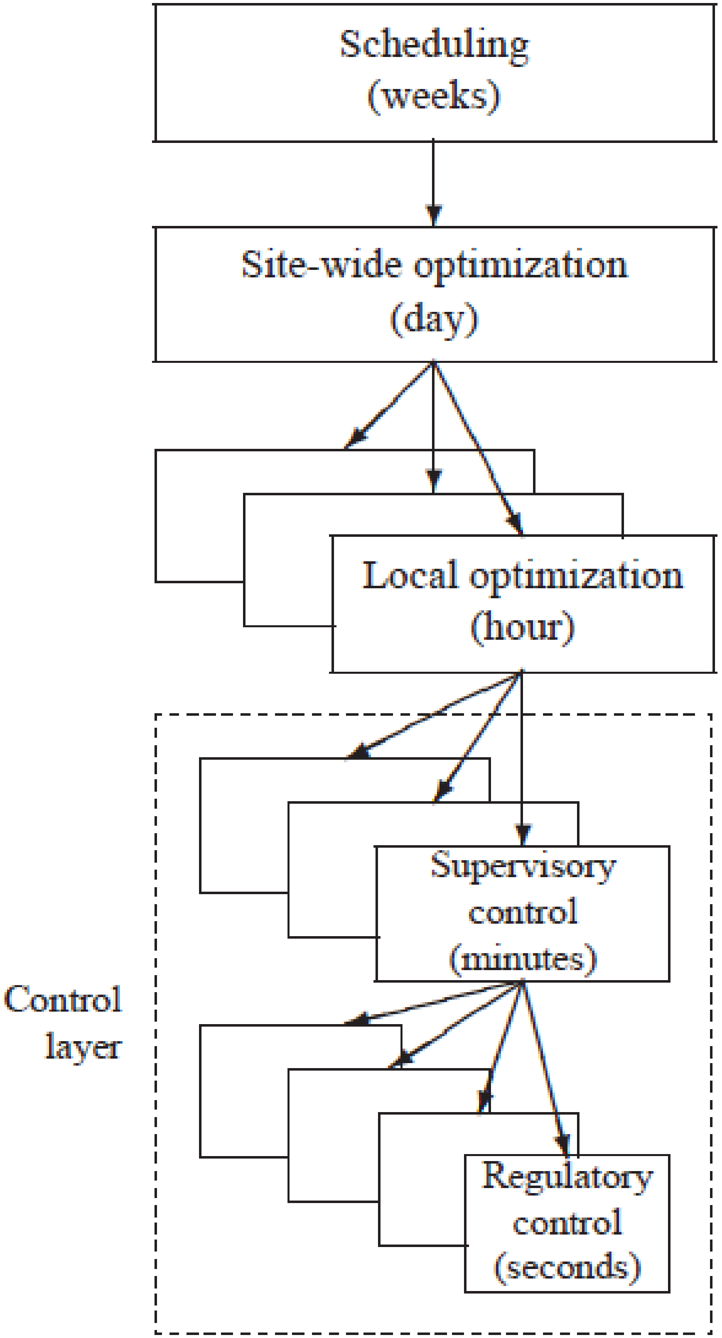
Trondheim, March 27, 2009

Presentation outline

- Introduction (Chapter 1)
- Self-consistency (Chapter 2)
- Maximum throughput (Chapter 3 (4,5,6))
  - Optimal operation
  - Bottleneck
  - Back off
- Dynamic degrees of freedom for tighter bottleneck control (Chapter 4)
- Coordinator MPC (Chapter 5,6)
  - Remaining capacity
  - Flow coordination
  - Industrial case
- Concluding remarks and and further work

Introduction

- Optimal economic operation
- This often corresponds to maximum throughput
  - Constrained optimization!
  - Identifying the constraints?
- How does this affect the plantwide control structure?
  - Frequent disturbances?
  - Moving constraints?



Chapter 2

SELF-CONSISTENT INVENTORY CONTROL

Self-consistent inventory control

- Inventory (material) balance control is an important part of process control

$$\frac{dI}{dt} = \text{Rate of change in inventory} = \text{Inflow} + \text{Generation - Outflow - Consumption}$$

- How design an appropriate structure?
- Many design rules in literature, but often poor justification
- Propose one rule that applies to all cases

→ self-consistency rule

Definitions

- Consistency: steady-state mass balances (total, component and phase) for the individual units and the overall plant are satisfied.
- Self-regulation: an acceptable variation in the output variable is achieved without the need for additional control when disturbances occur.
- Self-consistency: ***local*** “self-regulation” of all inventories (local inventory loops are sufficient)

  Self-consistency is a desired property because the mass balance for each unit is satisfied without the need to rely on control loops outside the unit

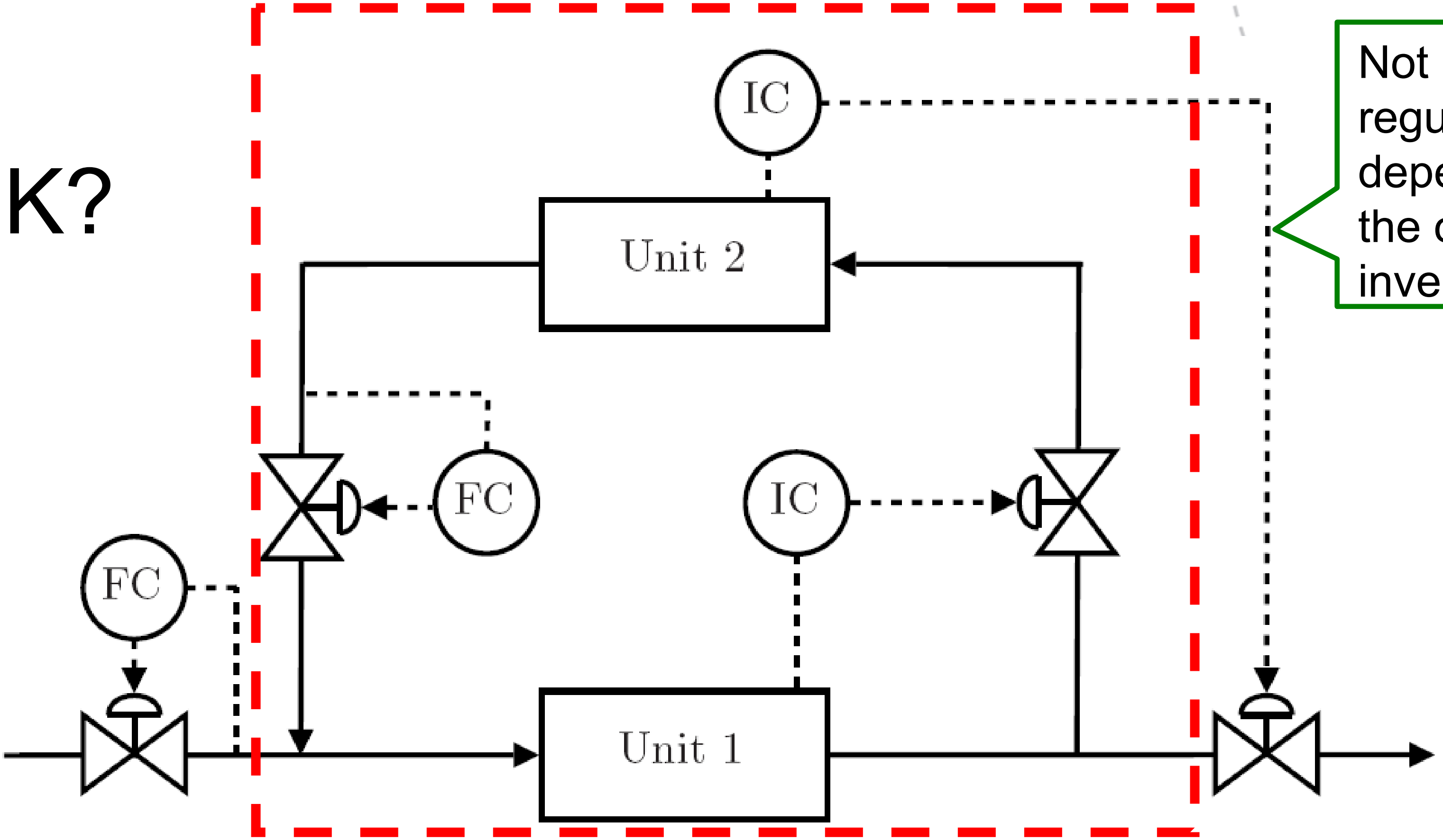
Self-consistency rule

Rule 2.1. *"Self-consistency rule":* *Self-consistency (local "self-regulation" of all inventories) requires that*

1. *The total inventory (mass) of any part of the process (unit) must be "self-regulated" by its in- or outflows, which implies that at least one flow in or out of any part of the process (unit) must depend on the inventory inside that part of the process (unit).*
2. *... and the inventory of each component*
3. *.. and the inventory of each phase*

Self-consistency: Example

OK?

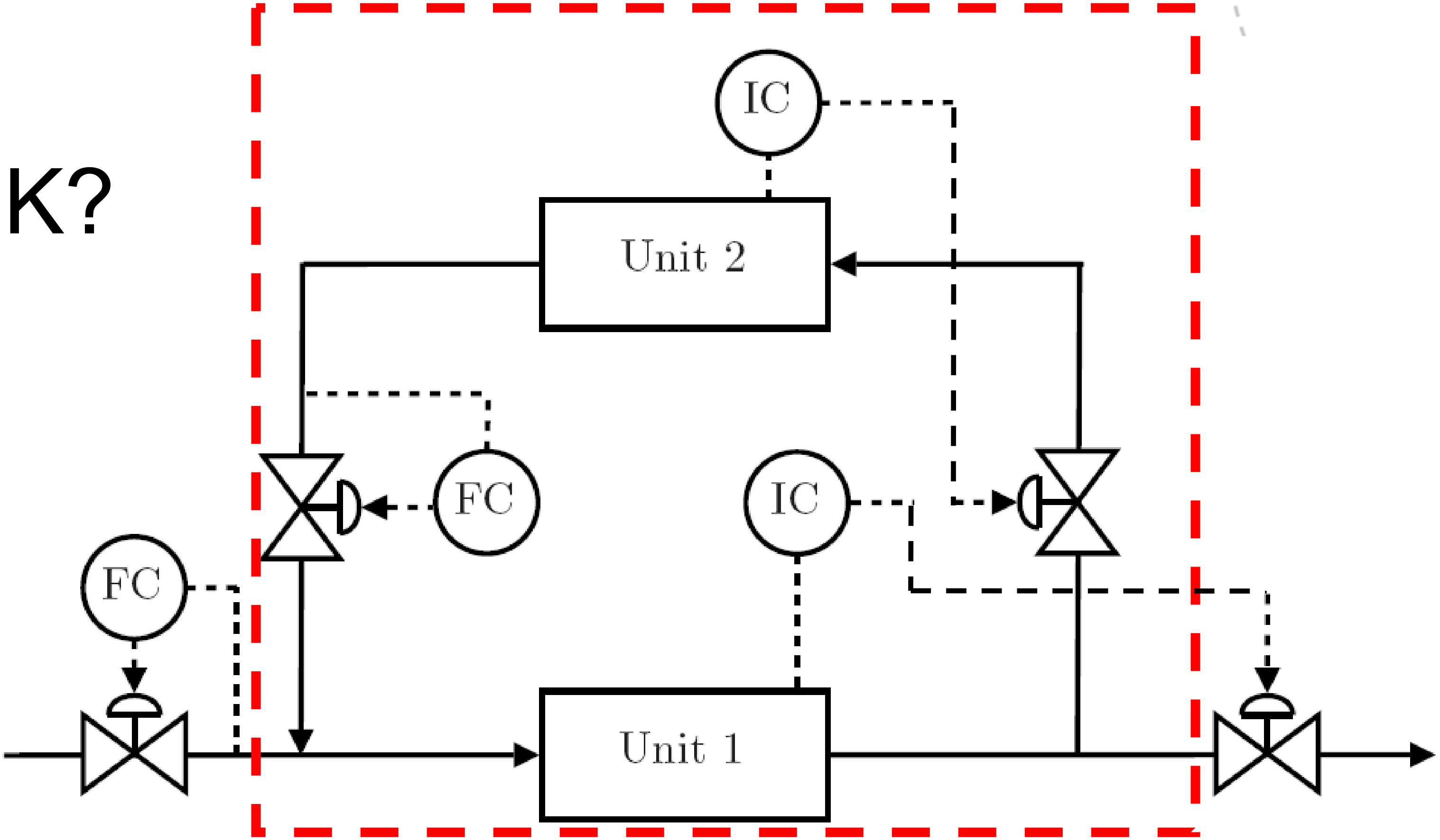


Not "self-regulated", depends on the other inventory loop

Consistent, but not self-consistent

Self-consistency: Example

OK?



Self-consistent:

Interchange the inventory loops

Chapter 3,(4,5 & 6)

MAXIMUM THROUGHPUT

Depending on market conditions: Two main modes of optimal operation

Mode 1. Given throughput ("nominal case")

Given feed or product rate

"Maximize efficiency": Unconstrained optimum

Mode 2. Max/Optimum throughput

Throughput is a degree of freedom + good product prices

2a) Maximum throughput

Increase throughput until constraints give infeasible operation

Constrained optimum - ***identify active constraints (bottleneck!)***

2b) Optimized throughput

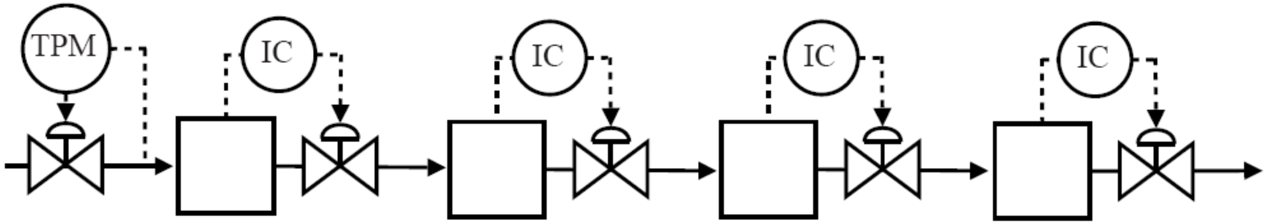
Increase throughput until further increase is uneconomical

Unconstrained optimum

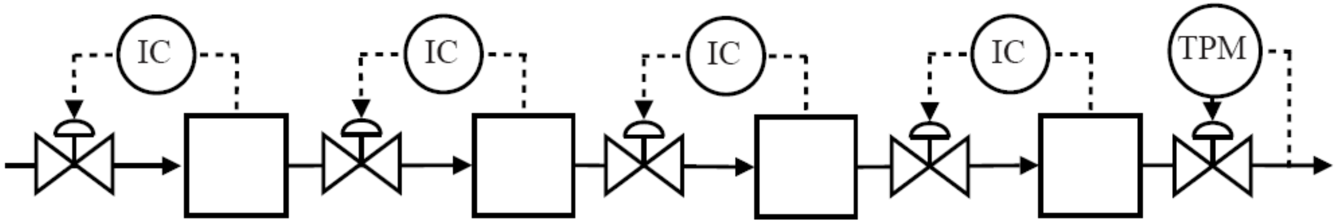
Throughput manipulator

Definition. *A throughput manipulator is a degree of freedom that affects the network flows, and which is not indirectly determined by other process requirements.*

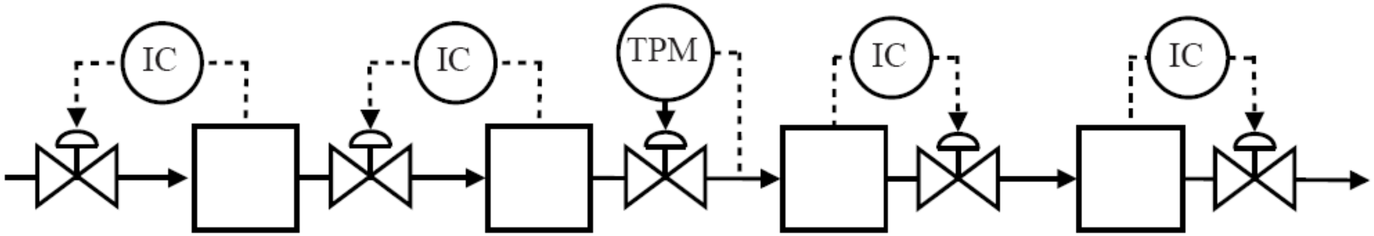
At feed:



At product:



Inside:



Bottleneck

Definition: *A unit is a bottleneck if maximum throughput (maximum network flow for the system) is obtained by operating this unit at maximum flow*

- If the flow for some time is not at its maximum through the bottleneck, then this loss can never be recovered

→ Maximum throughput requires tight control of the bottleneck unit

NTNU
Innovation and Creativity

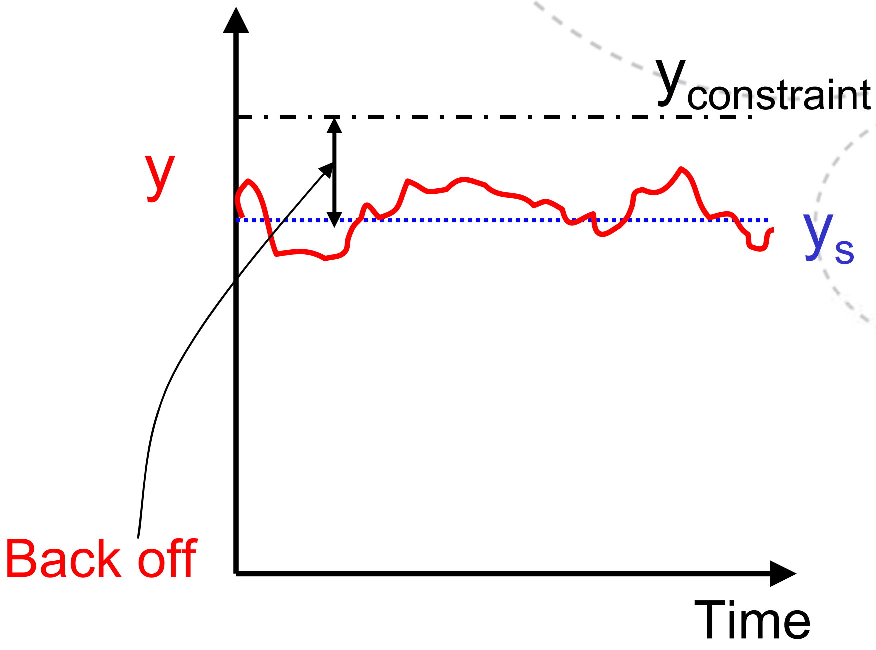
Back off

Definition: *The (chosen) back off is the distance between the (optimal)* ***active constraint*** *value ($y_{constraint}$) and its set point (y_s) (actual steady-state operation point),*

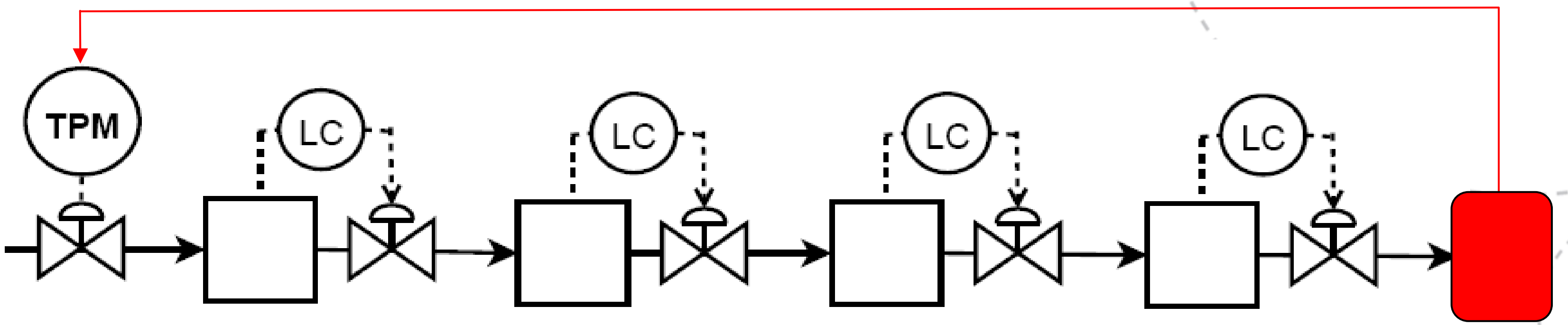
$$Back\ off = b = |y_{constraint} - y_s|,$$

which is needed to obtain feasible operation in spite of:

1. *Dynamic variations in the variable y caused by imperfect control*
2. *Measurement errors.*

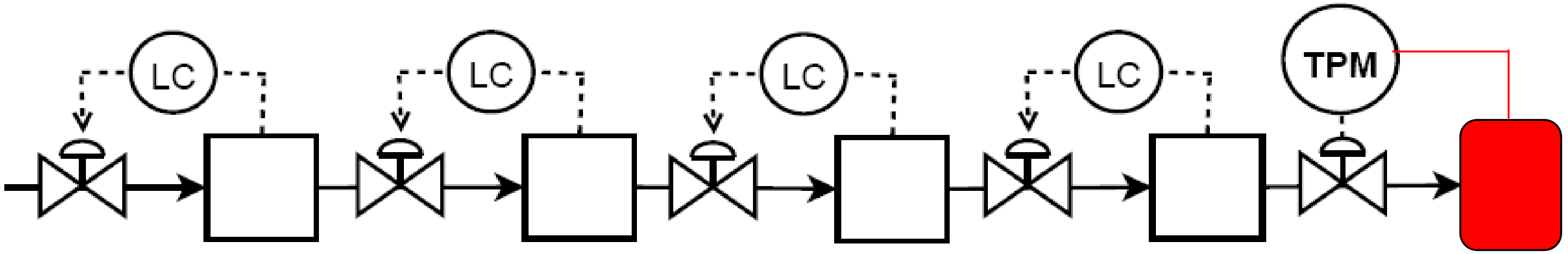


Realize maximum throughput



Best result (minimize back-off) if TPM permanently is moved to bottleneck unit

Bottleneck
(active constraint)
= max



Note: reconfiguration of inventory loops upstream TPM

Obtaining the back off

- Back off given by $b_{\min} = \max_{d,\Delta} \|y(t) - y_s\|_\infty$
- Exact estimation of back off difficult in practice
- Use controllability analysis to obtain “rule of thumb”
- Estimate back off to find economic incentive:

$$y = (I + GK)^{-1} \cdot G_d d = SG_d d$$

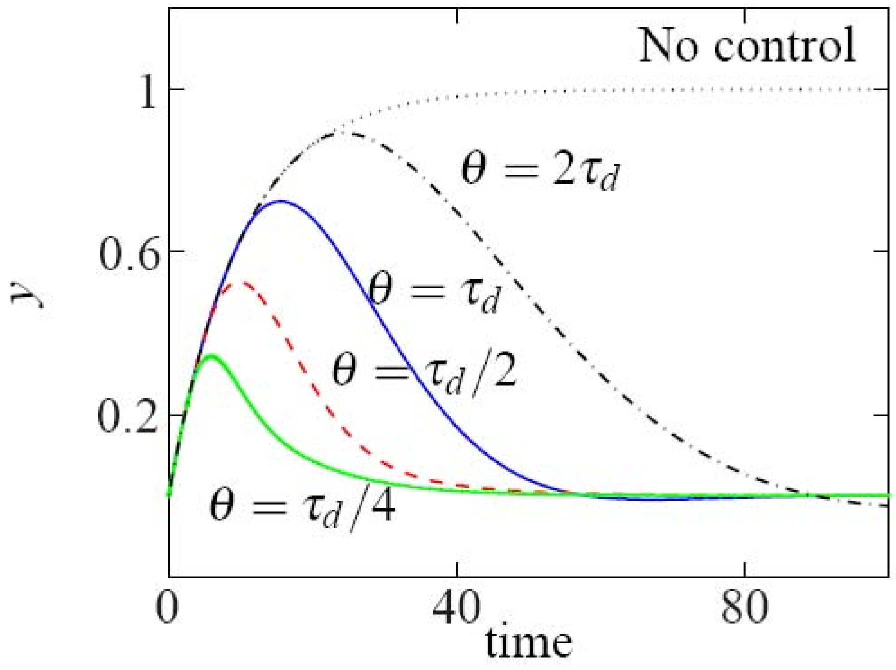
- Worst case amplification:

$$\text{Back off} = \max \|y\|_2 = \|SG_d\|_\infty \cdot \|d_0\|_2$$

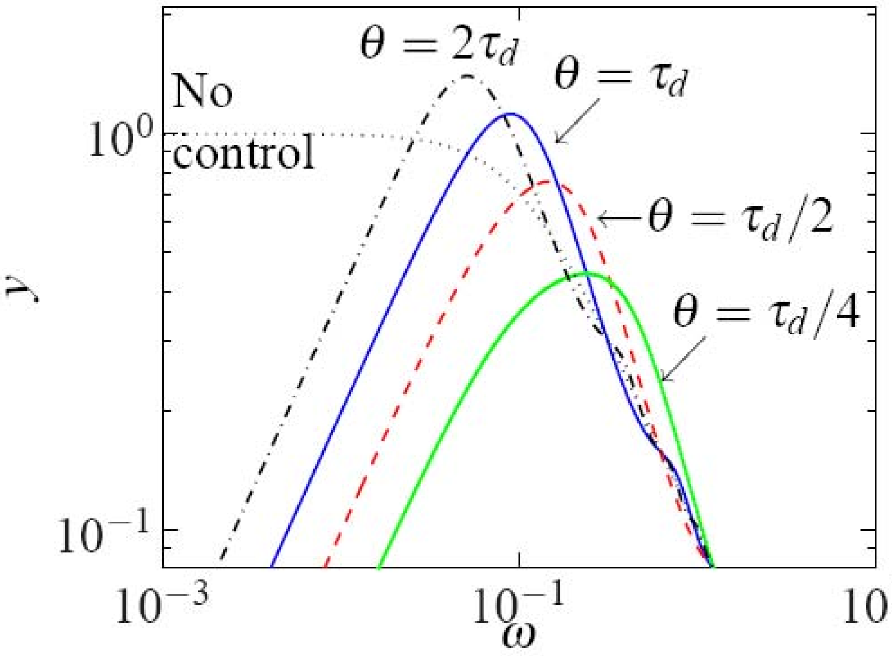
NTNU
Innovation and Creativity

Back off example:

PI-control of first order disturbance



Step response in d at t=0



Frequency response of Sg_d

τ_d : disturbance time constant

θ : time delay

Process: $g(s) = k\frac{e^{-\theta s}}{\tau_1 s+1}, \tau_1 = 10$

Disturbance: $g_d = \frac{1}{\tau_d s+1}, \tau_d = 10$

Controller: $c(s) = K_c\frac{\tau_I s+1}{\tau_I s}$ where $K_c = \frac{1}{k}\frac{\tau_1}{\tau_c+\theta}$ and $\tau_c = \theta$

Obtaining the back off (controllability analysis)

θ_{eff} : effective time delay from TPM to the bottleneck unit

1. "Easy disturbance" $\tau_d > 4\theta_{\mathrm{eff}}$
   - Benefit of control to reduce the peak
   - Minimum back off: $b_{\min} \approx \frac{2\theta_{\mathrm{eff}}}{\tau_d} \cdot k_d|d_0| \leq k_d|d_0|$

2. "Difficult disturbance" $\tau_d < 2\theta_{\mathrm{eff}}$
   - Control gives a larger back off (but needed for set point tracking)
   - "Smooth" tuning recommended to reduce peak (M_S)
   - Minimum back off:

$$b_{\min} \approx M_S \cdot k_d|d_0| \text{ where } M_S = \max_{\omega} |S(j\omega)|$$

Chapter 4

USE DYNAMIC DEGREES OF FREEDOM

NTNU
Innovation and Creativity

Reduce back off by using dynamic degrees of freedom

- TPM often located at feed (from design)
- Not always possible to move TPM
  - Reconfiguration undesirable (TPM and inventory)
  - Dynamic reasons (Luyben, 1999)
- Alternative solutions:

1. Use dynamic degrees of freedom (e.g. holdup volumes)
2. For plants with parallel trains: Use crossover and splits

Luyben, W.L. (1999). Inherent dynamic problems with on-demand control structures. *Ind. Eng. Chem. Res. 38(6), 2315–2329*.

Dynamic degrees of freedom: Main idea

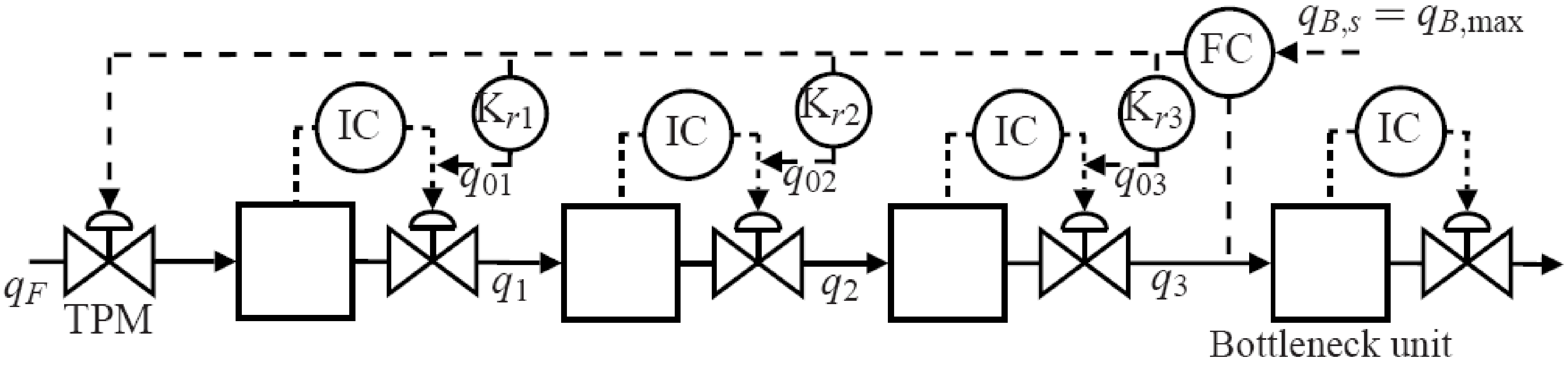
- Main idea: change the inventory to make temporary flow rate changes in the units between the TPM (feed) and the bottleneck

- *Improvement*: Tighter bottleneck control, the effective delay from the feed to the bottleneck may be significantly reduced

- *Cost:* Poorer inventory control (usually OK)

NTNU
Innovation and Creativity

Proposed control structure: Single-loop plus ratio control



- Change all upstream flows simultaneously
- *No reconfiguration of inventory loops*
- Bottleneck control only weakly dependent on inventory controller tuning

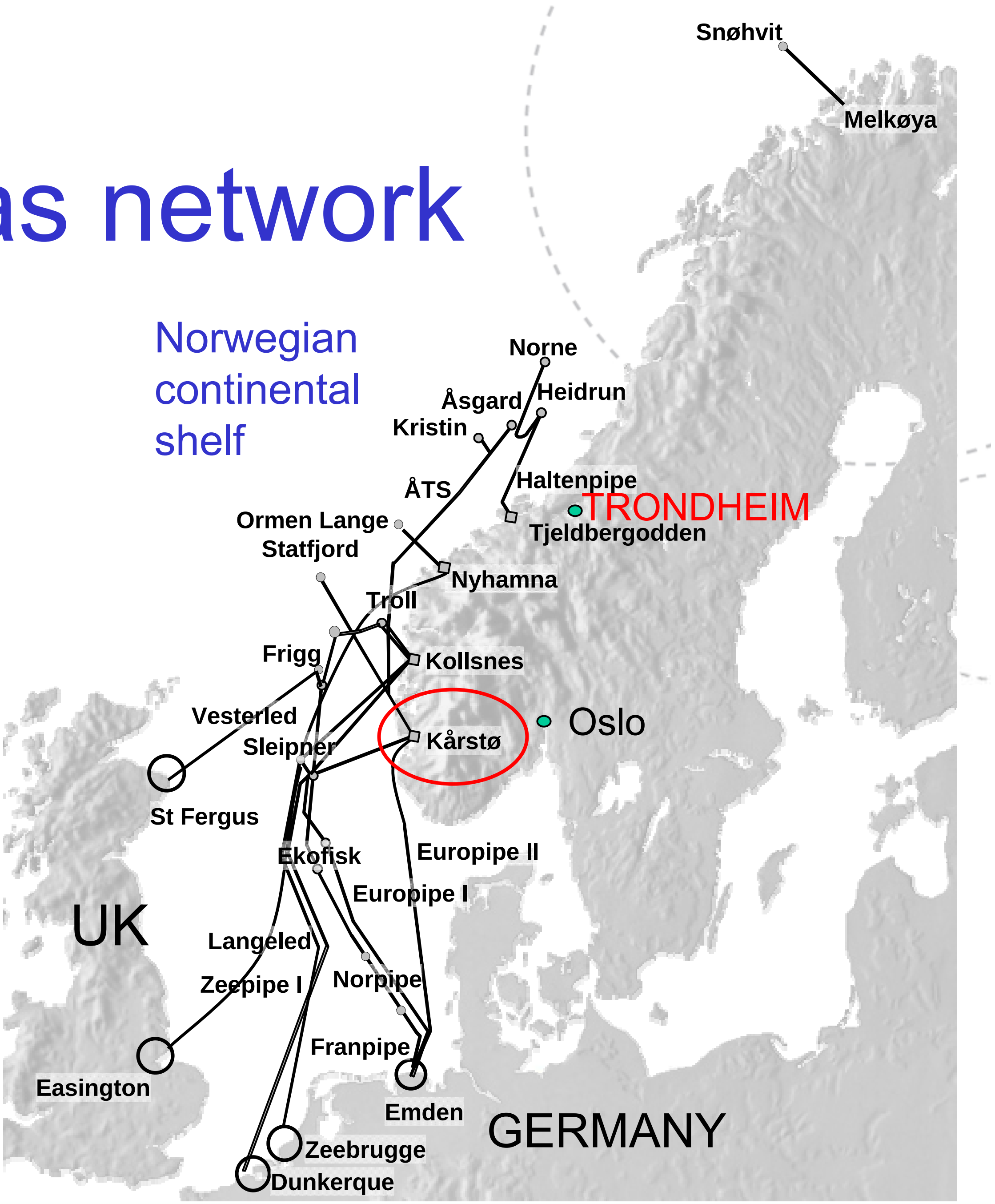
Chapter 5 & 6

COORDINATOR MPC

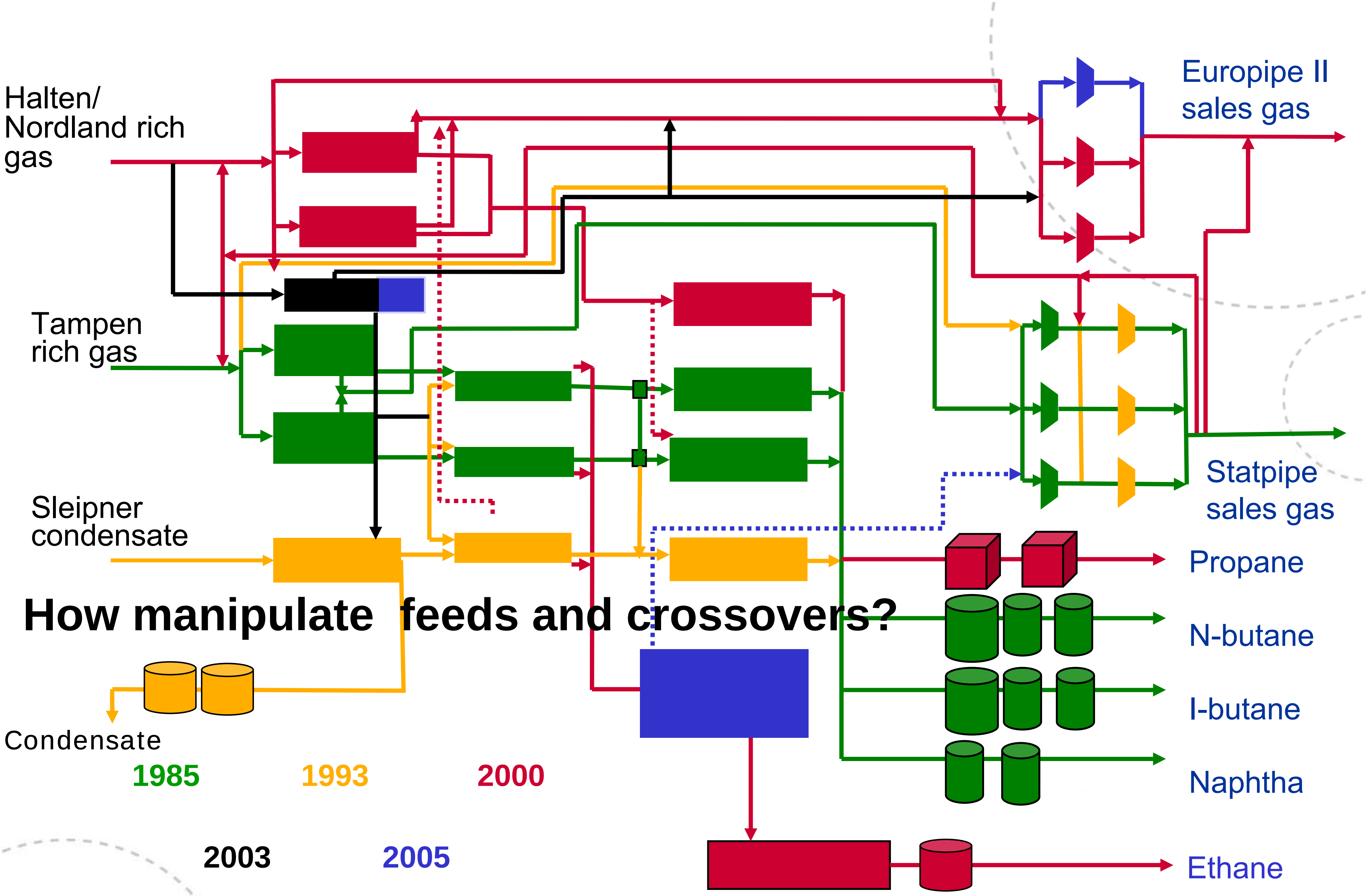
THE APPROACH AND THE IMPLEMENTATION AT KÅRSTØ GAS PLANT

North Sea gas network

- Kårstø plant: Receives gas from more than 30 offshore fields
- Limited capacity at Kårstø may limit offshore production (both oil and gas)



Motivation for coordinator MPC: Plant development over 20 years



How manipulate feeds and crossovers?

1985 **1993** **2000**

2003 **2005**

Maximum throughput

- Here: want maximum throughput

  → Obtain this by "Coordinator MPC":
- Manipulate TPMs (feed valves and crossovers) presently used by operators
- Throughput determined at plant-wide level (not by one single unit)

  → coordination required
- Frequent changes

  → dynamic model for optimization

NTNU
Innovation and Creativity

”Coordinator MPC”: Coordinates *network flows*, not MPCs

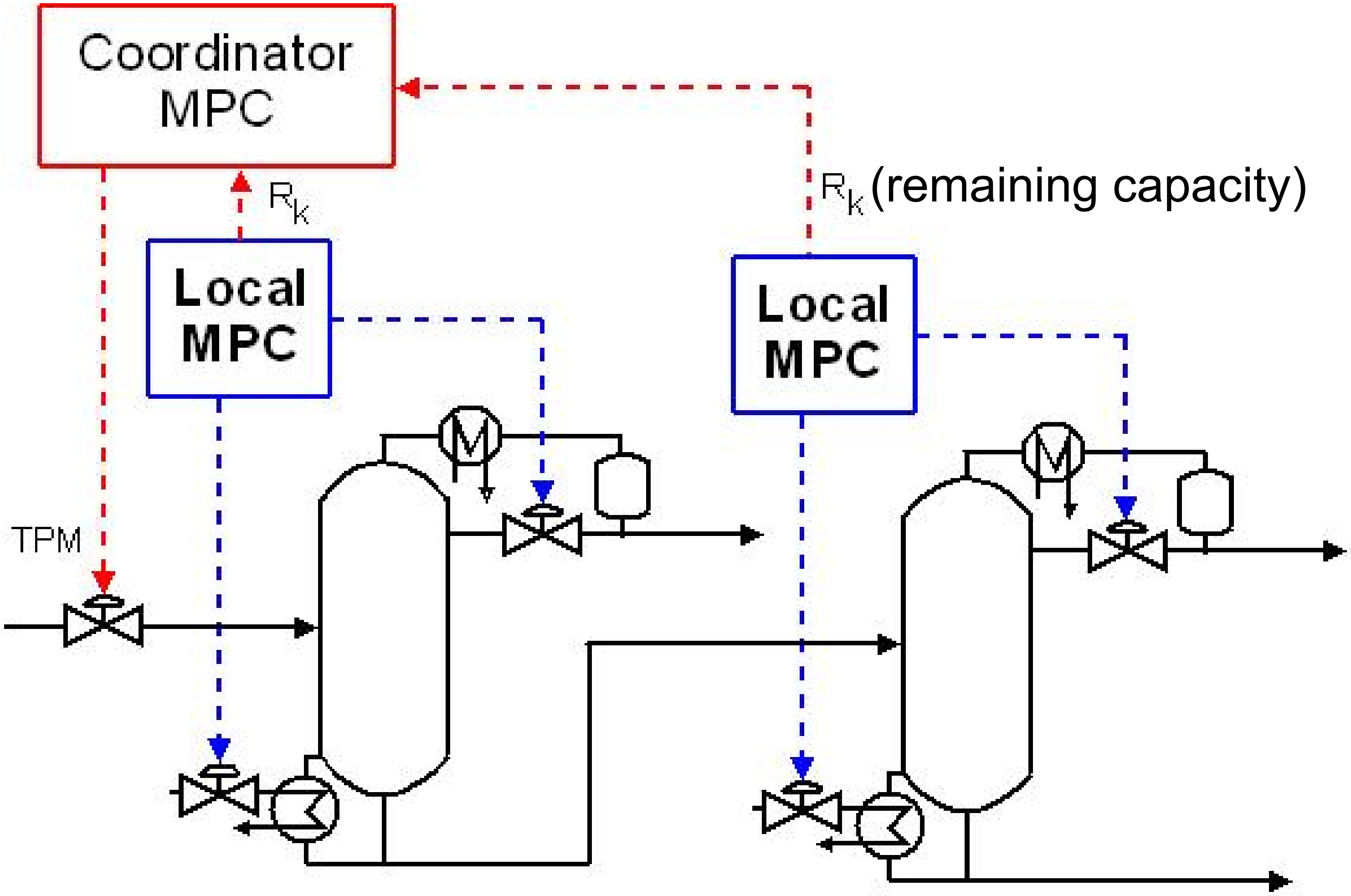
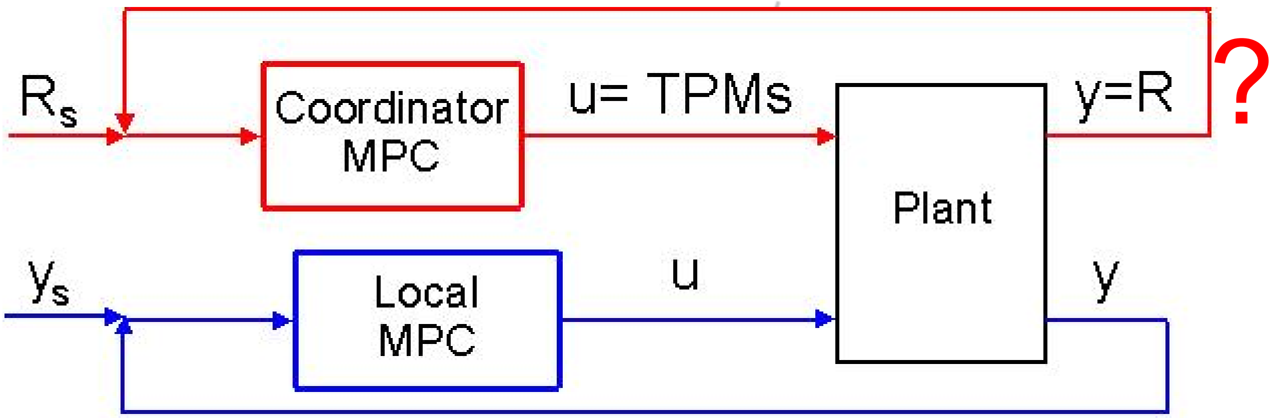


Illustration of the coordinator MPC

Approach



Use Coordinator MPC to optimally adjust TPMs:

- Coordinates the network flows to the local MPC applications
- Decompose the problem (decentralized).
  - Assume Local MPCs closed when running Coordinator MPC
    - Need flow network model (No need for a detailed model of the entire plant)
  - Decoupling: Treat TPMs as DVs in Local MPCs
  - **Use local MPCs to estimate feasible remaining capacity (R) in each unit**

Remaining capacity (using local MPCs)

- Feasible remaining feed capacity for unit *k*:

$$R_k = F_{k,max} - F_k$$

current feed to unit *k*

max feed to unit *k* within feasible operation

- Obtained by solving “extra” steady-state LP problem in each local MPC: $F^l_{k,max} = \max_{u^l_k, F^l_k} F^l_k$

  subject to present state, models and constraints in the local MPC
- Use end predictions for the variables
- Recalculated at every sample (updated measurements)
- *Very little extra effort!*

SEPTIC
Statoil Estimation and Prediction Tool
for Identification and Control

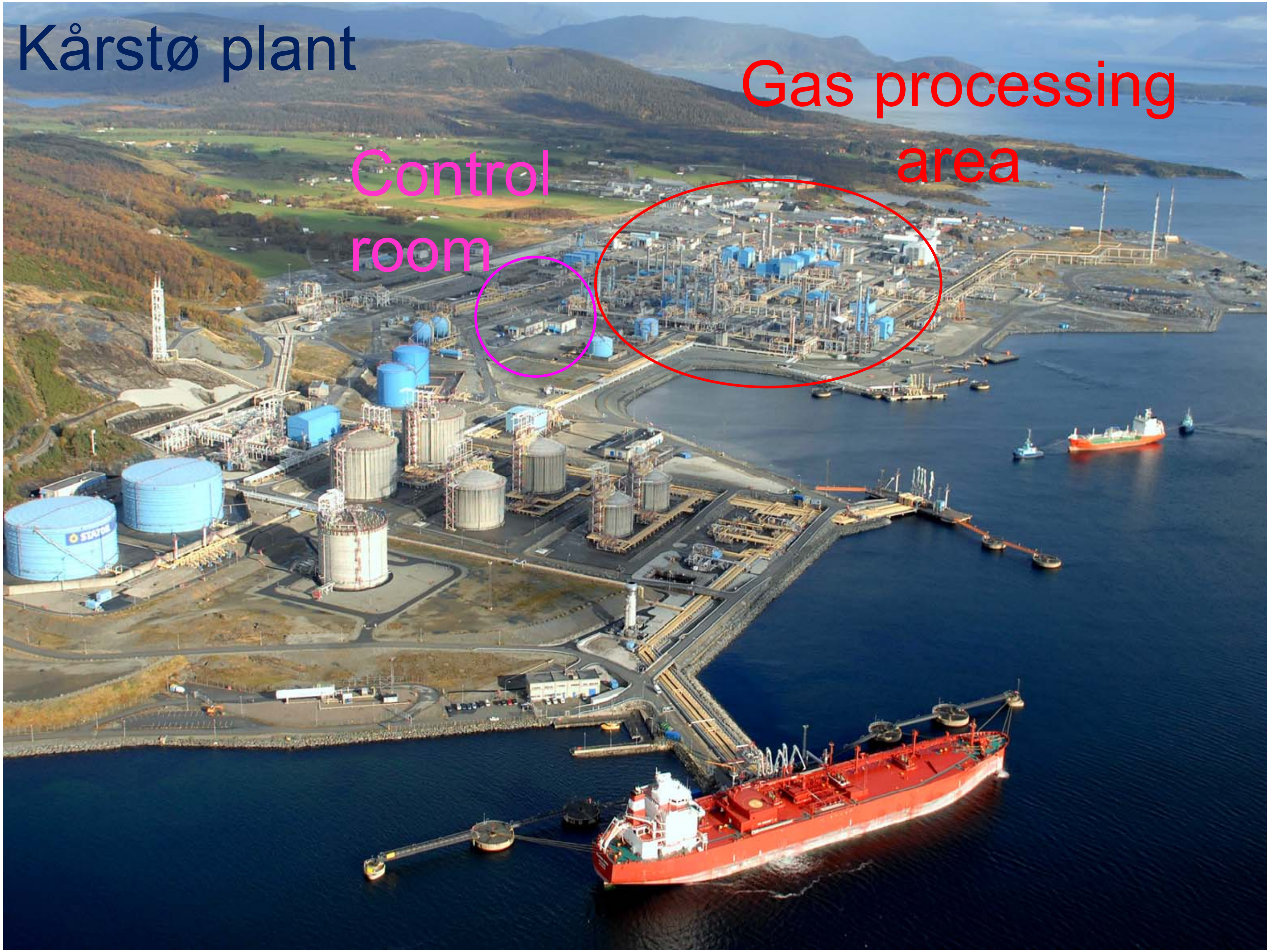
Coordinator MPC: Design

Objective: ***Maximize plant throughput, subject to achieving feasible operation***

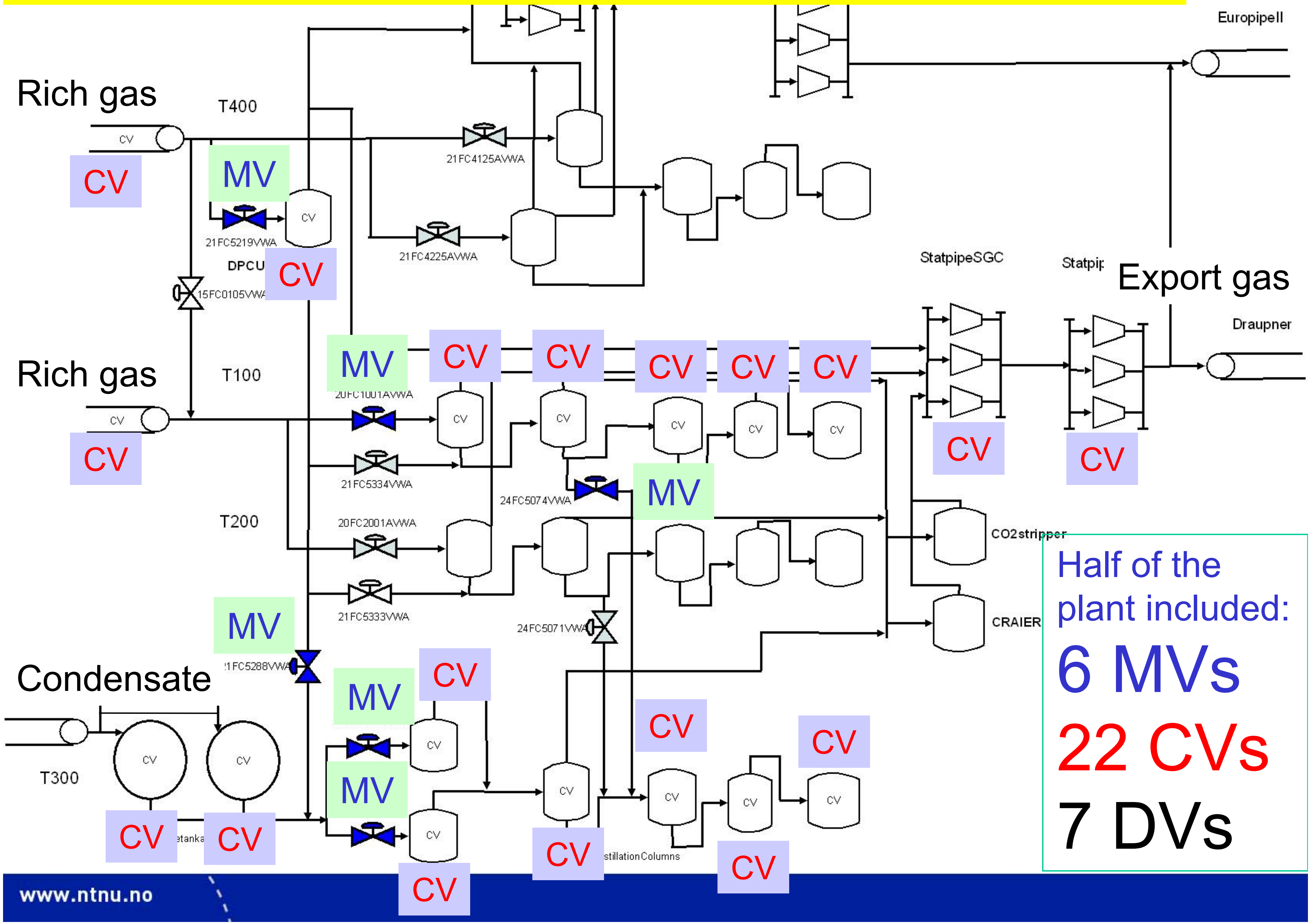
- MVs: TPMs (feeds and crossovers that affect several units)
- CVs: total plant feed + constraints:
  - Constraints (R > backoff > 0, etc.) at highest priority level
  - Objective function: Total plant feed as CV with *high, unreachable set point with lower priority*
- DVs: feed composition changes, disturbance flows
- Model: step-response models obtained from
  - Calculated steady-state gains (from feed composition)
  - Plant tests (dynamic)

NTNU
Innovation and Creativity

Kårstø plant



KÅRSTØ MPC COORDINATOR IMPLEMENTATION (2008)



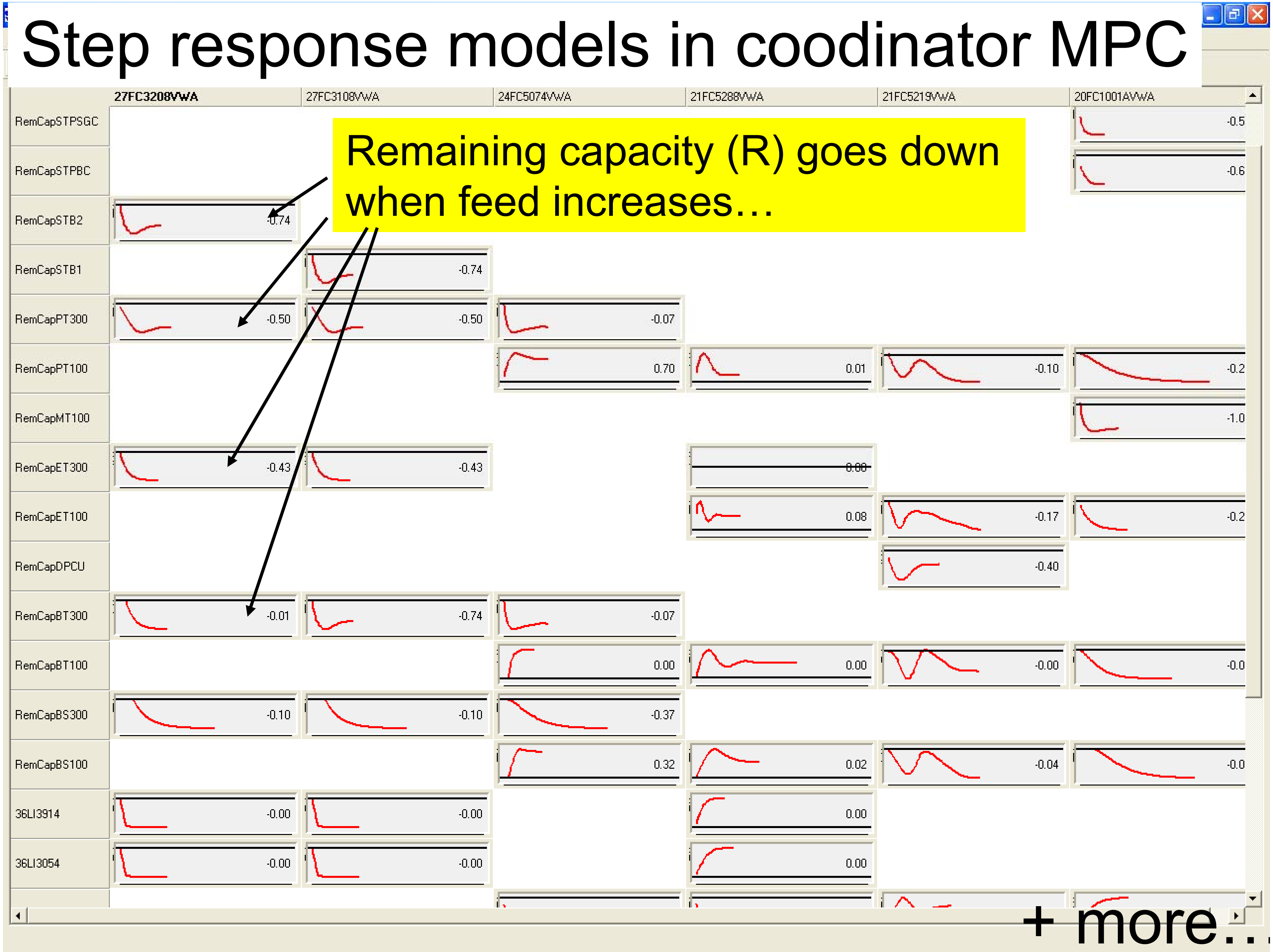
Half of the plant included:

6 MVs

22 CVs

7 DVs

Step response models in coodinator MPC



Remaining capacity (R) goes down when feed increases…

	27FC3208VWA	27FC3108VWA	24FC5074VWA	21FC5288VWA	21FC5219VWA	20FC1001AVWA
RemCapSTPSGC						-0.5
RemCapSTPBC						-0.6
RemCapSTB2	-0.74					
RemCapSTB1		-0.74				
RemCapPT300	-0.50	-0.50	-0.07			
RemCapPT100			0.70	0.01	-0.10	-0.2
RemCapMT100						-1.0
RemCapET300	-0.43	-0.43		0.00		
RemCapET100				0.08	-0.17	-0.2
RemCapDPCU					-0.40	
RemCapBT300	-0.01	-0.74	-0.07			
RemCapBT100			0.00	0.00	-0.00	-0.0
RemCapBS300	-0.10	-0.10	-0.37			
RemCapBS100			0.32	0.02	-0.04	-0.0
36LI3914	-0.00	-0.00		0.00		
36LI3054	-0.00	-0.00		0.00		

+ more…

Experiences

- Using local MPCs to estimate feasible remaining capacity leads to a plant-wide application with “reasonable” size
- The estimate remaining capacity relies on
  - accuracy of the steady-state models
  - correct and reasonable CV and MV constraints
  - use of gain scheduling to cope with larger nonlinearities (differential pressures)

→ Crucial to inspect the models and tuning of the local applications in a systematic manner

- Requires follow-up work and extensive training of operators and operator managers
  - “New way of thinking”
  - New operator handle instead of feed rate: R_s (back-off)

NTNU
Innovation and Creativity

CONCLUDING REMARKS AND FURTHER WORK

NTNU
Innovation and Creativity

Main contributions

- Plantwide decomposition by estimating the remaining capacity in each unit by using the local MPCs
- The idea of using a "decentralized" coordinator MPC to maximize throughput
- The proposed self-consistency rule, one rule that applies to all cases to check whether a inventory control system is consistent
- Single-loop with ratio control as an alternative structure to obtain tight bottleneck control

Further work

- Recycle systems not treated
- Information loss in plantwide composition
- Further implementation of coordinator MPC
  - Planned start-up autumn 2009 (after control system upgrade)

- Acknowledgments: Gassco, StatoilHydro ASA