Application of a Plantwide Control Design Procedure to a Distillation Column with Heat Pump

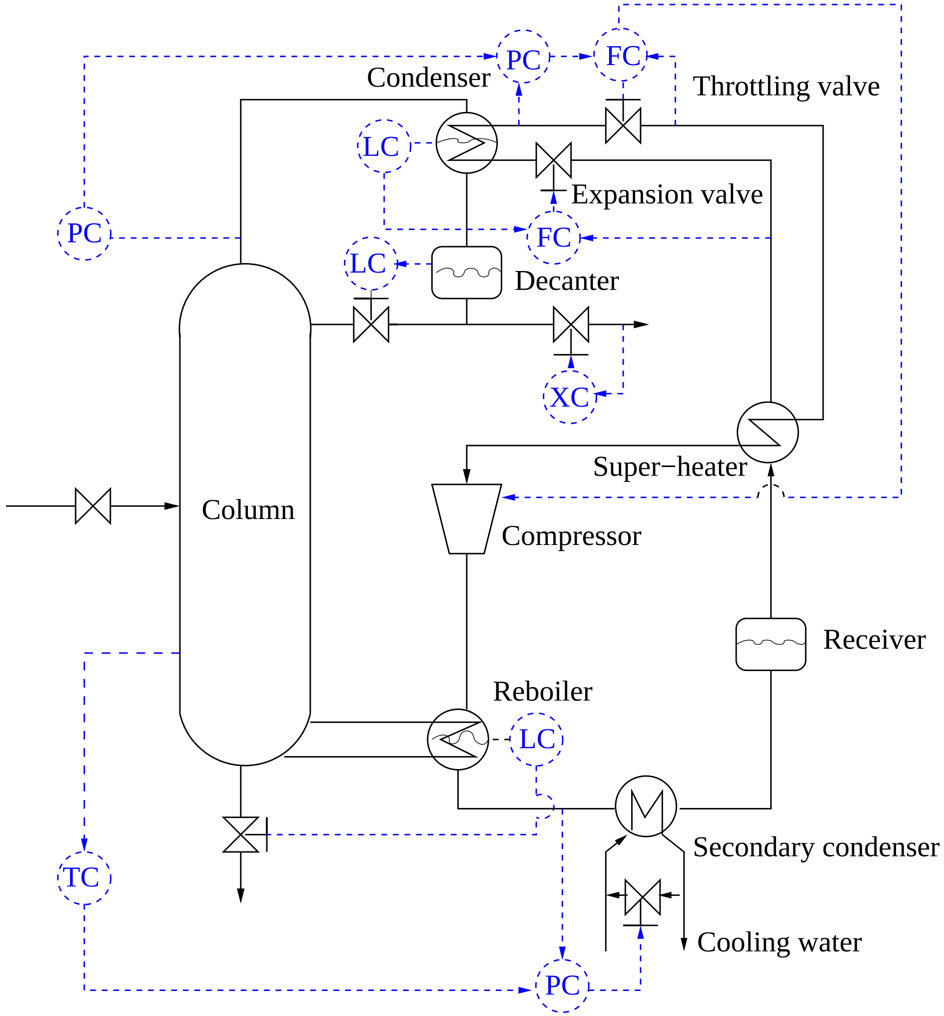
M. S. Govatsmark[1], *S. Skogestad*[1],
G. Sobočan[2], *P. Glavič*[2]

[1]*Department of Chemical Engineering, NTNU*
[2]*University of Maribor, Faculty of Chemistry and Chemical Engineering*

Outline

- Distillation column with heat pump
- Plantwide control
- Plantwide control procedure
- Application
- Concluding remarks

Distillation column with heat pump (Koggersbøl,1995)



Plantwide Control

Structural decisions of the control system for an overall plant

Important questions:

1 Which variables to control?

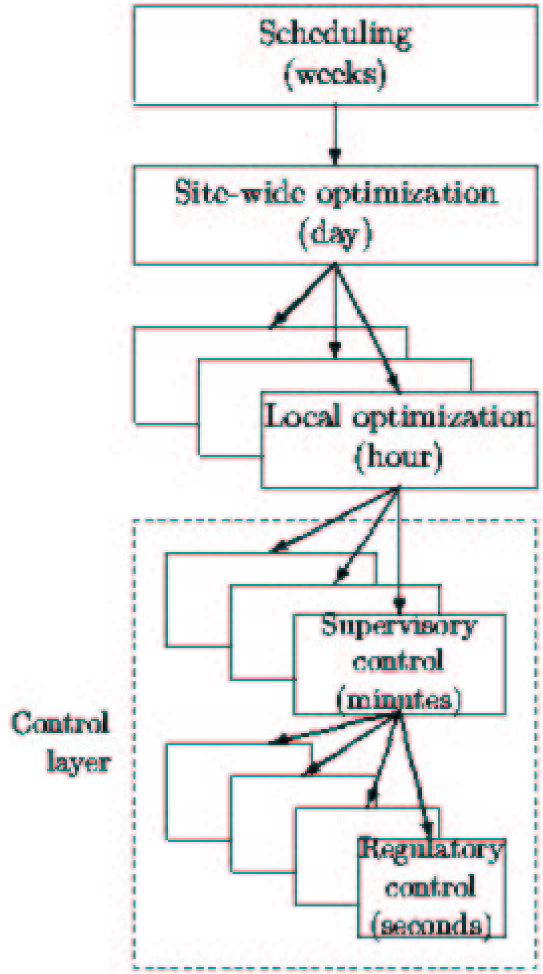
2 Which variables to manipulate?

3 Which control configuration?

4 Which controller type?

Difficult:

Integrated processes



Plantwide Control Procedure (Larsson and Skogestad,2000)

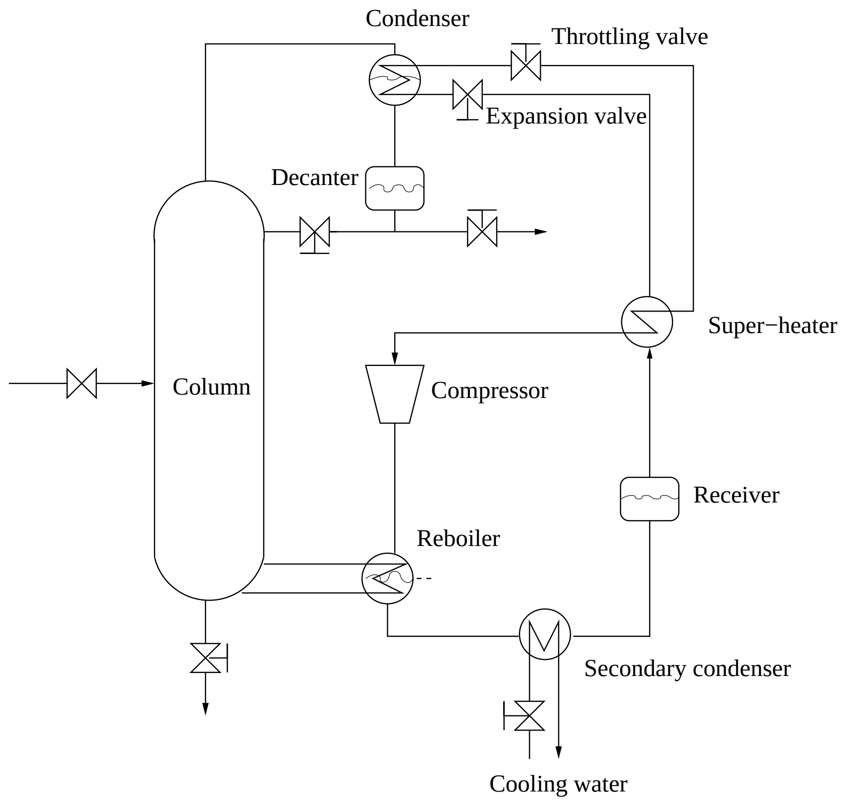
I. Top down analysis

1. Manipulated variables
2. Degree of freedom analysis
3. Primary controlled variables (steady-state economics)
4. Production rate manipulator

II. Bottom up design of the control system

5. Structure of regulatory control layer (secondary control variables)
6. Structure of supervisory control layer (MPC applications)
7. Structure of optimization layer

Step 1. Manipulated variables: 6
Step 2. Steady-state degrees of freedom: 3



DOF: 6-3(levels without steady-state effect)=3

Step 3. Primary controlled variables

3.1 Degrees of freedom for optimization

3.2 Define optimal operation (cost and constraints)

3.3 Identification of important disturbances

3.4 Optimization

3.5 Identification of candidate controlled variables

3.6 Evaluation of loss

3.1 Degrees of freedom for optimization: 3

3.2 Define optimal operation

Maximize profit

$$-J = D - 0.001 W_{comp}$$

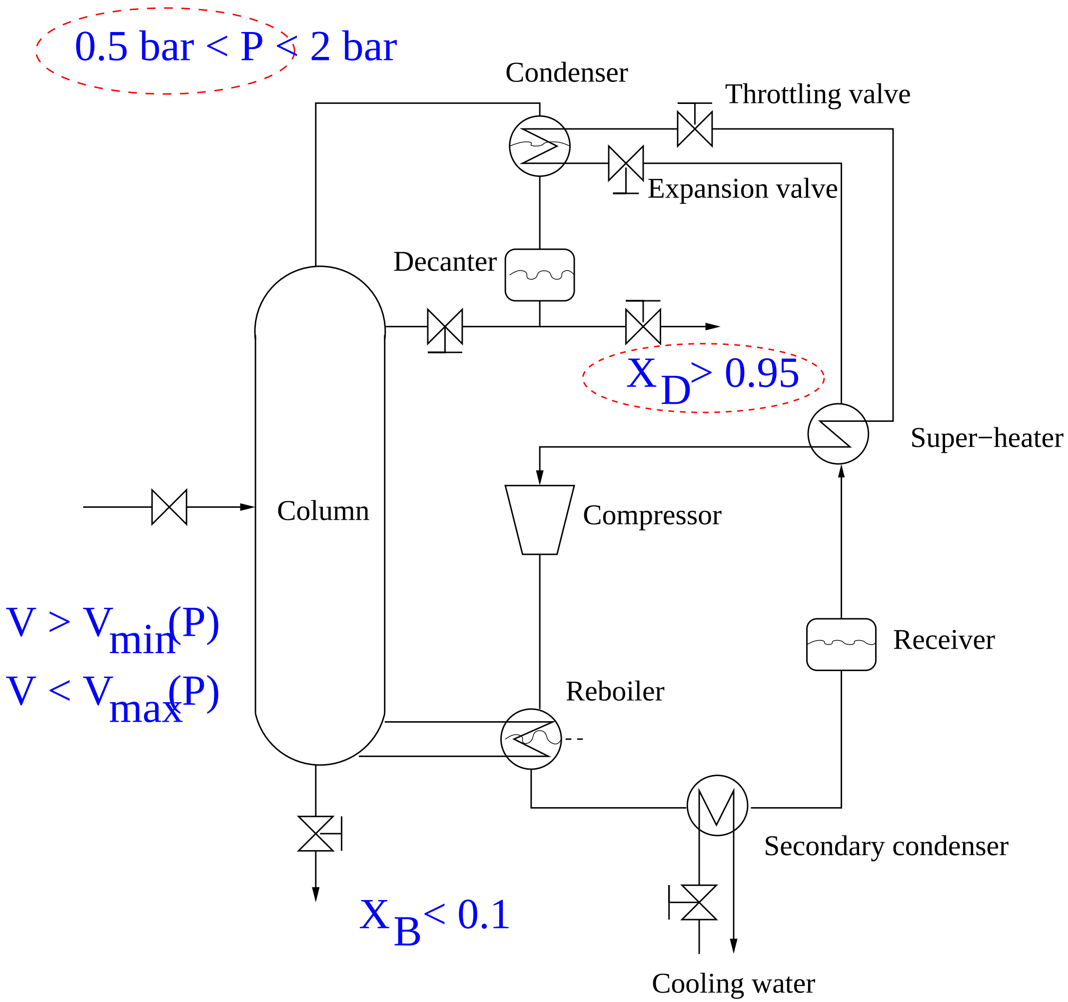
Constraints:

$$\begin{aligned} x_D &\geq 0.95 \text{ mol/mol} && \text{active} \\ x_B &\leq 0.10 \text{ mol/mol} && \\ p_{column} &\leq 2 \text{ bar} && \\ p_{column} &\geq 0.5 \text{ bar} && \text{active} \\ V &\leq V_{max}(p) && \\ V &\geq V_{min}(p) && \\ Flows &\geq 0 && \end{aligned}$$

3.3 Disturbances:

$$d = [F \;\; z_F] = [51.27 \pm 10.25 mol/min \;\; 0.5 \pm 0.1 mol/mol]$$

3.4 Optimization: 2 optimal active constraints


0.5 bar < P < 2 bar
Condenser
Throttling valve
Expansion valve
Decanter
$X_D > 0.95$
Super−heater
Column
Compressor
$V > V_{min}(P)$
$V < V_{max}(P)$
Receiver
Reboiler
Secondary condenser
$X_B < 0.1$
Cooling water

Step 3.5: Identify candidate controlled variables

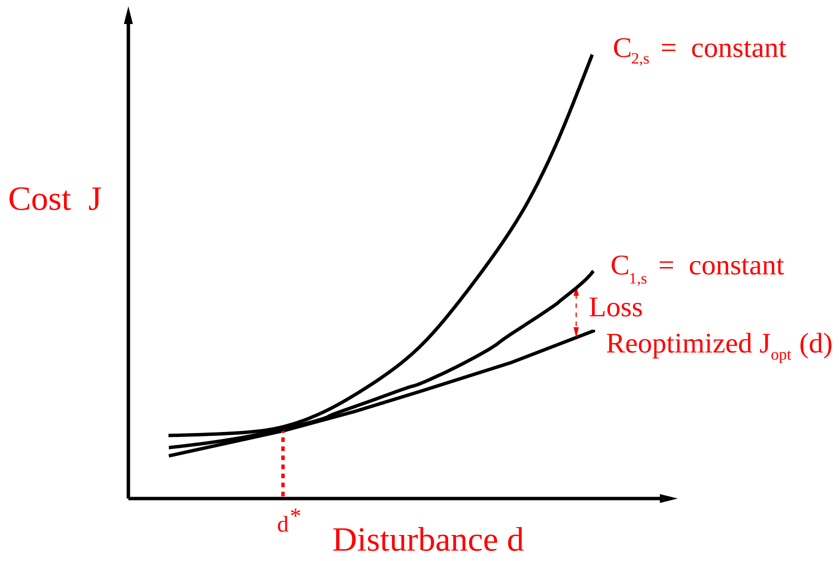
Use active constraint control $\Rightarrow$ 3-2= 1 unconstrained variable

Candidates	Implementation error
Composition	±0.01%
Flowrates	±10%
Pressures	±2%
Temperatures	±0.2^{o}C
x_D	±0.005%

Which variable should be controlled?

Step 3.6 Loss evaluation with nominal setpoints

Rank	Alt./c_3	Average loss
–	On-line opt.	0.89%
1	x_3	0.93%
2	x_2	0.94%
3	x_4	0.94%
4	T_4	0.96%
5	T_3	0.96%
6	T_2	0.98%
7	x_5	0.98%
8	T_5	0.98%
9	x_1	0.99%
10	T_1	1.01%
11	T_6	1.05%
12	x_6	1.09%
13	T_7	1.09%
14	x_7	1.12%
15	T_8	1.21%
16	x_8	1.23%
17	P_H	1.32%
18	P_L	1.85%
–	T_9, x_9	Infeasible



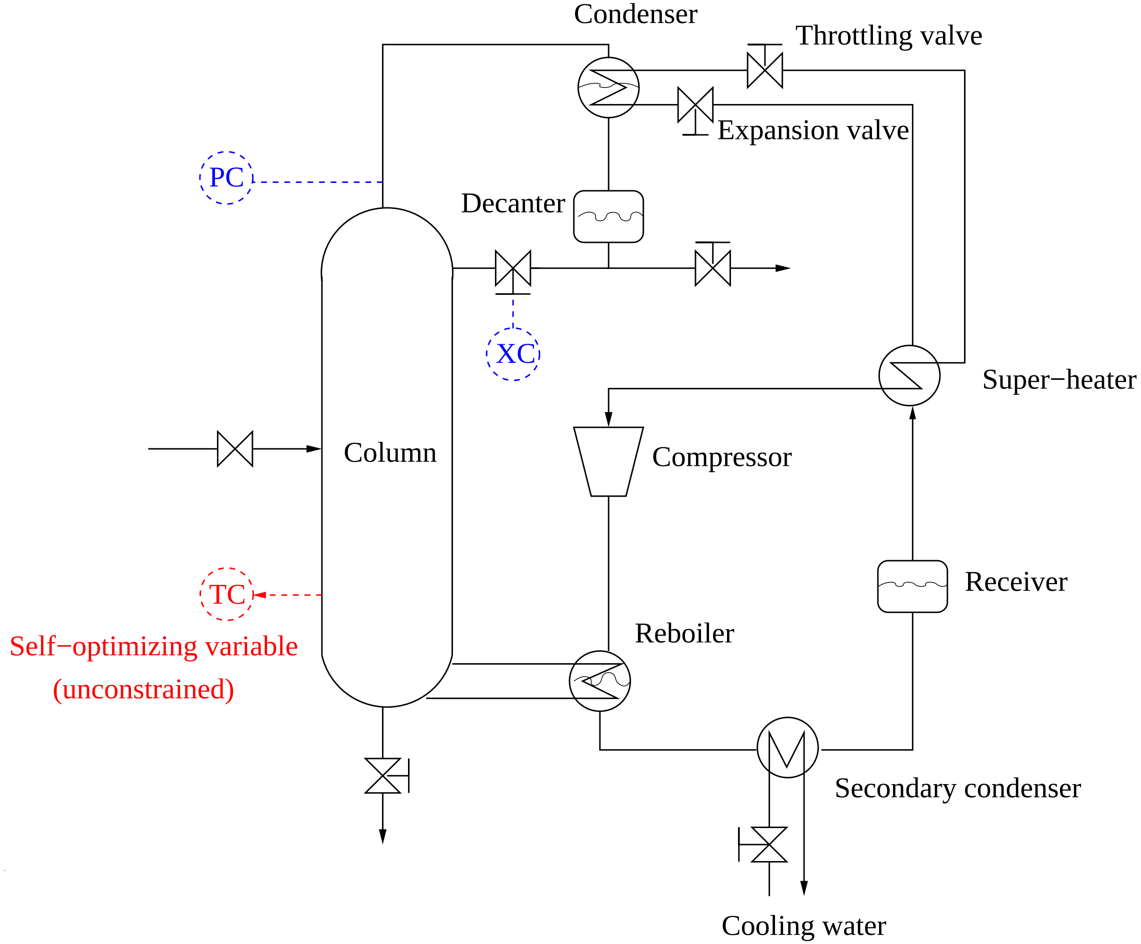
$$Loss = J(c_s + n, d) - J_{opt}(d)$$

Conclusion: Control T_4

Step 4. Production rate manipulator

The feed flowrate (F)

So far:



Condenser
Throttling valve
Expansion valve
PC
Decanter
XC
Super−heater
Column
Compressor
TC
Receiver
Self−optimizing variable
(unconstrained)
Reboiler
Secondary condenser
Cooling water

II: Bottom-up design of control system
Step 5. Structure of regulatory control layer

Stabilization:

Condenser drum holdup $\leftrightarrow$ Distillate flowrate

Reboiler drum holdup $\leftrightarrow$ Bottom product flowrate

LP heat pump drum holdup $\leftrightarrow$ Expansion valve flowrate

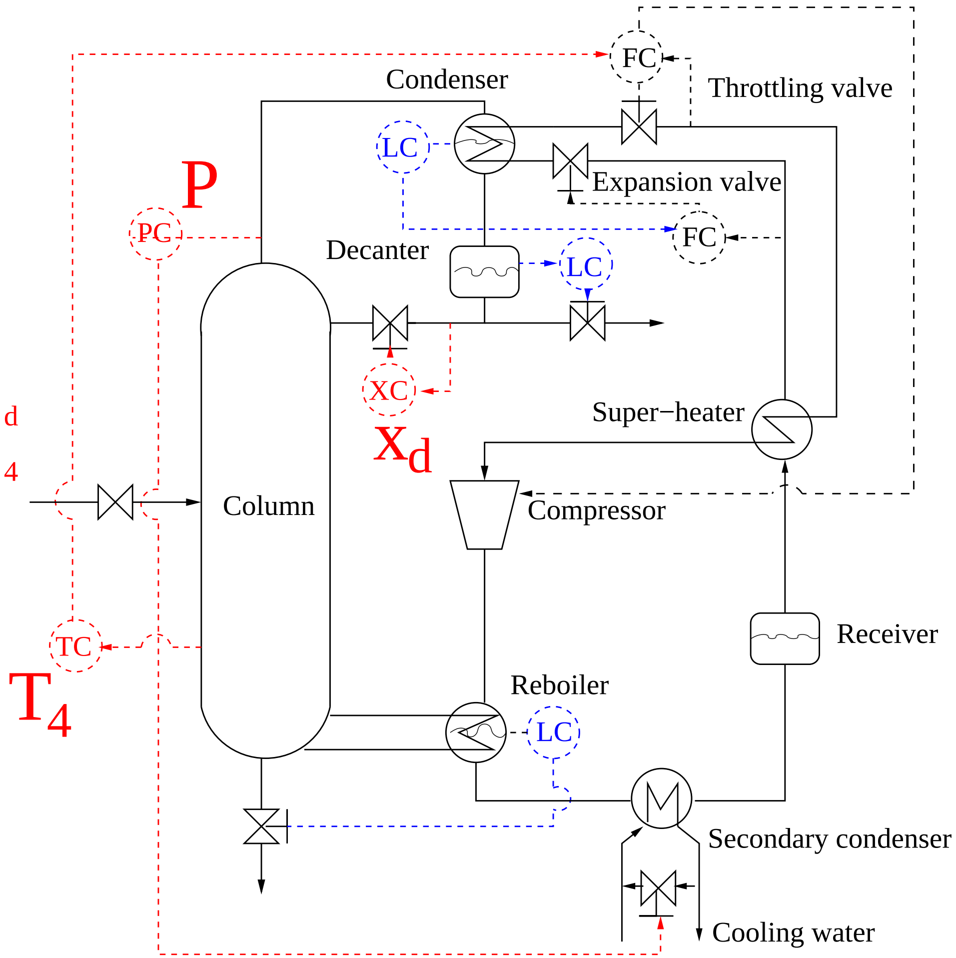
Local disturbance rejection: Use local flow controller

Step 6. Structure of supervisory control layer

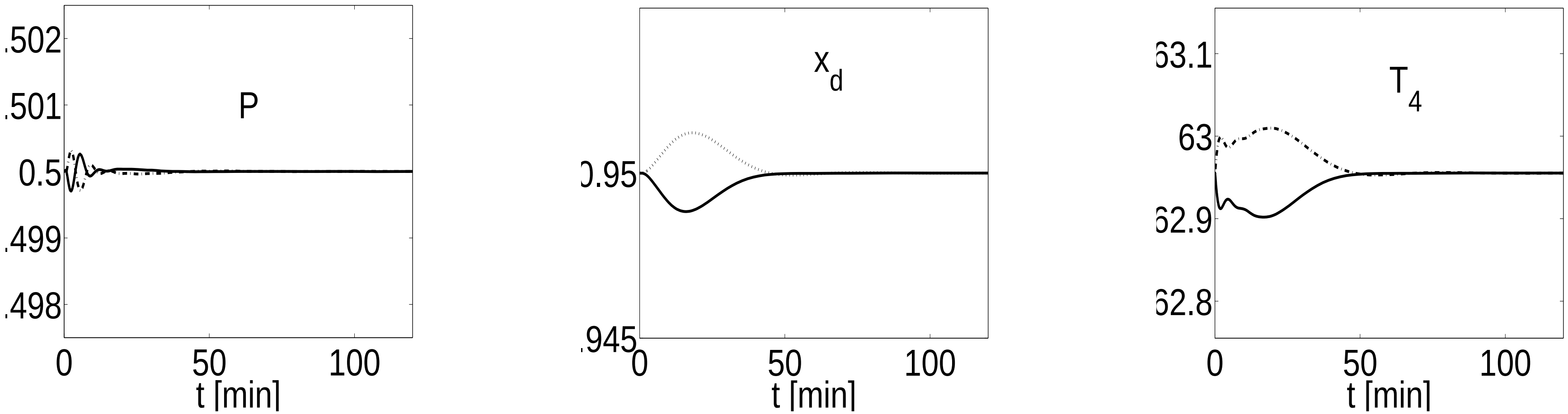
Proposed decentralized control structure

$$\text{RGA}(0) = \begin{array}{c} \\ \end{array}\begin{array}{ccc} L & F_{comp} & z_{cv,8} \end{array}$$

$$\text{RGA}(0) = \begin{bmatrix} 53.4 & -59.3 & 6.9 \\ 26.7 & -24.3 & -1.4 \\ -79.2 & 84.7 & -4.5 \end{bmatrix} \begin{matrix} P \\ x_d \\ T_4 \end{matrix}$$



Validation by simulation: $\Delta F = \pm 20\%$



Control: All alternatives OK

Step 7. Structure of optimization layer

On-line optimization is not needed.

Loss:
Temperature at stage 4, T_4 : 0.96%
On-line optimization : 0.89%

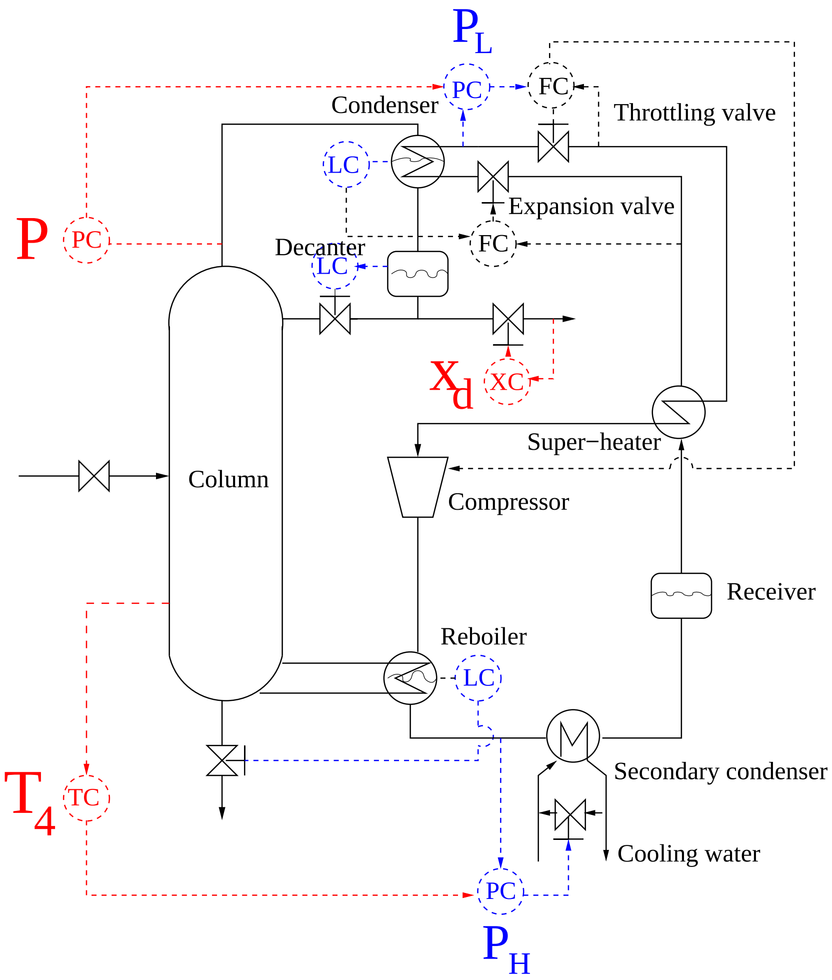
Concluding remarks

- Demonstrated a systematic procedure for selection of plantwide control structure on a distillation column with heat pump

- Control: Temperature at stage 4, T_4
  $\Rightarrow$ simple system + close to optimal operation

Step 6. Structure of supervisory control layer

Proposed decentralized control structure



Validation by simulation

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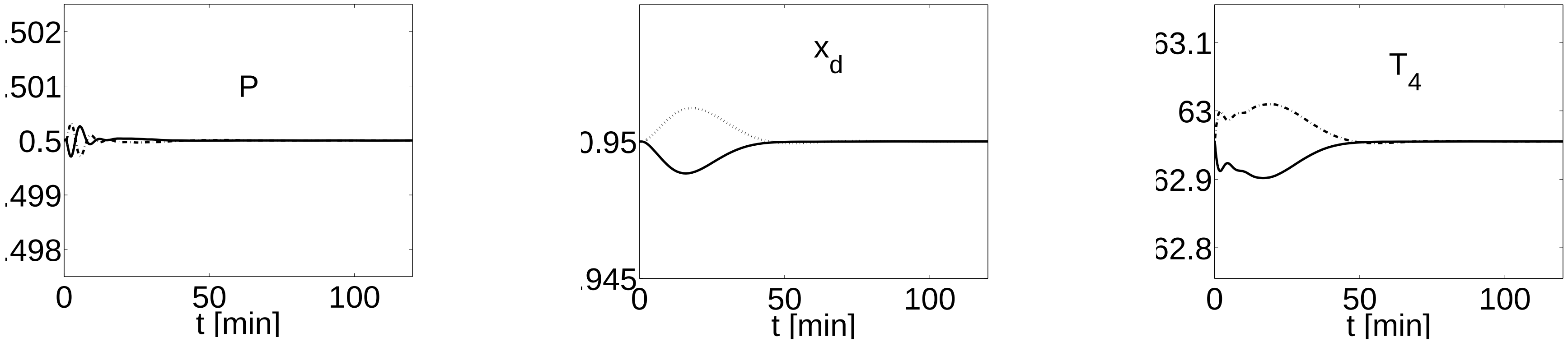
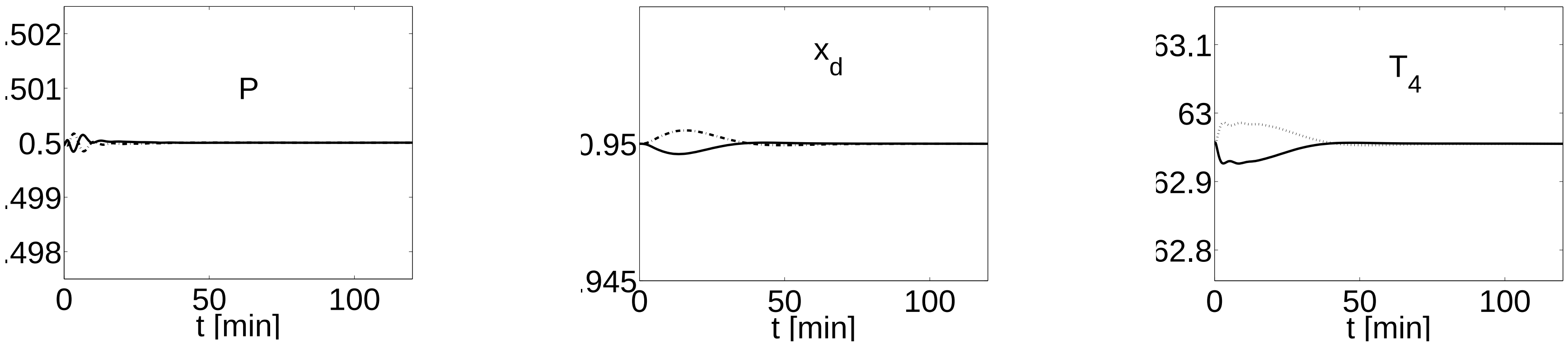
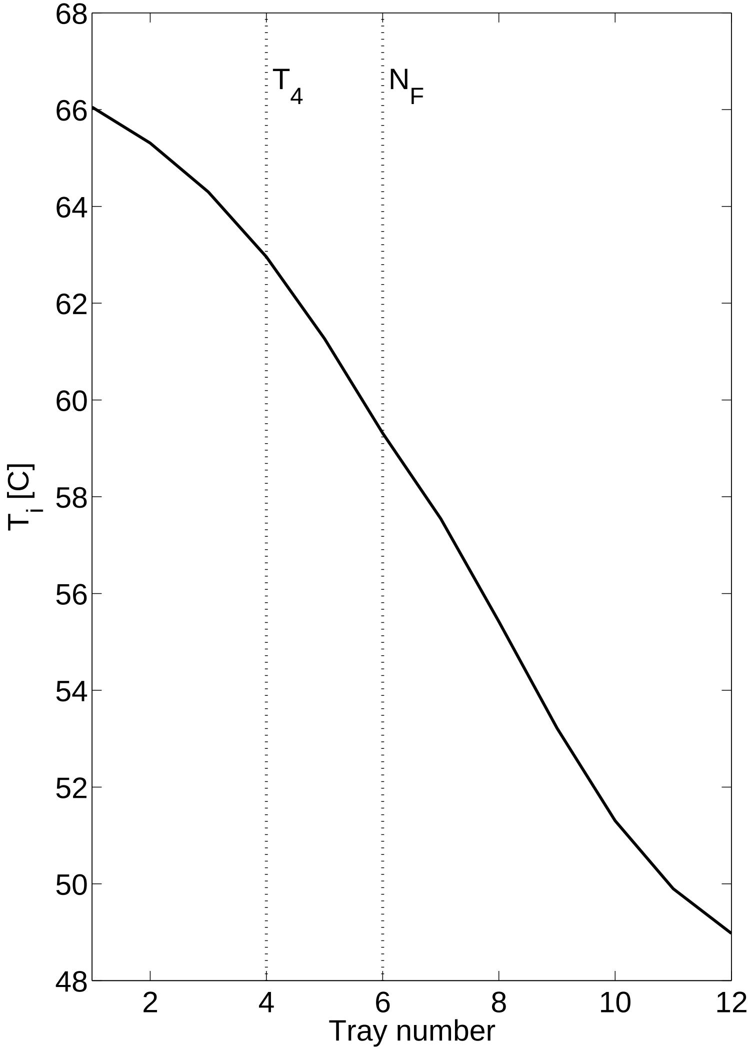


$\Delta z_F = \pm 0.1$

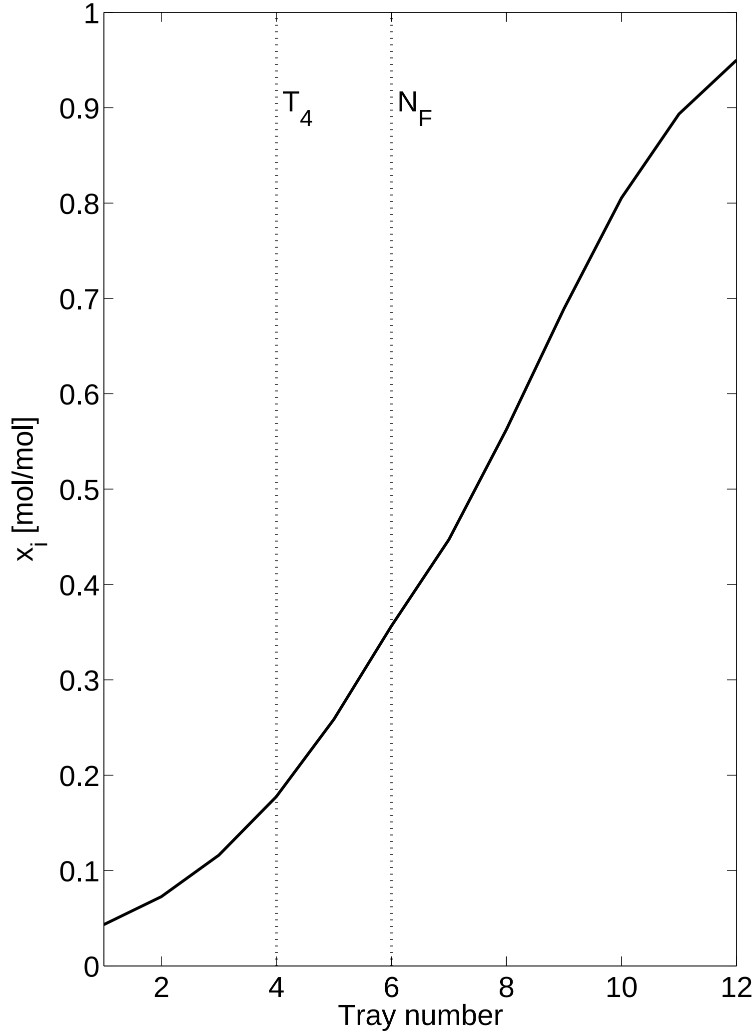


Control: All alternatives OK

Temperature profile

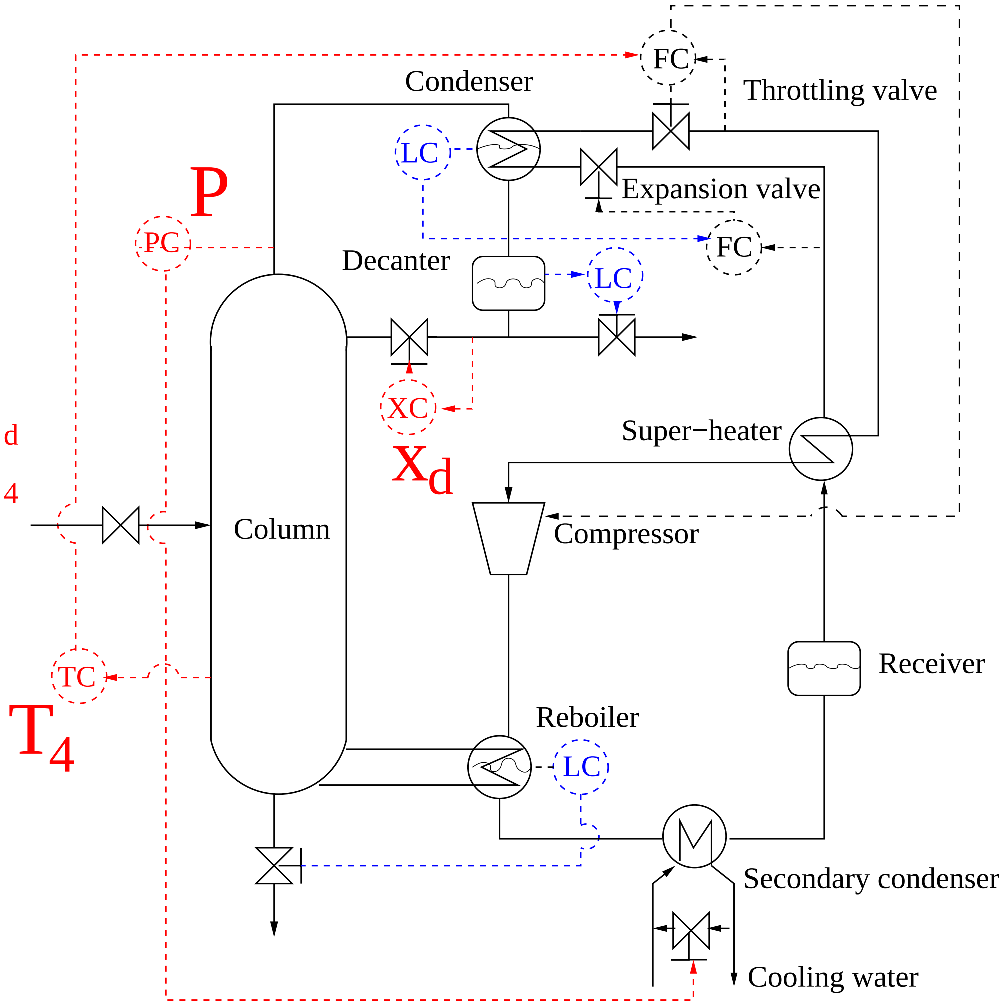


Composition profile



Possible decentralized control structure

$$
\begin{array}{c} \\ RGA(0) = \end{array}
\begin{array}{c}
\begin{array}{ccc} L & F_{comp} & z_{cv,8} \end{array} \\
\left[\begin{array}{ccc} 53.4 & -59.3 & 6.9 \\ 26.7 & -24.3 & -1.4 \\ -79.2 & 84.7 & -4.5 \end{array}\right]
\end{array}
\begin{array}{c} \\ P \\ x_d \\ T_4 \end{array}
$$



II: Bottom-up design of control system
Step 5. Structure of regulatory control layer

Stabilization:

Condenser drum holdup $\leftrightarrow$ Reflux flowrate

Reboiler drum holdup $\leftrightarrow$ Bottom product flowrate

LP heat pump drum holdup $\leftrightarrow$ Expansion valve flowrate

HP heat pump pressure $\leftrightarrow$ Cooling water valve

LP heat pump pressure $\leftrightarrow$ Compressor flowrate

Local disturbance rejection: Use local flow controller

Step 6. Structure of supervisory control layer

Proposed decentralized control structure

$$
\begin{array}{cc}
 & \begin{array}{ccc} D & P_{L,s} & P_{H,s} \end{array} \\
\mathrm{RGA}(0) = & \left[\begin{array}{ccc} 0.09 & 0.67 & 0.23 \\ 0.57 & 0.35 & 0.07 \\ 0.33 & -0.02 & 0.69 \end{array}\right] \begin{array}{c} P \\ x_d \\ T_4 \end{array}
\end{array}
$$