Optimal selection of controlled variables for the C3-MR process for liquefaction of natural gas
Outline of presentation

• Description of C3-MR process model
• Degrees of freedom for design, operation and control
• Summary of inputs and disturbances to the process
• Idea of self-optimizing control
  – Idea and method
  – Application to this specific process
• Challenges in optimization
• Further work
Modelling framework

Models have been constructed in two different programs.

- Unisim (from Honeywell, successor to Hysys)
- gProms, equations given manually
Model description

- Constant compressor efficiency (may be changed later)
- Main LNG exchanger modelled as two counter-current, multi-flow heat exchangers
- Simple heat exchanger models:
  - $U$ assumed constant
  - area is only variable parameter
  - pressure drops specified directly
- The propane kettles are modelled as a shell and tube heat exchanger followed by a flash tank.
Model, continued

- Besides given parameters and assumed given variables, there are 24 variables to specify:
  - Propane flow in each branch (2)
  - Four propane pressures, two mixed refrigerant pressures (6 in all)
  - 11 heat exchanger area values
  - Flow and composition of the mixed refrigerant (5)
Degrees of freedom

• Count number of variables that can be physically manipulated
  – Valves (here: 8, excluding cooling water flows and feed flow rate)
  – Compressors (here: 4)
  – Heat exchanger bypass flows (here: none)

• Subtract states that must be controlled, but have no steady-state effect
  – Here, these are the six propane vaporizer levels
DOF for optimizing operation

• We have $12 - 6 = 6$ degrees of freedom available.
• Some used to control active constraints
• Remaining variables used to optimize operation
Disturbances and inputs

• The disturbances \((d)\) are the cooling temperature, feed pressure and feed composition
  – If the model is altered to include heat loss to surroundings, the ambient temperature is also to be considered a disturbance
• MR composition might also vary due to leaks
• The physically manipulated variables \((u)\) in the process are the valve openings and compressor speeds
Optimum for nominal conditions

- Assume natural gas feed is 50 kmol/s
- Propane pressures are 5.5 bar, 3.15 bar and 1.1 bar
- MR compressor exit pressure: 46 bar
- MR pressure in cold end: 4.85 bar
- MR composition:
  - 47.5 % CH4, 42.5 % C2H6, 2.0 % C3H8, 8.0 % N2
- Propane flows:
  - 12.1 kmol/s in natural gas precoolers
  - 61.4 kmol/s in MR precoolers
- Total MR flow: 101.5 kmol/s
Active constraints

• Temperature of natural gas leaving main HEX
• Superheating of propane out of the two low-pressure propane boilers

• That gives 3 active constraints
  – Maximum utilization of sea water cooling is already assumed an active constraint and accounted for in model
Controlled variables

- The three active constraints
- For the last three, look for self-optimizing variables
Self-optimizing control

- The idea is: Choose to control variables that, when controlled at a constant set point, give acceptable loss when disturbances occur
Method of selecting variables

- Maximum scaled gain rule (Alstad and Skogestad):
  - We want our controlled variable(s) to be sensitive to changes in manipulated variables
  - We want the variation in optimal value to be small.

- That is – choose variables where $G_{scaled} = G/\text{span}(c)$ is large
  - $G$ is process gain
  - Span is sum of optimal variation and implementation error
Selection continued

- Examine the best candidates from maximum scaled gain method by using exact local method (Halvorsen et. al.)
What is required?

• The nominal optimum must be known (given the design of the plant)
• The cost function must be evaluated as a function of disturbances, for different choices of controlled variables \( c \)
  – We assume that active constraints are controlled.
• The process must also be reoptimized with the candidate variable free to vary, to find the optimal variation in \( c \).
Challenges in optimization

• Model is not robust to all variable changes
• Many constraints
  – Minimum temperature approach – in the model this sums up to 8 constraints
  – Superheating of compressor feed streams
  – Active set may change frequently
Further work

• Make model more robust to make optimization easier (fewer model evaluation failures)
• Complete the analysis outlined in this presentation
  – Reoptimize for disturbances
  – Calculate scaled gain for potential controlled variables