DESIGN OF PLANTWIDE CONTROL SYSTEMS
WITH FOCUS ON MAXIMIZING THROUGHPUT

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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 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

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

- How design an appropriate structure?
- Many design rules in literature, but often poor justification
- Propose one rule that applies to all cases
  \[\rightarrow \text{self-consistency rule}\]
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.
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?

Consistent, but not self-consistent

Not “self-regulated”, depends on the other inventory loop
Self-consistency: Example

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.
**Back off**

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

\[
\text{Back off} = b = \left| y_{\text{constraint}} - y_s \right|
\]

which is needed to obtain feasible operation in spite of:

1. *Dynamic variations in the variable* \( y \) *caused by imperfect control*
Realize maximum throughput

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

Note: reconfiguration of inventory loops upstream TPM
Obtaining the back off

- Back off given by $b_{\text{min}} = \max_{d, \Delta} \| y(t) - y_s \|_\infty$
- Exact estimation of back off difficult in practice
- Use controllability analysis to obtain “rule of thumb”
- Estimate back off to find economic incentive:
  $$y = (I + GK)^{-1} \cdot G_dd = SG_dd$$
- Worst case amplification:
  $$\text{Back off} = \max ||y||_2 = ||SG_d||_\infty \cdot ||d_0||_2$$
Back off example:
PI-control of first order disturbance

\[ \tau_d : \text{disturbance time constant} \]
\[ \theta : \text{time delay} \]

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

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

Controller: \[ c(s) = K_c \frac{\tau_d s + 1}{\tau_d s} \text{ where } K_c = \frac{1}{k} \frac{\tau_1}{\tau_c + \theta} \text{ and } \tau_c = \theta \]
Obtaining the back off (controllability analysis)

\( \theta_{\text{eff}} : \) effective time delay from TPM to the bottleneck unit

1. “Easy disturbance” \( \tau_d > 4\theta_{\text{eff}} \)
   - Benefit of control to reduce the peak
   - Minimum back off:
     \[ b_{\text{min}} \approx \frac{2\theta_{\text{eff}}}{\tau_d} \cdot k_d|d_0| \leq k_d|d_0| \]

2. “Difficult disturbance” \( \tau_d < 2\theta_{\text{eff}} \)
   - Control gives a larger back off (but needed for set point tracking)
   - “Smooth” tuning recommended to reduce peak \((M_S)\)
   - Minimum back off:
     \[ b_{\text{min}} \approx M_S \cdot k_d|d_0| \text{ where } M_S = \max_\omega |S(j\omega)| \]
Chapter 4

USE DYNAMIC DEGREES OF FREEDOM
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

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)
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?

Halten/Nordland rich gas

Tampen rich gas

Sleipner condensate

Condensate

Europipe II sales gas

Statpipe sales gas

Propane

N-butane

I-butane

Naphtha

Ethane

www.ntnu.no
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
”Coordinator MPC”: Coordinates *network flows*, not MPCs
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 $k$:
  \[ R_k = F_{k,max} - F_{k,\text{current feed to unit } k} \]
  \[ \text{max feed to unit } k \text{ within feasible operation} \]

- Obtained by solving “extra” steady-state LP problem in each local MPC:
  \[ F_{k,\max}^l = \max_{u_k^l, F_k} F_k^l \]
  \[ \text{subject to present state, models and constraints in the local MPC} \]

- Use end predictions for the variables
- Recalculated at every sample (updated measurements)
- Very little extra effort!
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*
- **DV:** feed composition changes, disturbance flows
- Model: step-response models obtained from
  - Calculated steady-state gains (from feed composition)
  - Plant tests (dynamic)
Half of the plant included:
6 MVs
22 CVs
7 DVs
Remaining capacity (R) goes down when feed increases...
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)
CONCLUDING REMARKS AND FURTHER WORK
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)

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