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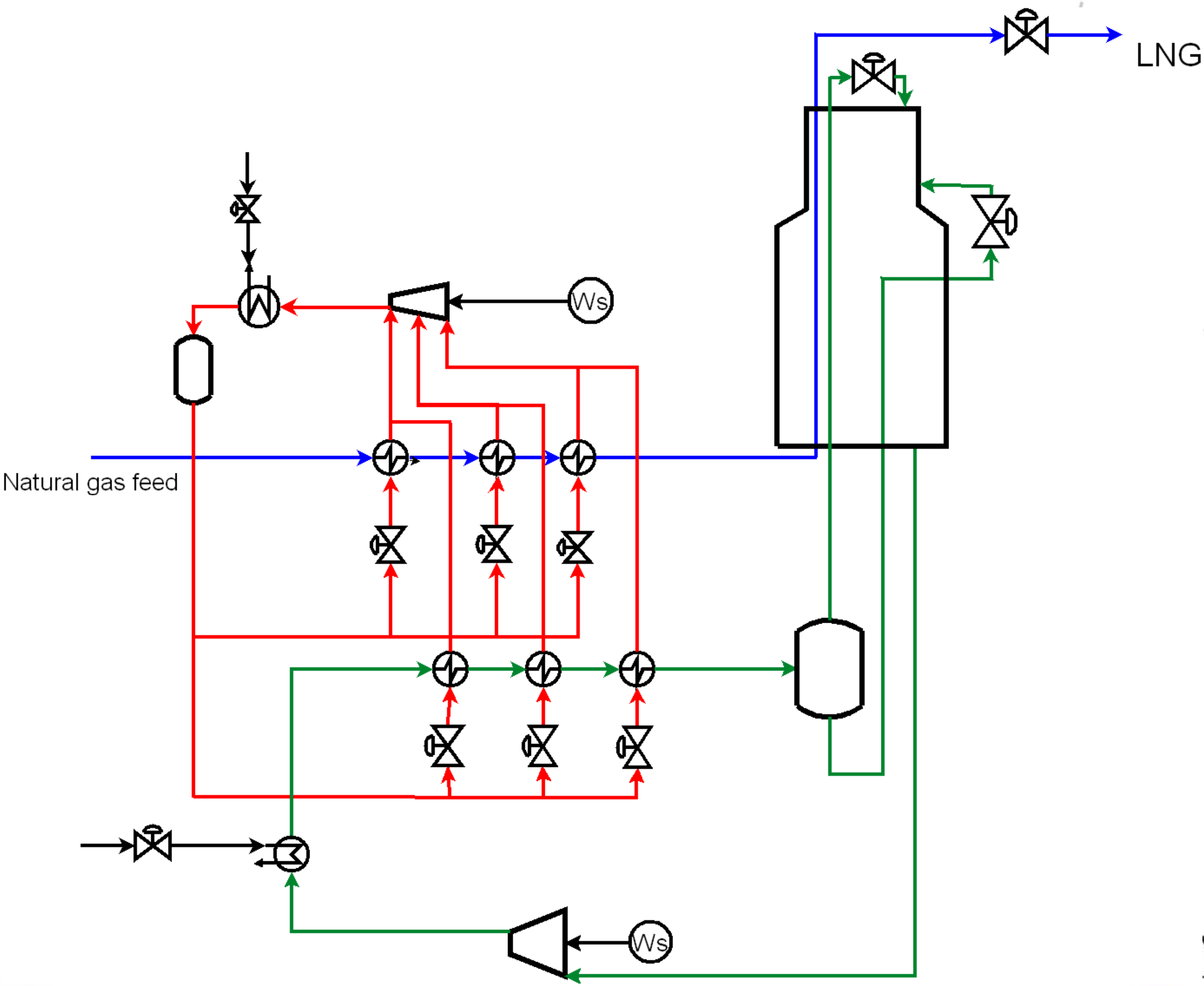
Optimal selection of controlled variables for the C3-MR process for liquefaction of natural gas

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



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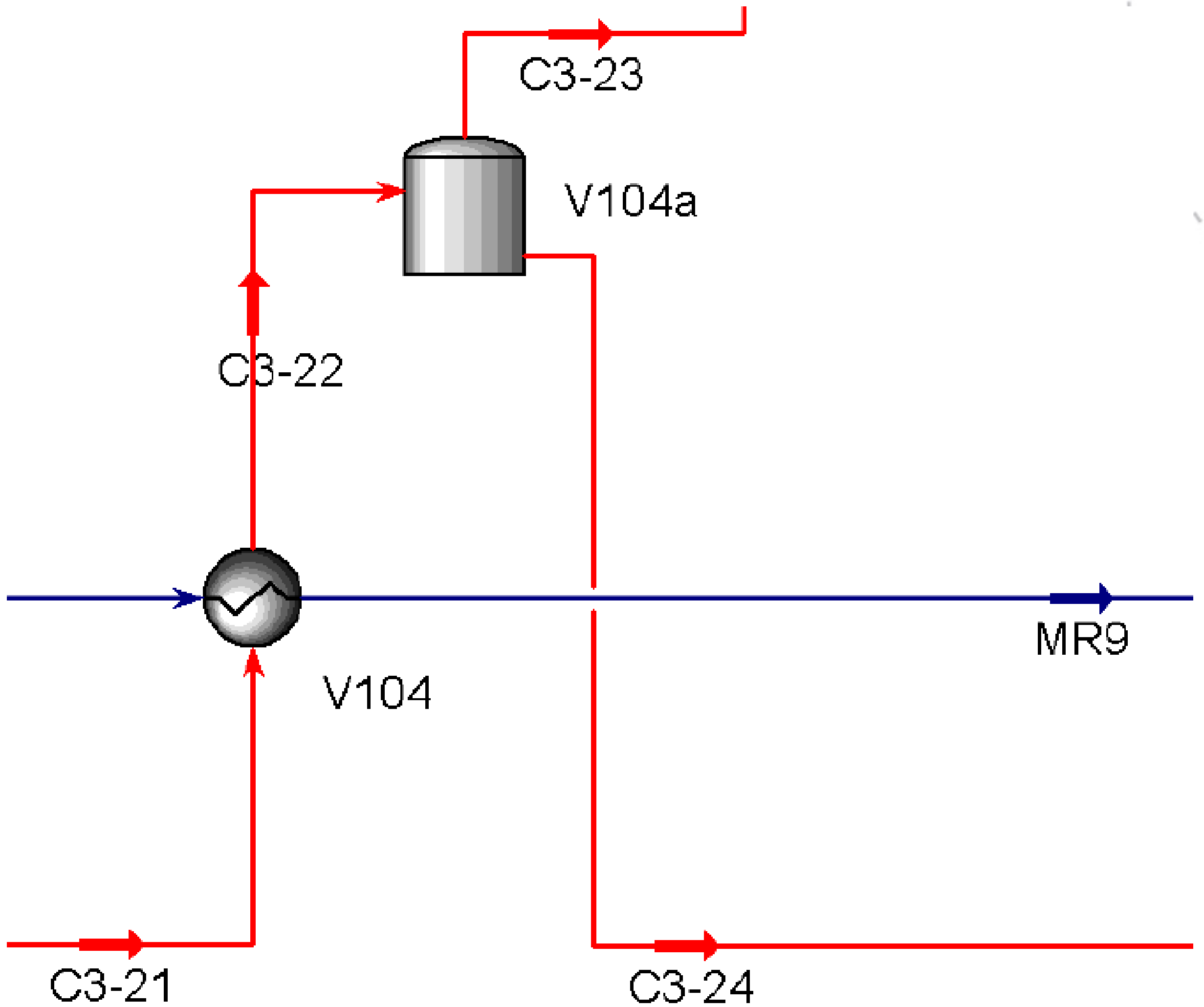
Modelling framework

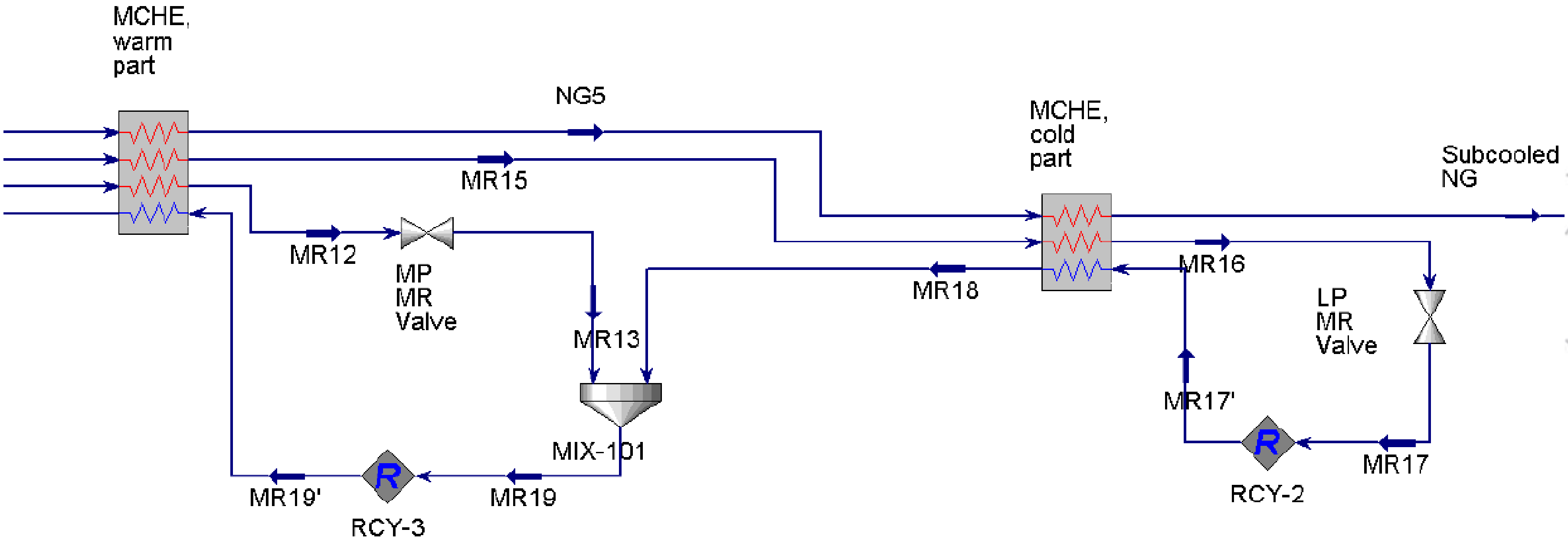
Models have been constructed in two different programs.

- Unisim (from Honeywell, sucessor 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.


C3-23
V104a
C3-22
V104
MR9
C3-21
C3-24


MCHE,
warm
part
NG5
MR15
MR12
MP
MR
Valve
MR13
MIX-101
MR19
RCY-3
MR19'
MCHE,
cold
part
MR18
MR16
LP
MR
Valve
Subcooled
NG
MR17'
RCY-2
MR17

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 presure: 46 bar
- MR pressure in cold end: 4.85 bar
- MR composition :
  - 47.5 % CH_4, 42.5 % C_2H_6, 2.0 % C_3H_8, 8.0 % N_2
- 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

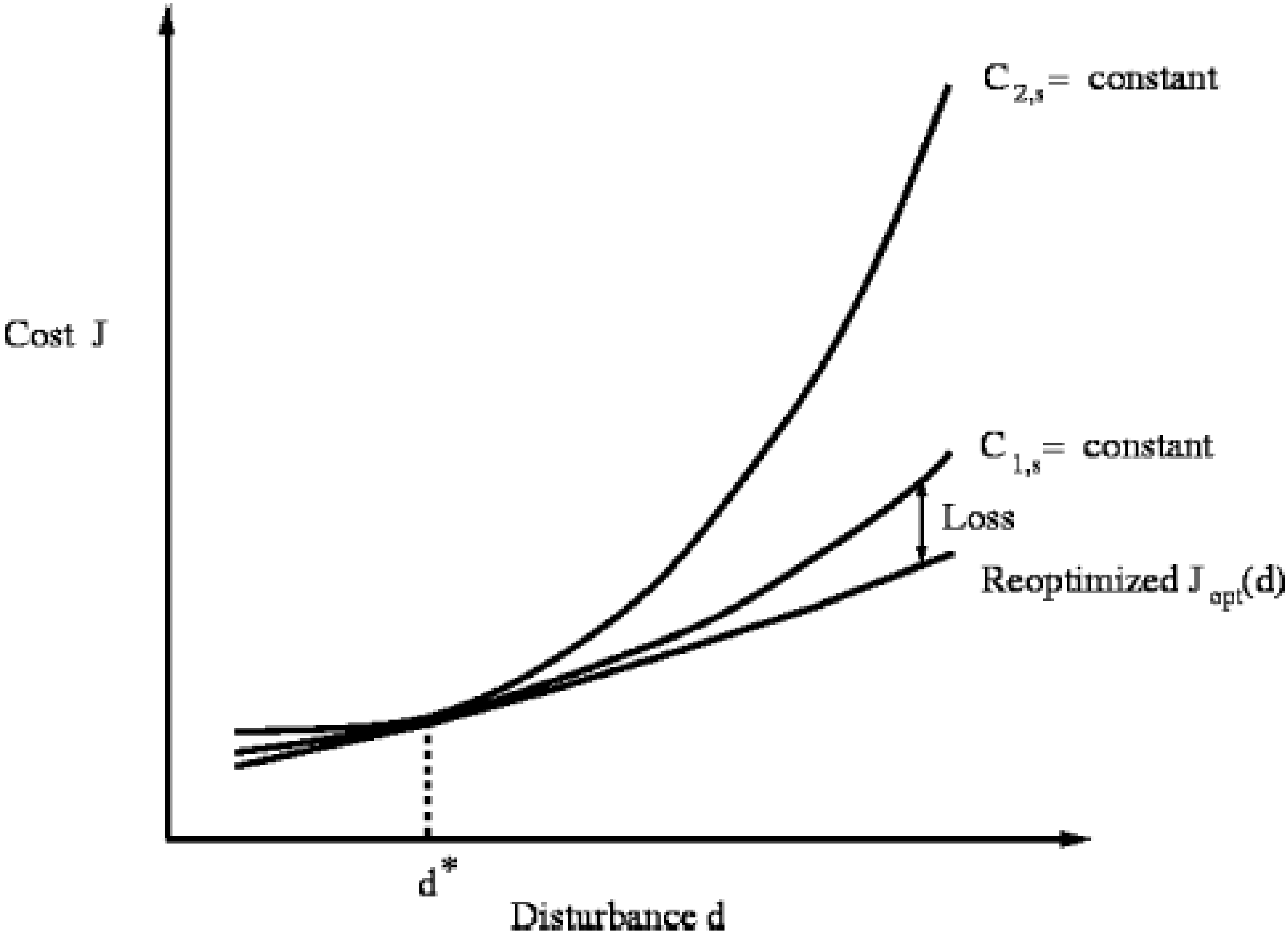
- That gives 3 active constraints
  - Maximum utilization of sea water cooling is already assumed an active constraint and accounted for in model

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


Cost J
C 2,s = constant
C 1,s = constant
Loss
Reoptimized J opt(d)
d*
Disturbance d

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

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Selection continued

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

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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

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