Active constraint regions for optimal operation of a simple LNG process

Magnus G. Jacobsen and Sigurd Skogestad
Department of Chemical Engineering
NTNU
Trondheim, Norway

2nd Trondheim Gas Technology Conference
November 3rd, 2011

NTNU
Norwegian University of Science and Technology

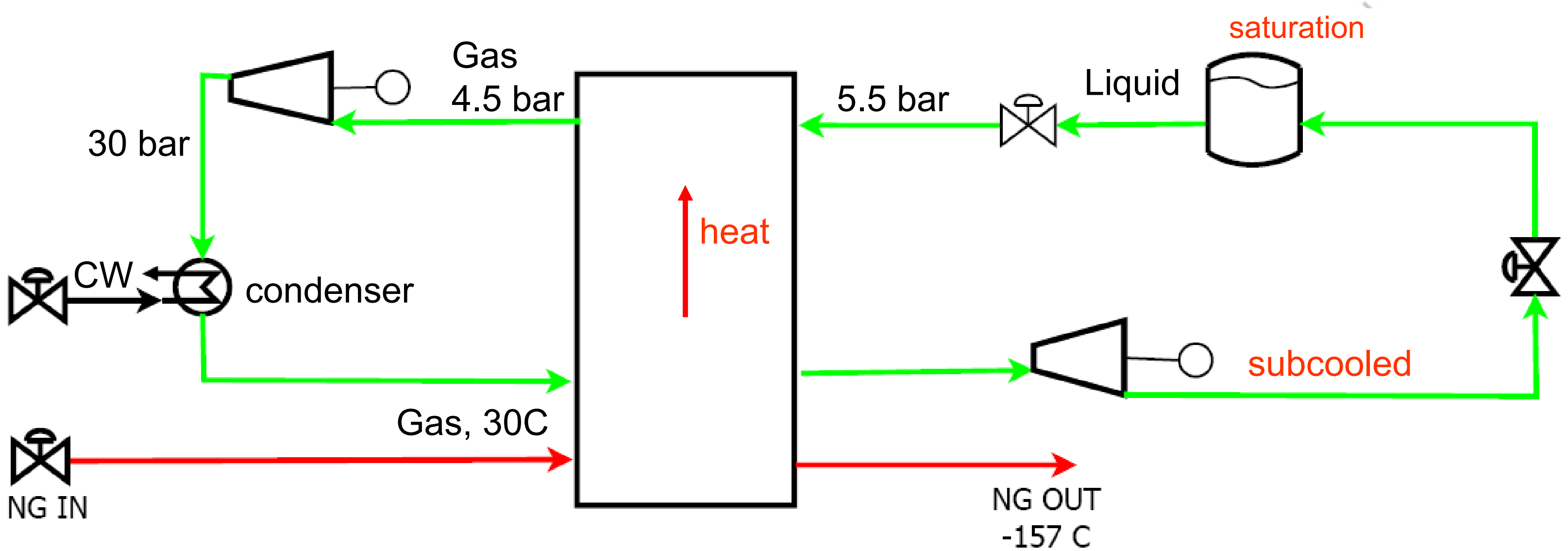
Active constraint regions for a simple liquefaction process.

OUTLINE:

- The PRICO process
- Modelling
- Definition of optimal operation
  - Minimize compressor work
  - Degrees of freedom
  - Constraints
- Optimal operation
  - Active constraint regions as a function of disturbances in feedrate and ambient temperature
- Control

The PRICO process

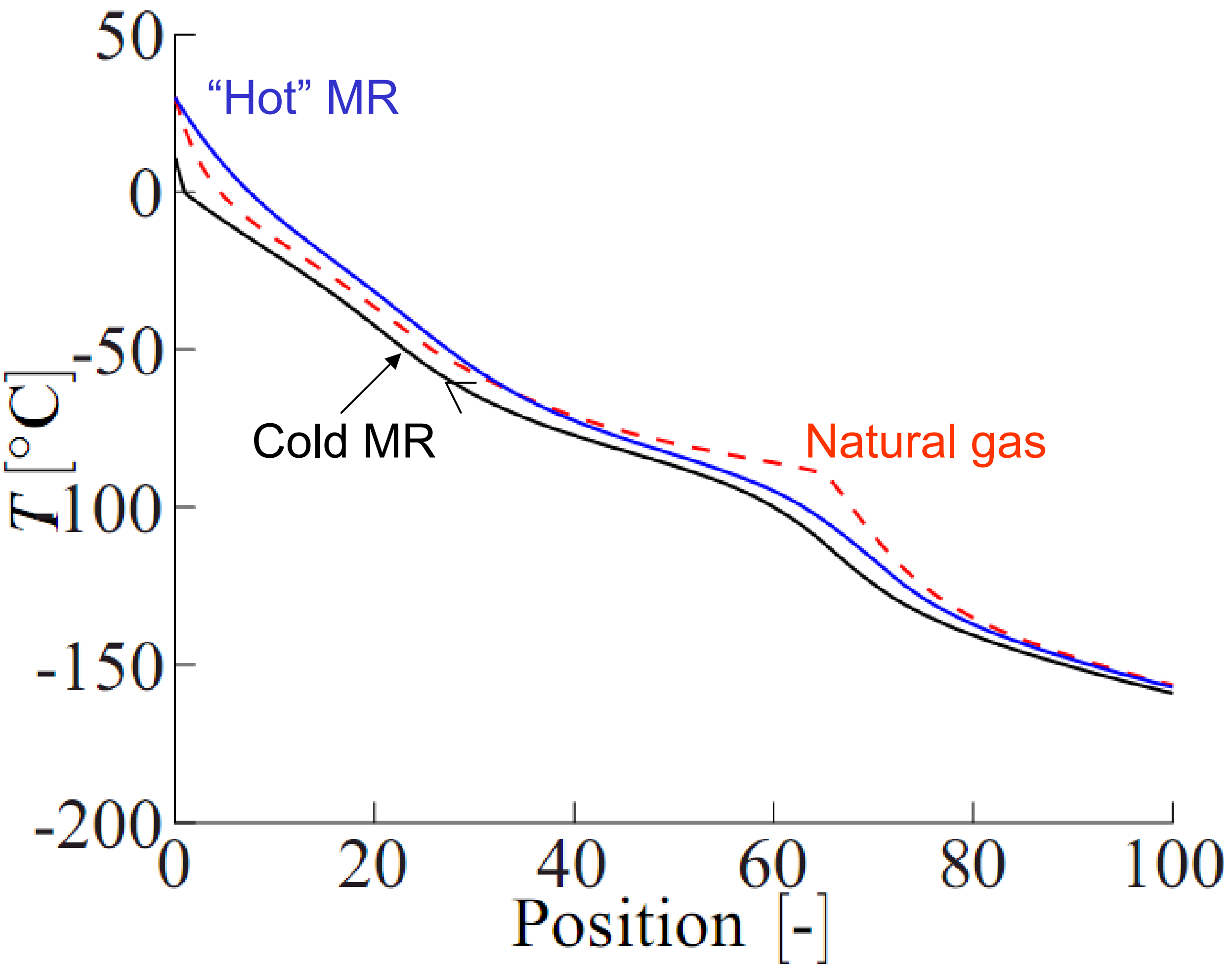
- Simple LNG liquefaction process with one multi-stream heat exchanger and a mixed refrigerant



Natural gas (NG): 90% C1, 5% C2, 2% C3, 0.1% C4, 3% N2 (mole-%)
Mixed refrigerant (MR): 33% C1, 34%C2, 0% C3, 23% C4, 10% N2

NTNU
Norwegian University of Science and Technology

Temperature profile in main heat exchanger



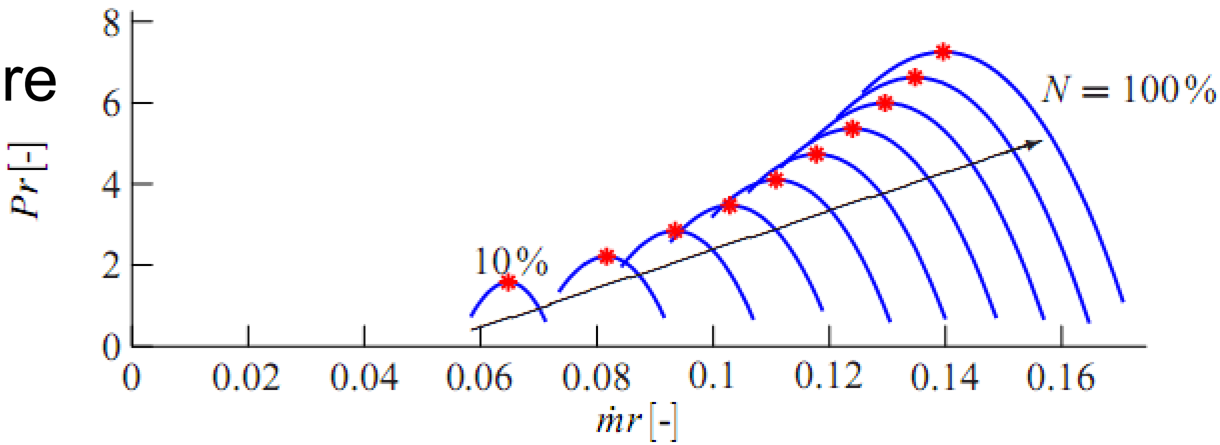
Modelling

- Unisim flowsheet simulator (Honewell) = Hysys (Aspen)
- SRK equation of state
- Data from Jensen and Skogestad (Adchem 2006)
  - Natural gas feed (1517 kmol/h, 40 bar, 30C): 90% C1,5% C2, 2% C3, 3%N2
  - Mixed refrigerant (6930 kmol/h): 33% C1, 34%C2, 0% C3, 23% C4, 10% N2
  - Cycle pressures: About 30 bar and 5 bar
  - Compressor speed = 1000 rms
  - Given compressor characteristics

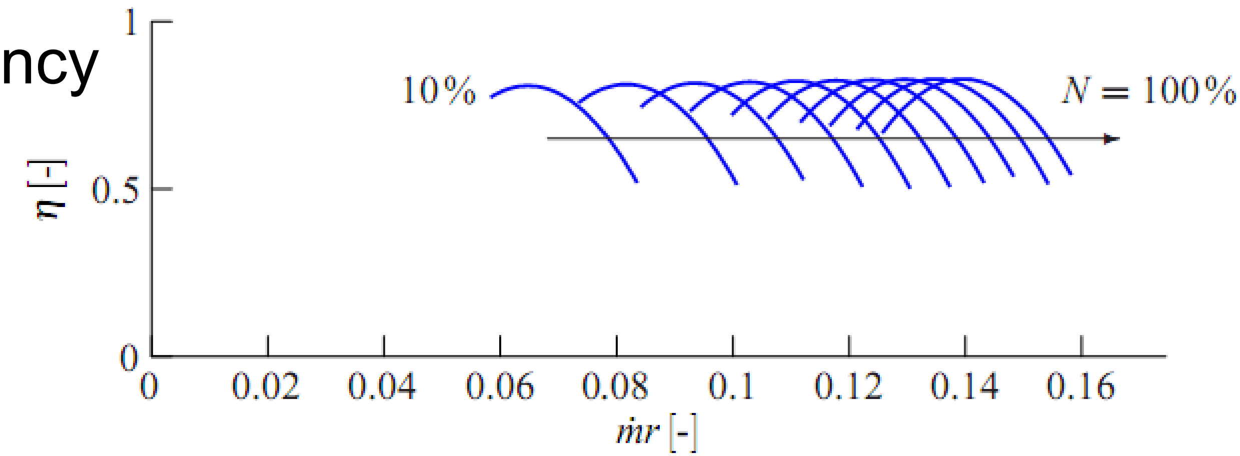
NTNU
Norwegian University of Science and Technology

Compressor map as function of speed (N) and MR flowrate

Pressure ratio



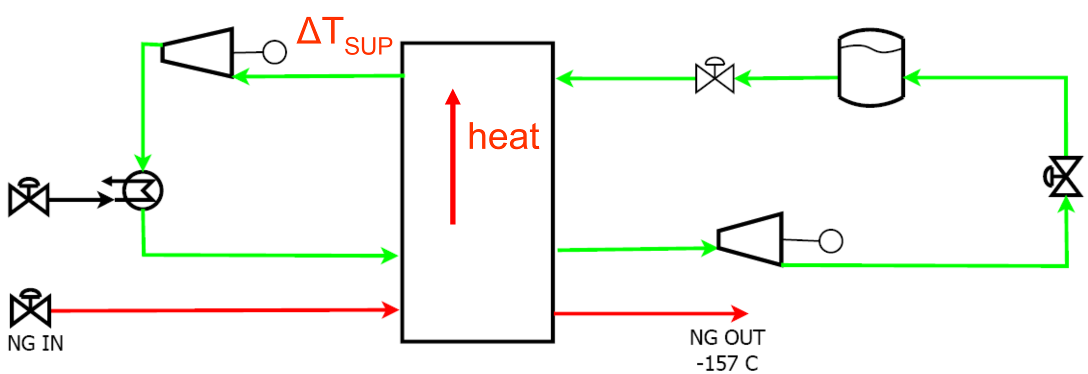
Efficiency



Key variables (nominal conditions)

Variable	This work	Jensen's work*
W_s [MW]	119	120
Compressor outlet pressure [bar]	30.2	30.0
Compressor efficiency η	81.8	82.8
ΔT_{sup} [°C]	5.1	11.3
$\Delta T_{min,HX}$ [°C]	1.57	
UA_{NG} [kW/°C]	$9.20 \cdot 10^3$	$8.45 \cdot 10^3$
UA_{MR} [kW/°C]	$4.62 \cdot 10^4$	$5.32 \cdot 10^4$

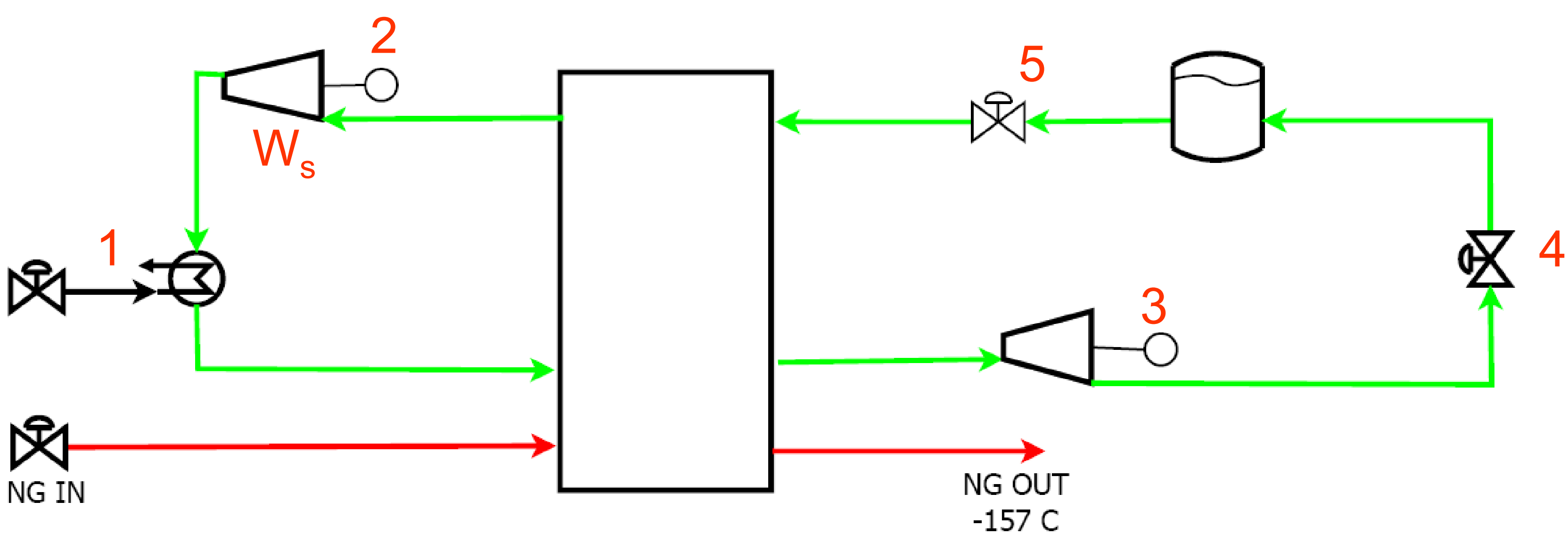
*gProms



NTNU
Norwegian University of Science and Technology

Optimal operation

- Equipment fixed (UA-values, compressor map)!
- Optimization objective: Minimize compressor work (cost J = W_s)
- Five degrees of freedom for operation:
  1. Amount of cooling in condenser (assumed at max)
  2. Compressor speed
  3. Turbine speed
  4. Choke valve opening
  5. Active charge (level in liquid receiver)



y of
ogy

Constraints for operation

1. Refrigerant to compressor must be superheated, $\Delta T_{sup} > 5°C$
2. Compressor must not operate in surge, $\Delta M_{surge} > 0$
3. Maximum compressor work, $W_s \leq 132MW$
4. Turbine exit stream must be liquid only, $\Delta P_{sat} > 0$
5. Maximum compressor speed: $\omega_{comp} \leq \omega_{max} = 1200rpm$

+ Exit temperature for natural gas, $T_{NG,out} \leq -157°C$ (always active)
+ constraints on fully closed or open valves (cooling assumed at max)

-> 5 CONSTRAINTS + REMAIN TO BE CONSIDERED
+ 3 UNCONSTRAINED DOFs

NTNU
Norwegian University of Science and Technology

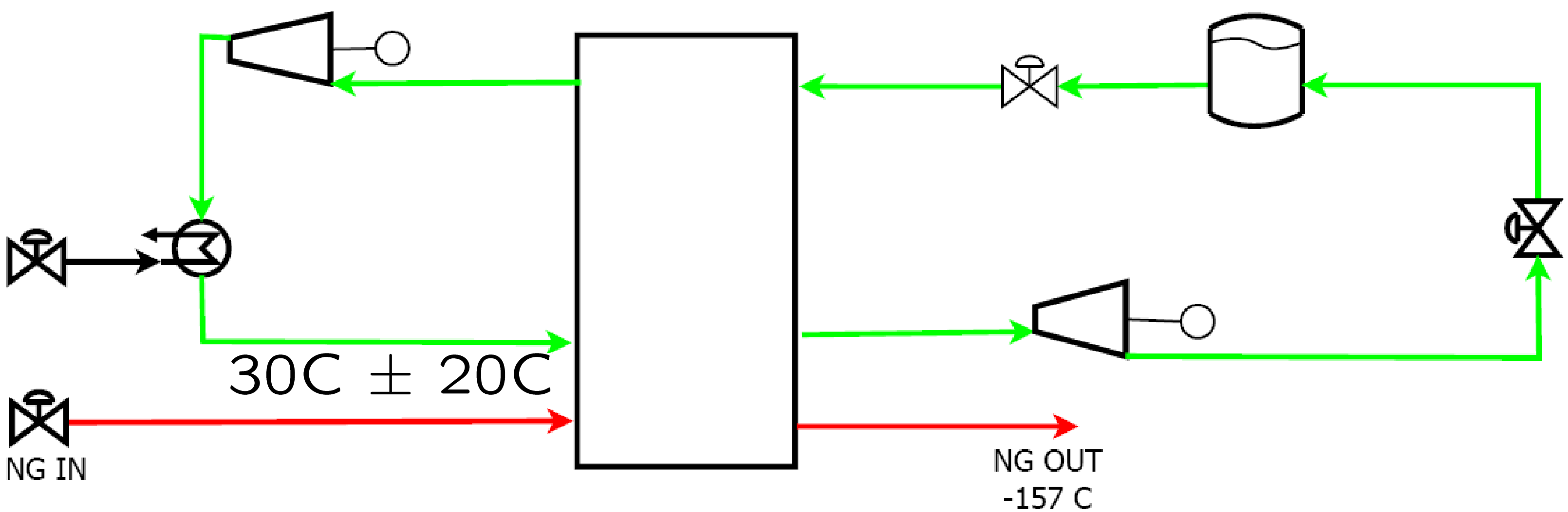
Optimal operation with compressor speed as DOF (nominal feedrate)

Variable	This work	Jensen's work
MR flow rate [kmol/s]	16.94	18.70
Compressor speed ω [rpm]	1143	1000
Compressor inlet pressure [kPa]	383.2	414.0
Turbine outlet pressure [kPa]	552.5	1029
Compressor inlet T [°C]	15.8	N/A
T_{MR} **at HX outlet [°C]**	-163.9	-157.0
T_{NG} **at HX outlet [°C]**	-157.0	-157.0
Compressor work W_s [MW]	116.4	120.0
ΔT_{sup} [°C]	19.4	11.3
$\Delta T_{min,HX}$ [°C]	0.7	N/A
Compressor efficiency η	82.1	82.8
$\Delta M_{\mathrm{surge}}$ [%]	0	0
ΔP_{sat} [kPa]	1.1	20

1 (of 5) active constraint

Want optimal operation also for disturbances

- NG feed flow rate [mol/s] , +- 20%
- Ambient temperature [°C] – or actually cold inlet temperature to HEX for NG and MR (nominally 30C)

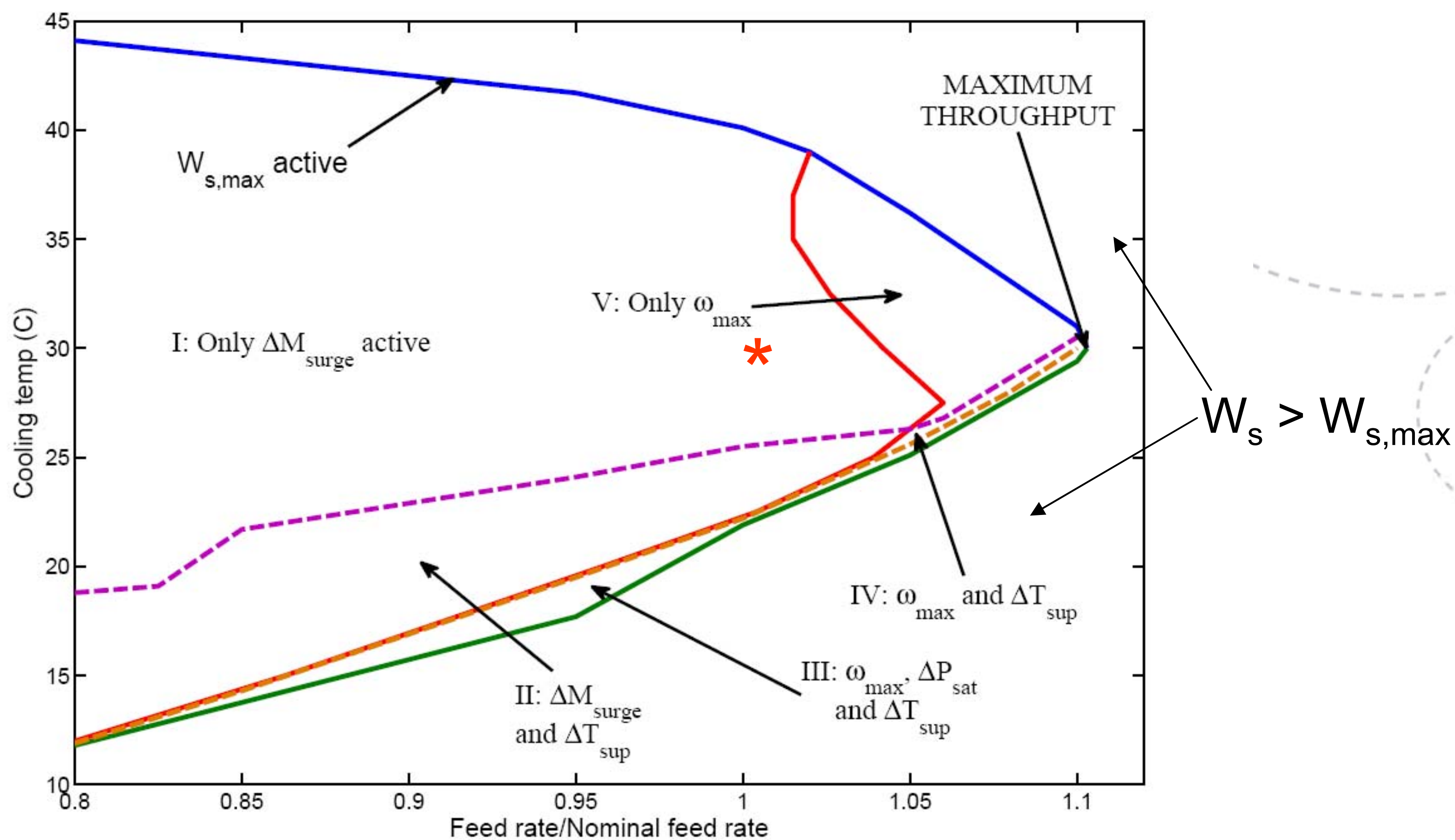


How do active constraints change?

- Have 3 DOFs and 5 constraints
  - $\Delta T_{sup,}$, $W_{s,}$ $\Delta P_{sat,}$ ω_{comp}
- 26 possible constraint combinations (of 3 or less)
- Only 5 combinations (”regions”) found in our simulations:
  - I. ΔM_{surge} is active
  - II. ΔT_{sup} and ΔM_{surge} are active
  - III. ΔT_{sup}, ΔP_{sat} and ω_{max} are active
  - IV. ΔT_{sup} and ω_{max} are active
  - V. ω_{max} is active

NTNU
Norwegian University of Science and Technology

Constrains regions for PRICO process



Upper blue line: Cannot exceed $W_{s,max}$ since we minimize $J=W_s$

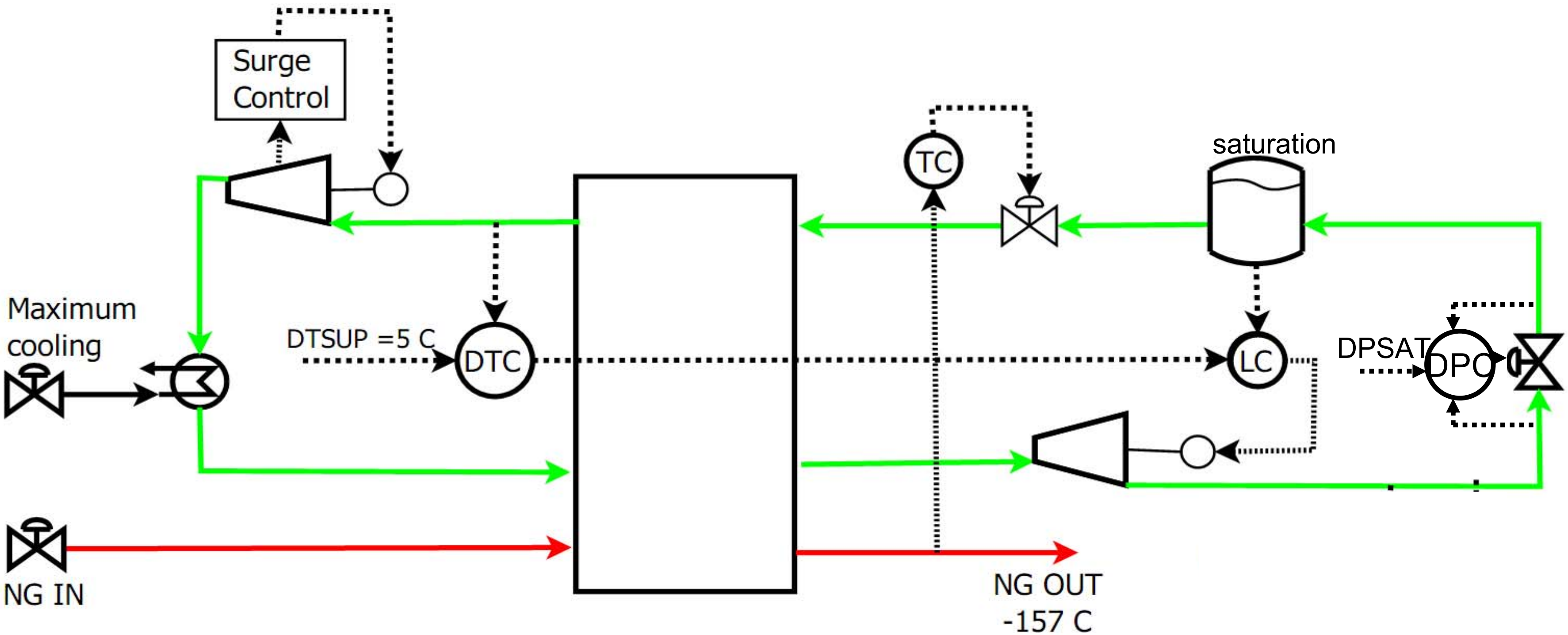
Lower green line: Too cold to get supersaturation > 5C…
cool less or adjust MR composition

Control of PRICO process

- 5 regions → 5 control structures?
- ΔP_{sat} is optimally close to zero in all regions
  - Keep at zero to simplify
- Surge margin and max speed: closely connected (switch)
  - Use compressor speed to control ΔM_{surge} when $\omega_{opt} < \omega_{max}$
- We can use two control structures!
  - One for Regions I and V (where ΔT_{sup} is inactive)
  - One for Regions II, III and IV (where ΔT_{sup} is active)

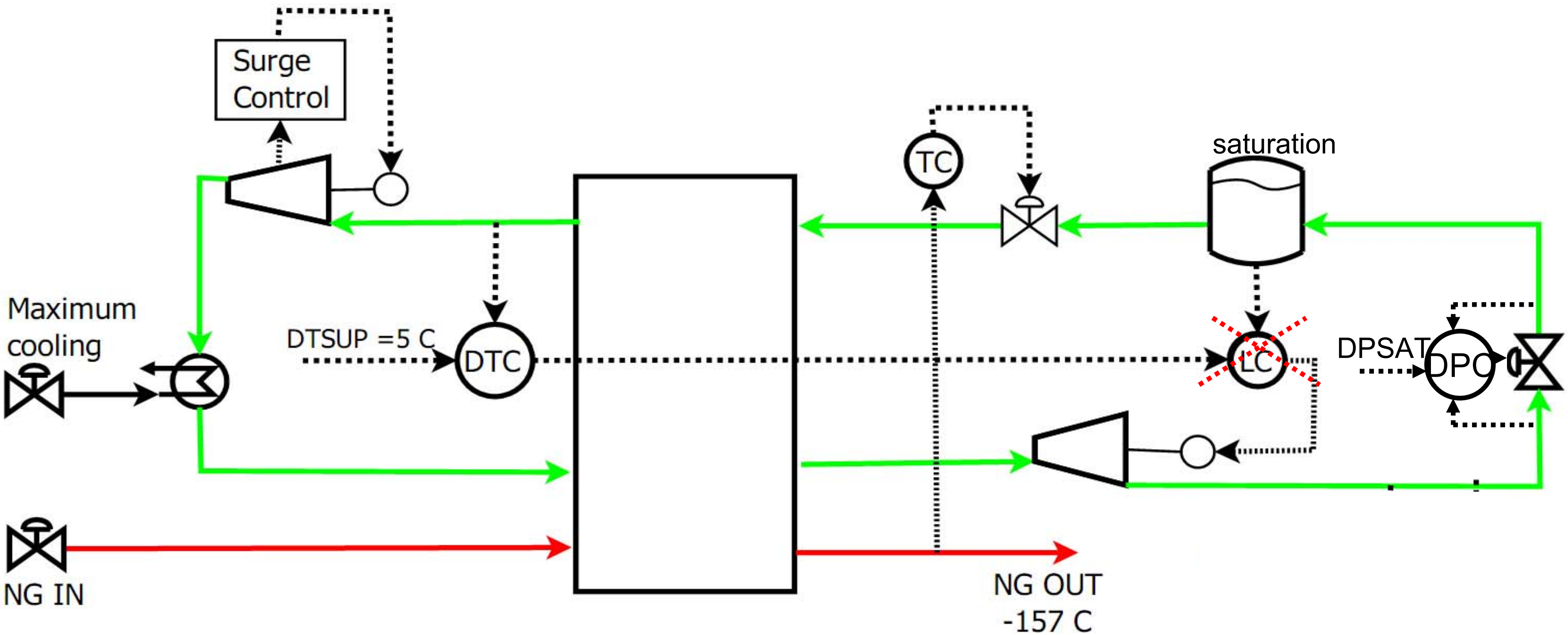
NTNU
Norwegian University of Science and Technology

Control structure



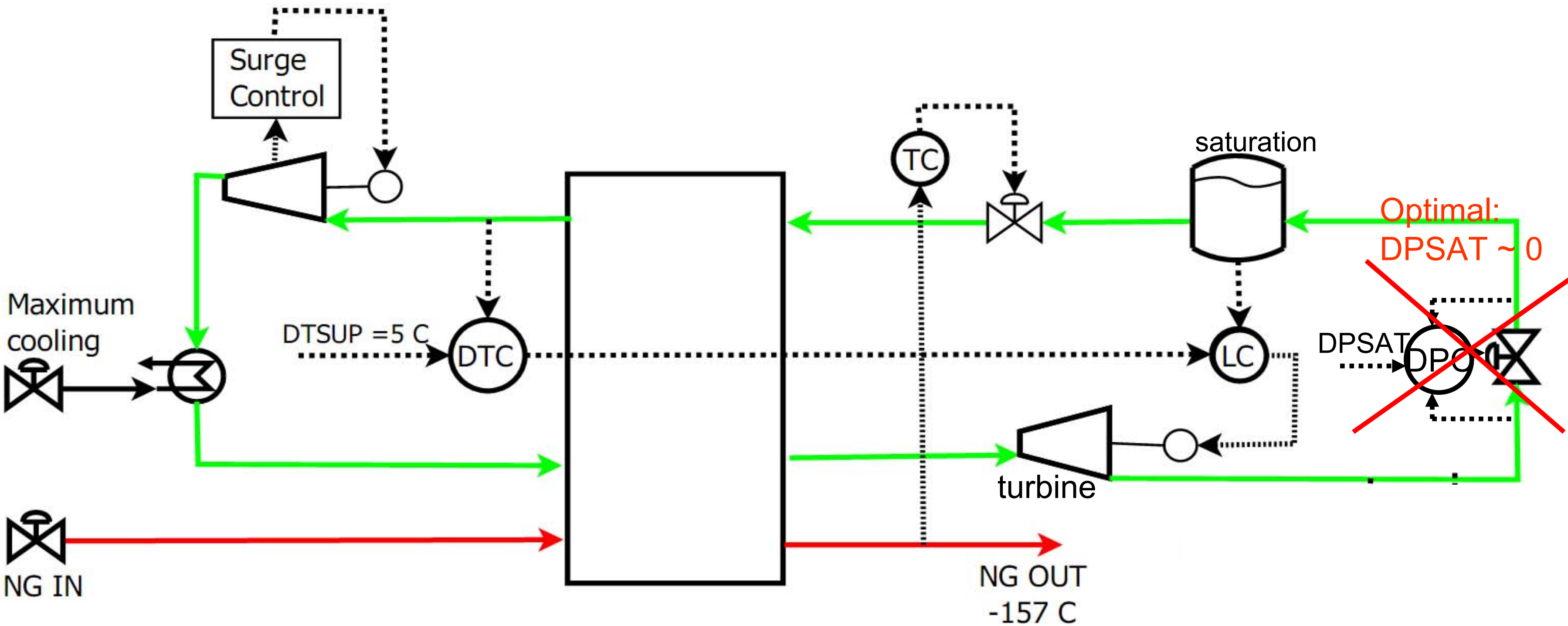
NTNU
Norwegian University of Science and Technology

Control structure



But: Constant level assumed used as self-optimizing variable when constraint on DTSUP is not active

Control structure



But: DPSAT >0 (and valve) may be needed to make sure we have no vapor in turbine

NTNU
Norwegian University of
Science and Technology

Conclusions

- Optimization of PRICO LNG-process (Unisim/Hysys)
- Optimal operation (given UA-values + compressor) is often not same as optimal design
- Propose simple control structure to achieve optimal operation for disturbances in feed rate and temperature
- Still remains: Find self-optimizing variable when constraint on ΔT_{SUP} is not active