A Batch Reactor Heat Recovery Challenge Problem

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Innovation and Creativity

Outline

Introduction

Optimizing real processes consists of 2 parts:

1. Optimization problem
   - Formulating the problem
   - Solving it systematically, often using a model 

2. Implement the solution in the real process 

This presentation:

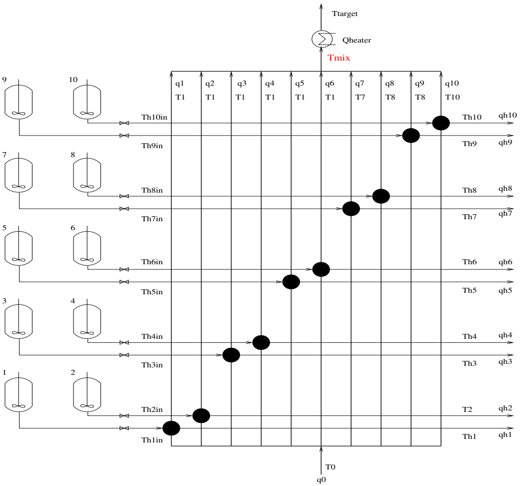
- Challenge problem to test
  - Optimization
  - Implementation
- Discussion

Introduction

Some challenges when optimizing real systems

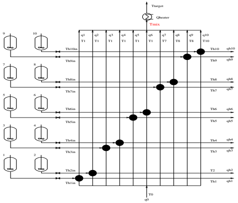
- Optimization part
  - Non-linearity
  - Non-convexity
  - Integer variables
  - Non-smoothness
  - Time-varying systems (Dynamic systems)
- Implementation part
  - Missing information
  - Uncertainty
    - Disturbances (parametric uncertainty)
    - Noise
    - Structural model mismatch
    - Temporal uncertainty

Heat recovery challenge problem

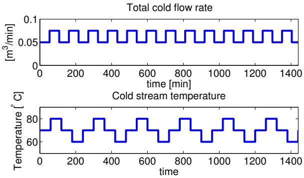


Objective: Adjust split to maximize Tmix

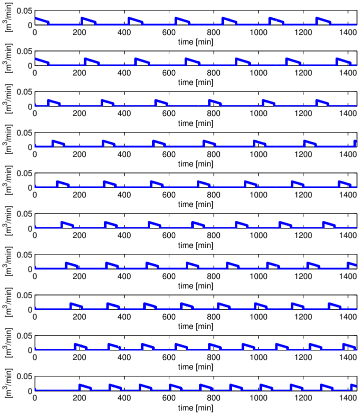
Heat recovery challenge problem



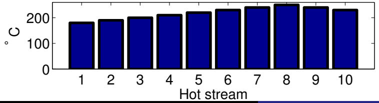
Cold flow rate and temperature



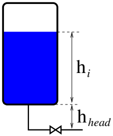
Hot flow rates



Hot stream temperatures



Heat recovery challenge problem
Batch discharge



- Flow rate:

$$q^j_{hi}(t) = \begin{cases} 0 & \text{for} \quad t < t_s \\ k_i\sqrt{\Delta p^j_i} & \text{for} \quad t^j_{sj} \le t \le t^j_{si} + t^j_{ei} \\ 0 & \text{for} \quad t > t^j_{si} + t^j_{ei} \end{cases}$$

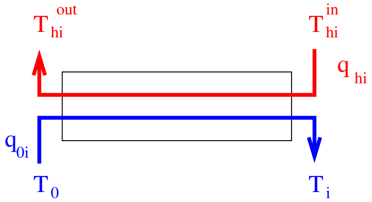
- t^j_{si} Start time of discharge j
- t^j_{ei} End time of discharge j ($h^j_i = 0$)
- Pressure drop at valve

$$\Delta p^j_i = \rho g(h^j_i + h_{head})$$

- Level during discharge j

$$A\frac{dh^j_i}{dt} = -q^j_i$$

Heat exchangers



- SS-assumption:
- Energy balances

$$Q_i = q_{0i}(T_i - T_0)$$
$$Q_i = q_{hi}(T_{hi}^{in} - T_{hi}^{out})$$

- Heat transfer

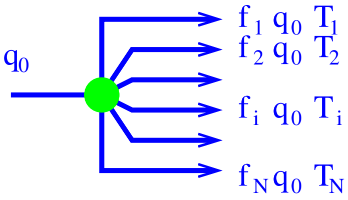
$$Q_i = UA(q_{hi})\Delta T_{log,i}$$

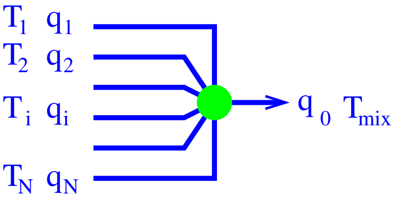
- Heat transfer

$$\Delta T_{log,i} = \frac{(T_{h,i} - T_0) - (T_{hi}^{in} - T_i)}{\log \frac{(T_{h,i} - T_0)}{(T_{hi}^{in} - T_i)}}$$

$$UA_i(q_{hi}) = UA_{0i}\left(\frac{q_{hi}(t)}{q_{h0i}}\right)^{0.8}$$

Splitter and mixer





- Splitter

$$T_i = T_0$$
$$q_i = f_i q_0$$
$$\sum_{i=1}^{N} f_i = 1$$

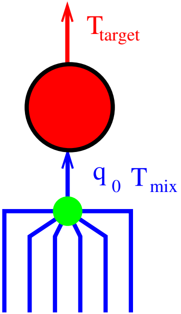
- Mixer

$$T_{mix} = \frac{1}{q_0} \sum_{i=1}^{N} q_{hi} T_i$$
$$q_0 = \sum_{i=1}^{N} q_i$$

Objective function and heater

- Heater duty

$$Q_{heat}(t) = q_0 c_p \left(T_{target} - T_{mix}(t)\right)$$

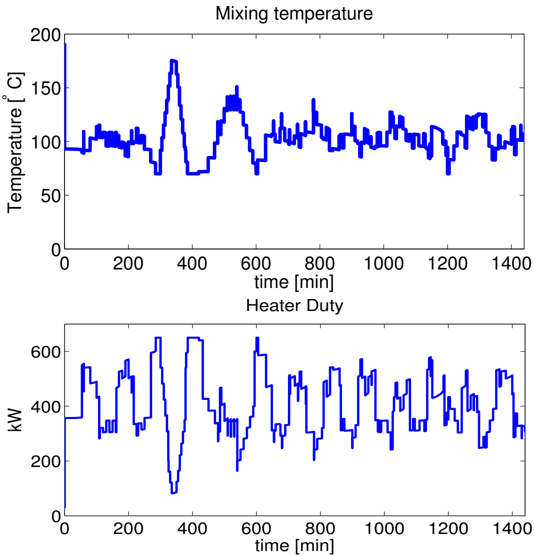


Objective:

$$\min_{f_i} \int_0^{24h} Q_{heater}(t) dt$$

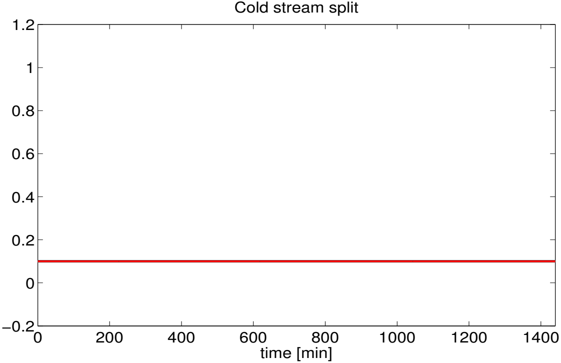
Open-loop Simulation – equal f_i

- Equal fractions in all parallel branches



Open-loop Simulation – equal f_i

- Equal fractions in all parallel branches



$$J = \int_0^{24h} Q_{heat} dt = 35005.17 MJ$$

"Optimization"

Definition

An active branch is a branch connected to a no-zero hot stream

Idea

$$q_i = f_i q_0$$

- assign flow only to active branches

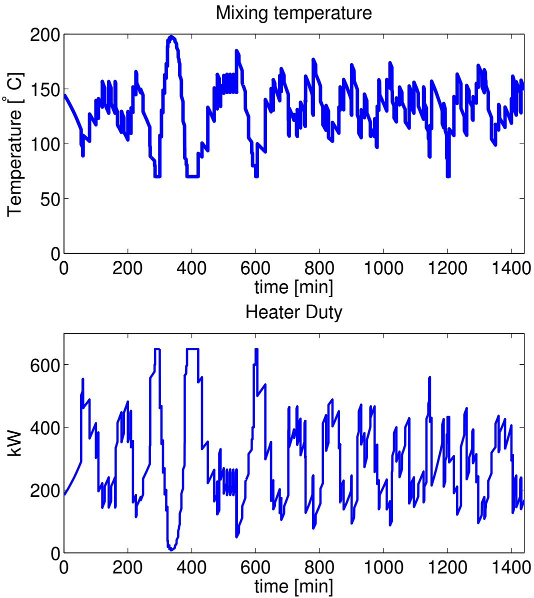
$$f_{i,active} = 1/n_{active}$$

$$f_{i,inactive} = 0$$

- if no branch is active, then

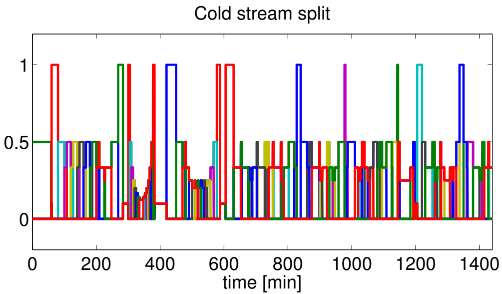
$$f_i = 1/n_{total}$$

“Optimized”



Mixing temperature
Temperature [°C]
200
150
100
50
0
0
200
400
600
800
1000
1200
1400
time [min]
Heater Duty
kW
600
400
200
0
0
200
400
600
800
1000
1200
1400
time [min]

"Optimized"



$$J = \int_0^{24h} Q_{heat} dt = 25364.11 MJ$$

Discussion

Implementation of "optimal solution"

- Very simple
- Assumption: Only hot flows measured
- Clearly sub-optimal

Optimization

- Nonlinear problem
- Time-varying
- Static optimization at each time instant
- Suboptimal policy
  - Temperatures not used.
  - Piecewise constant f_i
- Large improvement

$$35,005.17MJ \Longrightarrow 25,364.11MJ$$

Conclusions

- Nonlinear optimization problem:
  - Sub-optimal solution
  - Simple implementation
- For true optimal solution:
  - More information required
    - Temperatures
    - Flow rates
    - Estimate unmeasured parameters (UA_0)

Future work

- Improve "optimization" algorithm
  - Include temperature measurements
  - Time varying f_i
- Assume flows are not measured
- Modify problem
  - Add buffer tank before split

Thank you *!*

A simulink model will be made available on
`http://www.nt.ntnu.no/users/skoge/publications/2012/BatchChallenge`