Integrated optimization and control

Marius Støre Govatsmark

Department of Chemical Engineering, NTNU

18. September 2003

Outline

- Thesis overview
- Selection of controlled variables and setpoints (chap. 2-4)
  - Self-optimizing control
  - Ex 1: Long-distance running
  - Ex 2: Reactor, separator and recycle process
- Plantwide control (chap. 5-6)
- Controllability and distillation column (chap. 7)
- Concluding remarks and further work

Thesis overview

- **Chapter 2:**
  Control Structure Selection for Reactor, Separator and Recycle Process

- **Chapter 3:**
  Selection of Controlled Variables and Robust Setpoints

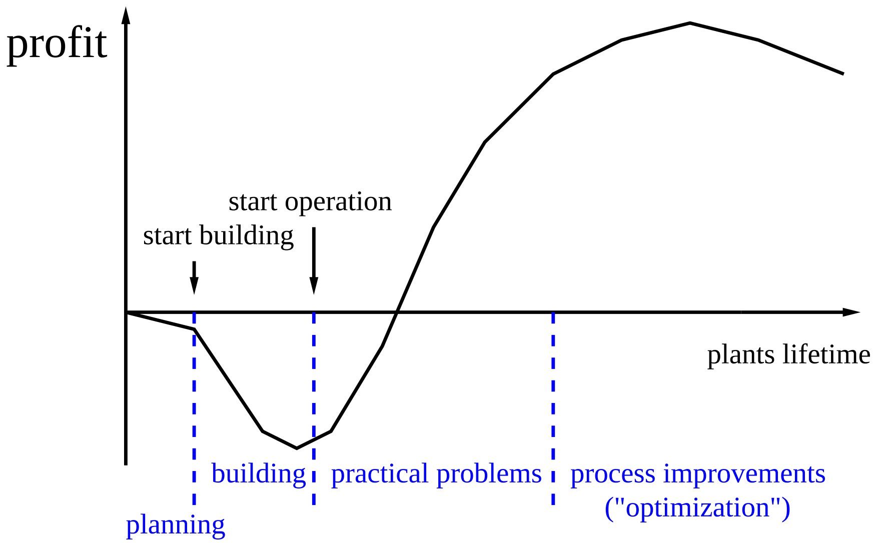
- **Chapter 4:**
  Control Structure Design for An Evaporation Process

- **Chapter 5:**
  Application of a Plantwide Control Design Procedure to a Combined Cycle Power Plant

- **Chapter 6:**
  Application of a Plantwide Control Design Procedure to a Distillation Column with Heat Pump

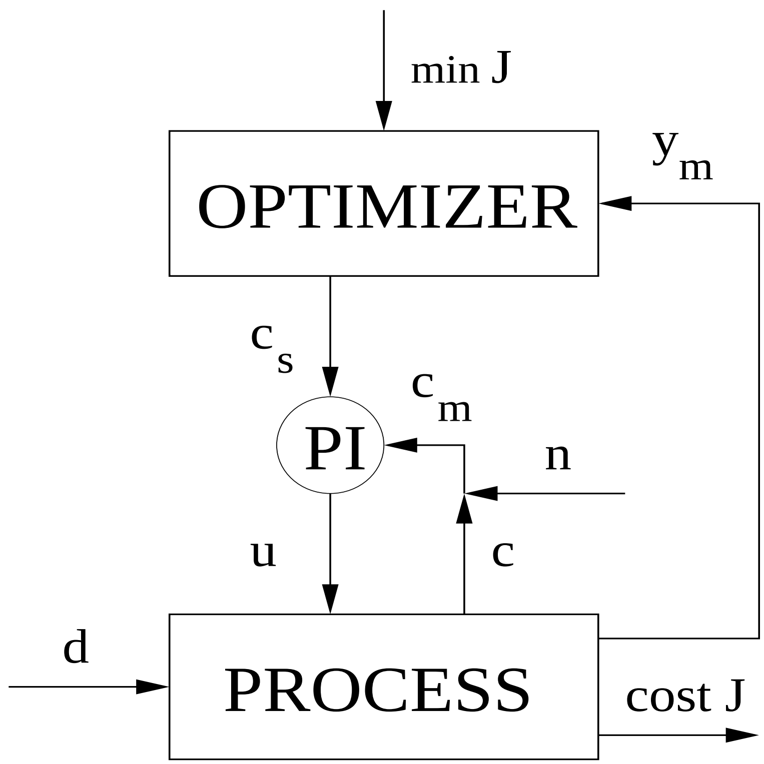
- **Chapter 7:**
  Optimal Number of Stages in Distillation with respect to Controllability

Where am I?



- Process industry
- Primary mature phase
- Improving operation ("optimization")

Selection of controlled variables and setpoints (chap. 2-4)



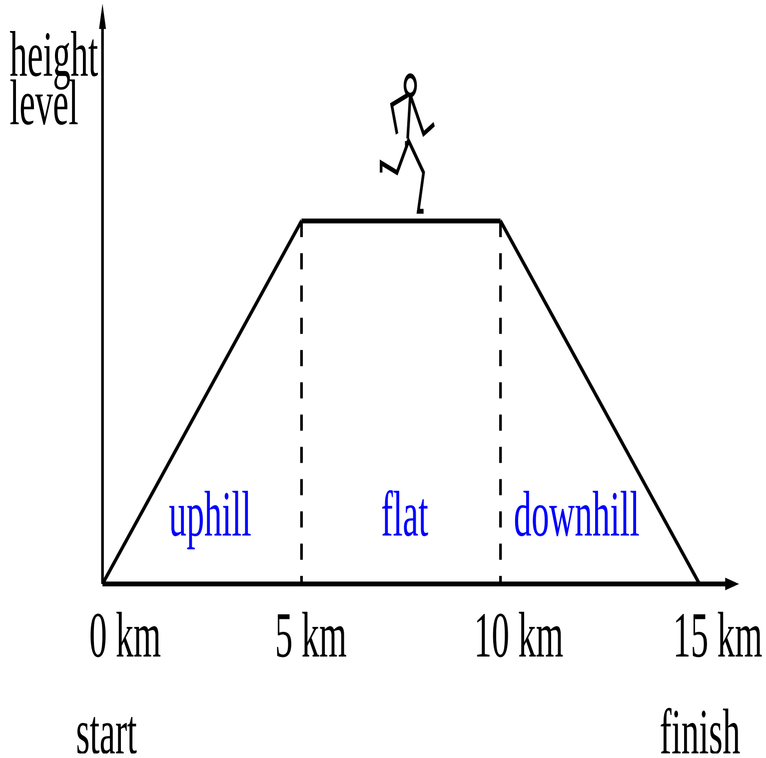
- Which variables? c
- Which setpoints? c_s (robust optimization)
- Can we achieve acceptable economic operation with constant setpoints (self-optimizing control)?

$d_c = c - c_s$: implementation error

Mathematical formulation: Best constant setpoint policy

$$\{c(x,u,d), c_s\} = arg \left\{ \min_{c(u,x,d)} \left[\begin{array}{c} \min_{x_i,u_i,c_s} \sum_i w_i J(x_i,u_i,d_i) \\ f(x_i,u_i,d_i) = 0 \\ g(x_i,u_i,d_i) \leq 0 \\ c(x_i,u_i,d_i) = c_s + d_{c,i} \\ d_i = d_0 + \Delta d_i \\ d_{c,i} = d_{c,0} + \Delta d_{c,i} \\ \Delta d_i \in D_d, \;\; \Delta d_{c,i} \in D_c \end{array} \right] \right\}$$

Example 1: Long-distance running



Optimal running (operation):
$u_{opt} = u_{opt}(terraine, energy) \neq u_{max}$

Problem:
Complex model + uncertainties

Manipulated variables:

$$u^T = [speed]$$

Steady-state degrees of freedom: 1

Minimize time consume

$$J = t_{consumed}$$

Constraints:

$$u \leq u_{max}(terraine, energy)$$

Disturbances (uncertainty):

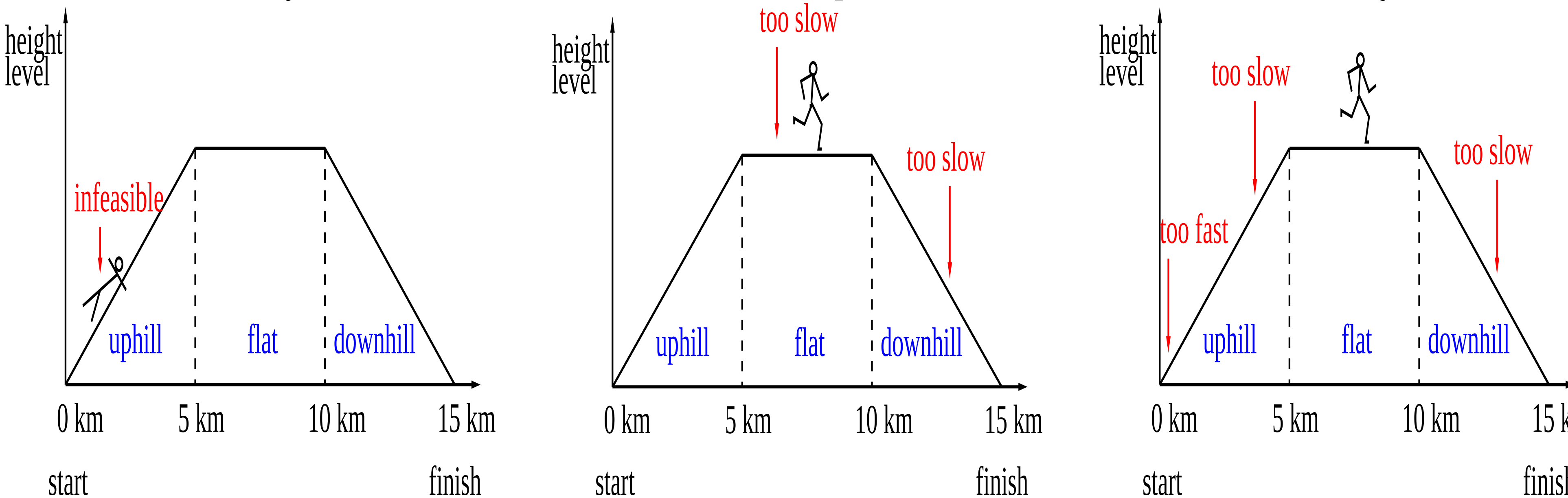
$$d^T = [terraine\ energy]$$
$$terraine = \{uphill, flat, downhill\}$$

Candidate controlled variables:

$$c^T = [speed\ heart-frequency]$$

Controlled variable: Speed (c=u)

Nominal speed ($c_s = u_{flat}$) | Robust speed ($c_s = u_{uphill}$) | Flexible speed ($c_s = u_{flat}$)

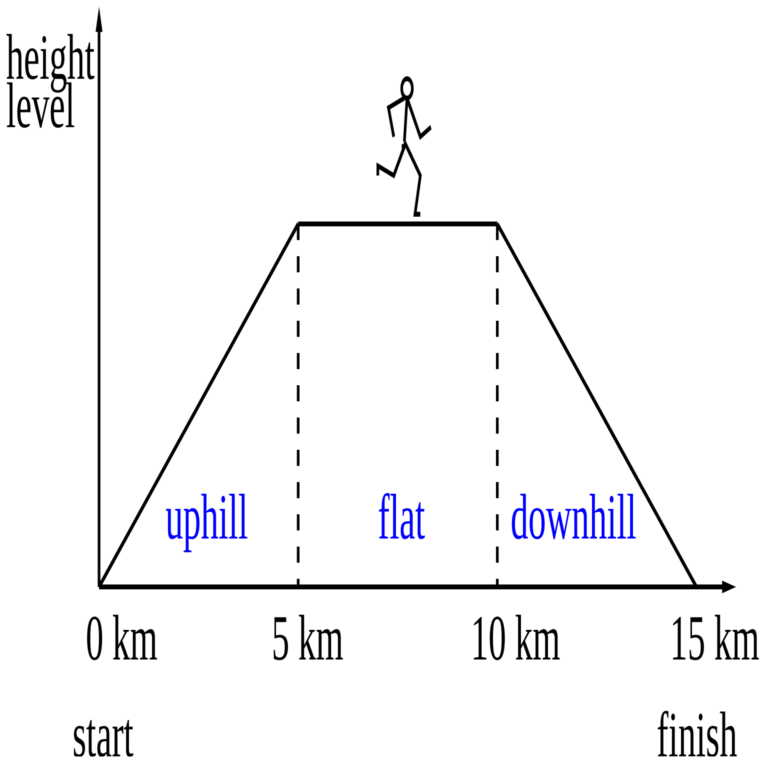


Infeasible | Feasible | Feasible

Controlled variable: Heart frequency (c=f)

Nominal heart frequency

$(c_s = f_{flat})$

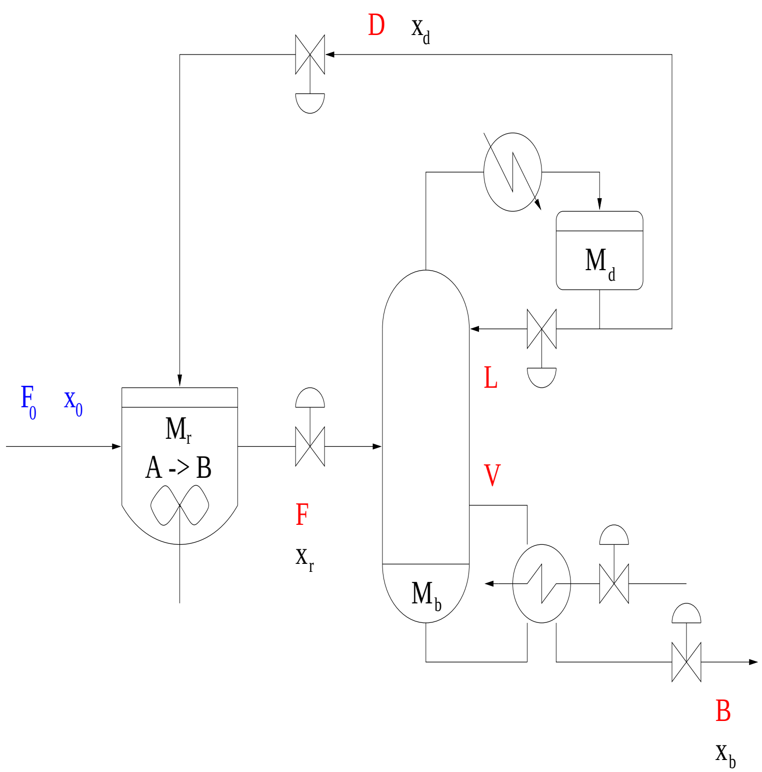


Feasible + close to optimal

$(u \approx u_{opt}(terraine, distance))$

Self-optimizing control

Example 2: Reactor-Distillation-Recycle System (Papadourakis,1987)



Manipulated variables:

$$u^T = [V \; L \; B \; D \; F]$$

Steady-state degrees of freedom: 3

Minimize costs

$$J = V$$

Constraints:

x_b	$\leq 0.015 \; \frac{\text{molA}}{\text{mol}}$	active
M_r	≤ 2800 kmol	active
V	≤ 5000 kmol/h	
$Flows$	≥ 0 kmol/h	

Disturbances:

$$d^T = [F_0 \; x_0] = [460 \pm 92 \; \frac{\text{kmol}}{\text{h}} \; 0.90 \pm 0.05 \; \frac{\text{m}}{\text{r}}$$

Procedure for selecting controlled variables (self-optimizing control)

Step 1. Initial system analysis
- Economic objective and constraints
- Degrees of freedom
- Disturbances

Step 2. Identify candidate controlled variable sets
- Use active constraint control
- Initial screening: Minimum singular value
- Process insight

Step 3. Lossevaluation for controlled variable sets, with:
- **a.** Constant nominal setpoints
- **b.** Constant robust setpoints
- **c.** Nominal setpoints with online feasibility correction (flexible setpoints)

Step 4. Final evaluation and selection of control structure

Step 2: Identify candidate controlled variables

Candidate controlled variables (20):

$$c^T = [L \ V \ D \ B \ F \ M_r \ x_r \ x_B \ x_D \ \frac{L}{F} \ \frac{V}{F} \ \frac{B}{F} \ \frac{D}{F} \ \frac{V}{L} \ \frac{B}{L} \ \frac{D}{L} \ \frac{B}{V} \ \frac{D}{V} \ \frac{B}{D} \ \frac{F}{F_0}]$$

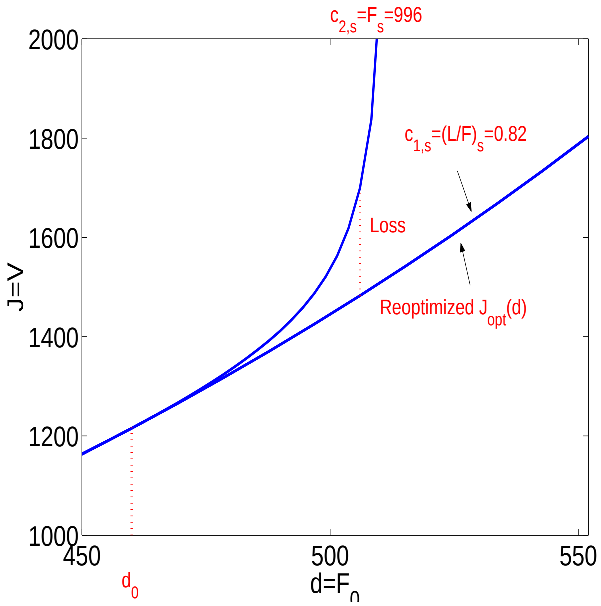
Active constraint control

- Product composition (x_B)
- Reactor holdup (M_r)

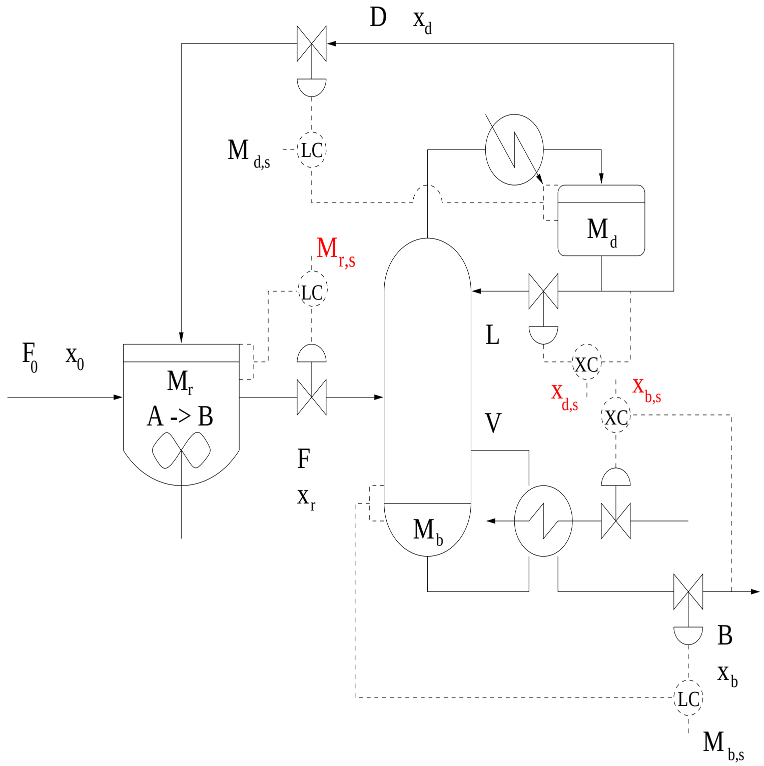
Unconstrained degree of freedom: 1

Step 3a: Loss evaluation with constant nominal setpoints

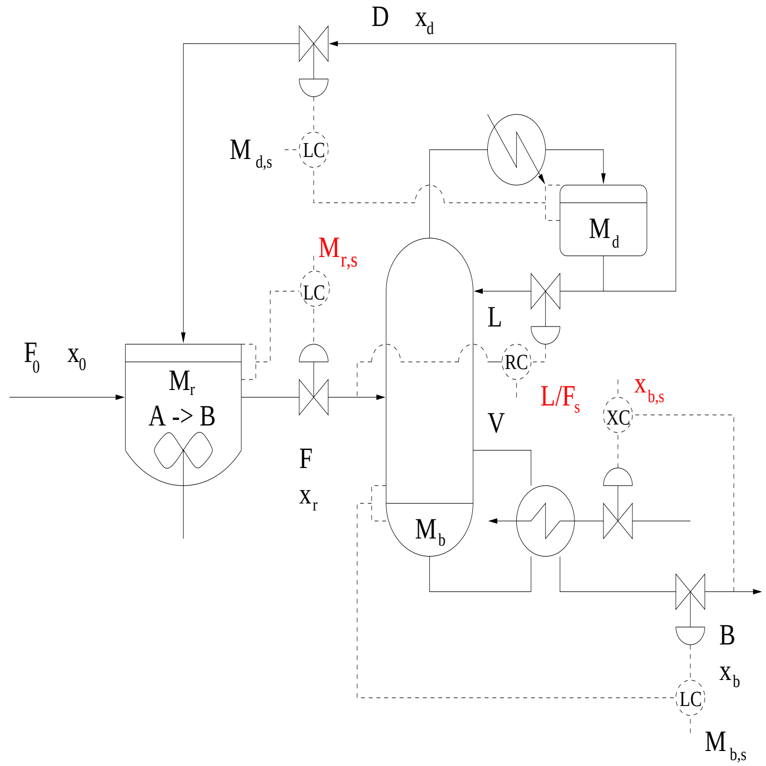
c_1,c_2,c_3	Nominal setpoints		
	$c_{3,s}$	L_w(%)	L_{max}(%)
Reoptimized	$c^*_{opt}(d)$	5.16	11.03
x_B,M_r,x_D	0.825	5.22	11.04
x_B,M_r,L/F	0.871	5.39	11.24
x_B,M_r,D/L	0.600	5.40	11.15
x_B,M_r,D/V	0.375	5.60	11.15
x_B,M_r,V/F	1.392	6.05	11.37
x_B,M_r,B/L	0.549	6.31	13.70
x_B,M_r,L	837.4	6.68	22.95
x_B,M_r,V/L	1.600	8.64	41.31
x_B,M_r,B/D	0.916	11.2	47.77
x_B,M_r,F/F_0	2.091	inf	inf
x_B,M_r,B/F	0.478	inf	inf
x_B,M_r,D/F	0.522	inf	inf
x_B,M_r,D	502.0	inf	inf
x_B,M_r,F	962.0	inf	inf
x_B,F/F_0,V/B	–	inf	inf
x_B,F/F_0,x_D	–	inf	inf
x_B,x_D,x_R(BS)	–	inf	inf
x_B,F/F_0,L/D	–	inf	inf
x_B,F,x_D(LS)	–	inf	inf
V/B,F/F_0,x_D	–	inf	inf



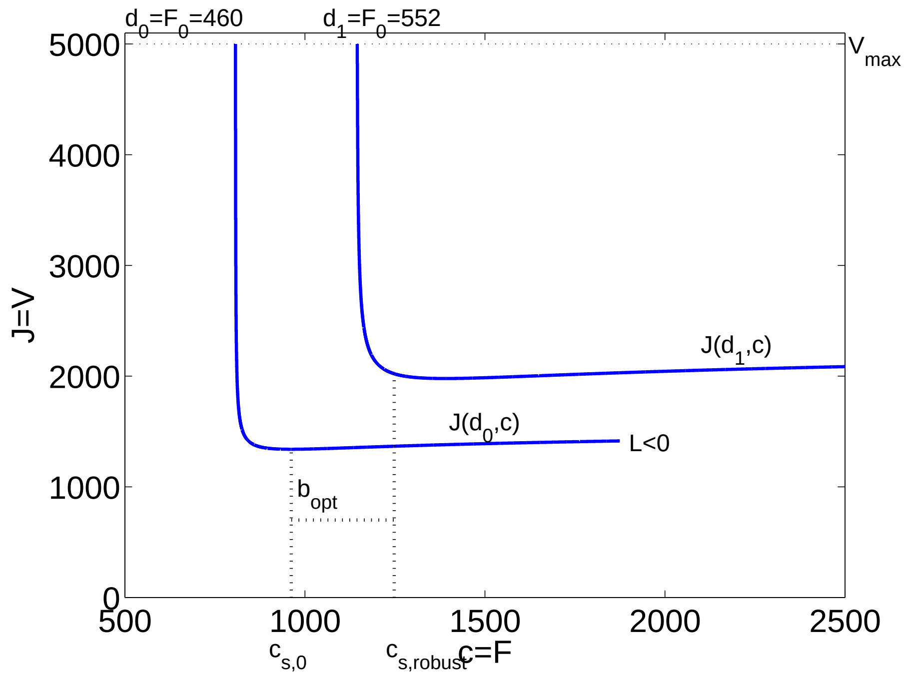
Conventional (x_D)



Larsson et.al.(L/F)



Finding optimal setpoints by robust optimization (Glemmestad et.al.,1998)



Robust optimization:

$$\min_{x_i, u_i, c_s} \sum_i w_i J(x_i, u_i, d_i)$$

$$f(x_i, u_i, d_i) = 0$$

$$g(x_i, u_i, d_i) \leq 0$$

$$c(x_i, u_i, d_i) = c_s + d_{c,i}$$

$$d_i = d_0 + \Delta d_i$$

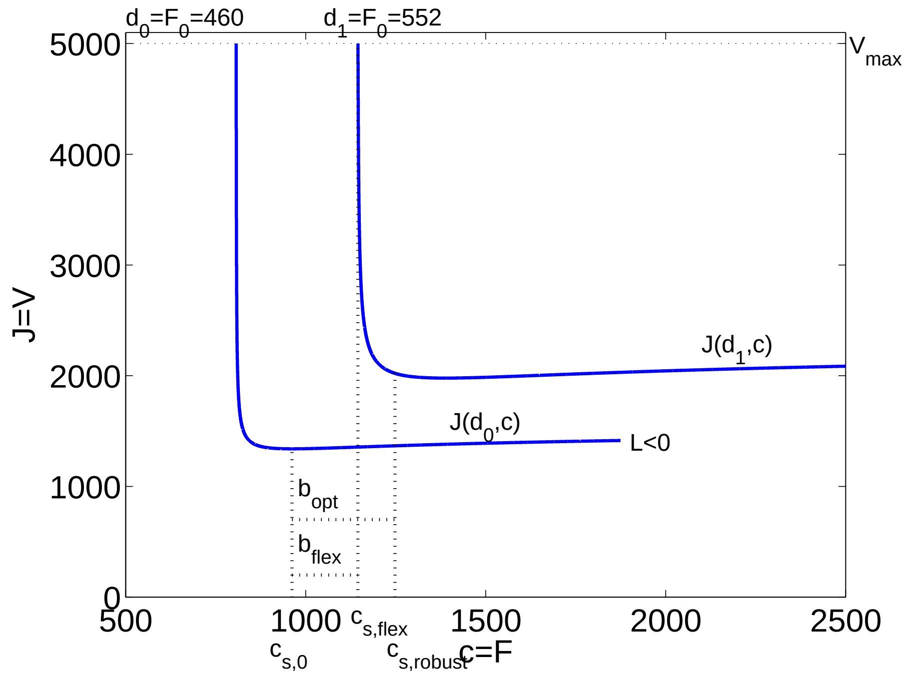
$$d_{c,i} = d_{c,0} + \Delta d_{c,i}$$

$$\Delta d_i \in D_d, \;\; \Delta d_{c,i} \in D_c$$

"Optimal backoff":

$$b_{opt} = c_{s,robust} - c_{s,0}$$

Finding flexible setpoints by online feasibility correction (Lid et.al.,2001)



Online feasibility correction:

$$\min_{x,u,c_{flex}} (c_{II,flex} - c_{II,s})^T Q_{II} (c_{II,flex} - c_{II,s})$$

$$f(x,u,d) = 0$$

$$g(x,u,d) + d_{g,max} - d_g \leq 0$$

$$c(x,u,d) = c_{flex} + d_c$$

$$c_{I,flex} = c_{I,s}$$

"Flexible backoff":

$$b_{flex}(d,d_c) = c_{s,flex}(d,d_c) - c_{s,0}$$

Step 3: Loss evaluation

c_1,c_2,c_3	Nominal setpoints			Robust setpoints			Flexible setpoints		
	$c_{3,s}$	L_w (%)	L_{max} (%)	$b_{3,opt}$	L_w (%)	L_{max} (%)	$b^{max}_{3,flex}$	L_w (%)	L_{max} (%)
Reoptimized	$c^*_{opt}(d)$	5.16	11.03	–	5.16	11.03	–	4.97	11.03
x_B,M_r,x_D	0.825	5.22	11.04	0.005	5.21	11.03	0	5.22	11.04
x_B,M_r,L/F	0.871	5.39	11.24	−0.021	5.35	11.34	0	5.39	11.24
x_B,M_r,D/L	0.600	5.40	11.15	0.047	5.34	11.35	0	5.40	11.15
x_B,M_r,D/V	0.375	5.60	11.15	0.026	5.49	11.46	0	5.60	11.15
x_B,M_r,V/F	1.392	6.05	11.37	−0.037	5.93	11.67	0	6.05	11.37
x_B,M_r,B/L	0.549	6.31	13.70	0.054	6.05	12.60	0	6.31	13.70
x_B,M_r,L	837.4	6.68	22.95	−64	6.46	15.87	0	6.68	22.95
x_B,M_r,V/L	1.600	8.64	41.31	0.206	5.89	12.19	0	8.64	41.31
x_B,M_r,B/D	0.916	11.2	47.77	−0.140	6.00	11.68	0	11.2	47.77
x_B,M_r,F/F_0	2.091	inf	inf	0.289	6.22	12.15	0.1280	36.82	291.78
x_B,M_r,B/F	0.478	inf	inf	−0.056	6.36	12.08	0.0145	36.87	291.78
x_B,M_r,D/F	0.522	inf	inf	0.061	6.50	12.24	0.0242	36.89	291.78
x_B,M_r,D	502.0	inf	inf	191	6.79	12.82	91	26.63	165.24
x_B,M_r,F	962.0	inf	inf	286	7.51	13.90	183	26.90	165.24
x_B,F/F_0,V/B	–	inf	inf	–	25.87	54.38	0.6718	9.40	20.28
x_B,F/F_0,x_D	–	inf	inf	–	25.91	54.38	0.0001	8.24	24.36
x_B,x_D,x_R(BS)	–	inf	inf	–	26.08	54.38	0	6.36	16.24
x_B,F/F_0,L/D	–	inf	inf	–	33.13	63.59	0.0001	10.06	26.59
x_B,F,x_D(LS)	–	inf	inf	–	43.10	94.37	0.1735	30.84	165.24
V/B,F/F_0,x_D	–	inf	inf	–	45.74	78.75	0.0321	8.95	28.28

Step 4: Final evaluation and selection of control structure

Stabilize reboiler, condenser and reactor holdup

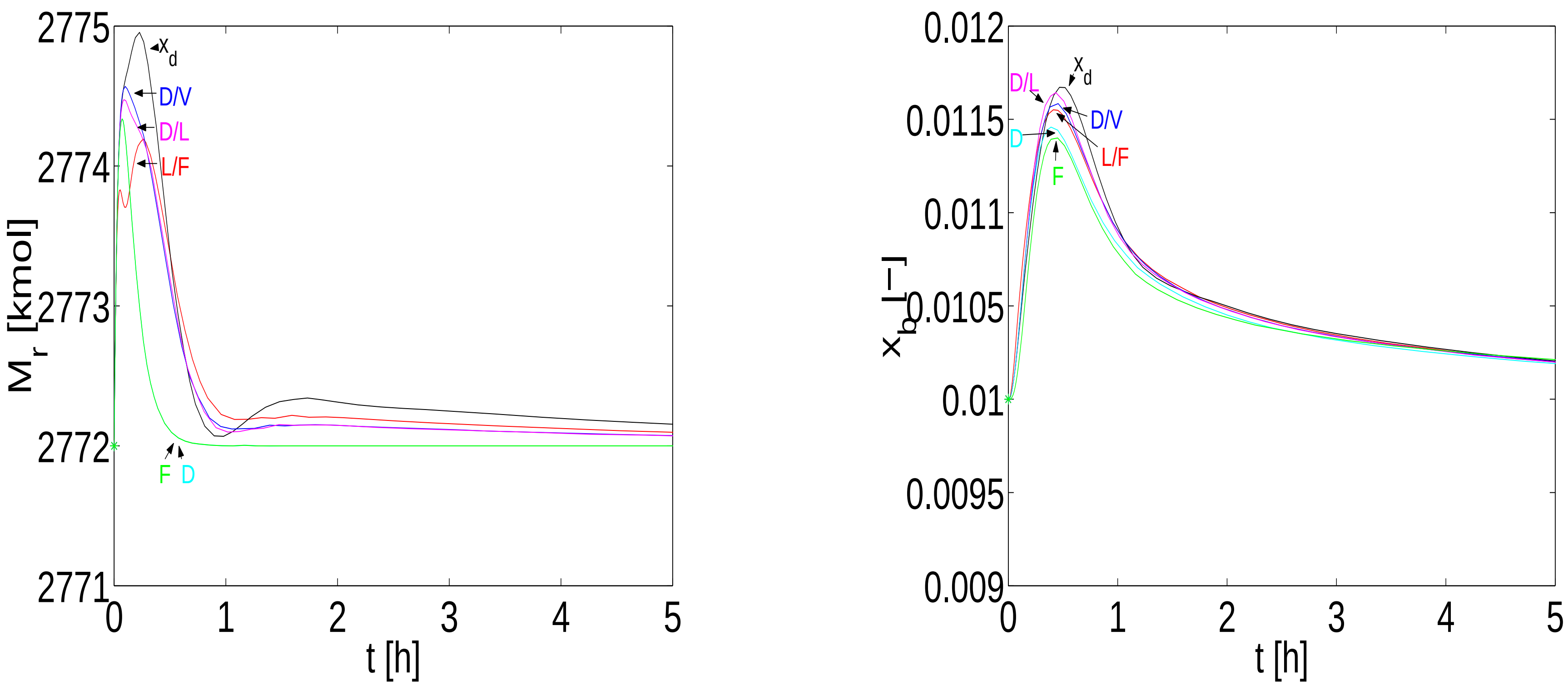
Pairing based on relative gain array (RGA):

Alt.	$Loop$ 1	$Loop$ 2	$Loop$ 3	$Loop$ 4	$Loop$ 5
x_d	$M_b \leftrightarrow B$	$M_d \leftrightarrow D$	$M_r \leftrightarrow F$	$x_b \leftrightarrow V$	$x_d \leftrightarrow L$
L/F	$M_b \leftrightarrow B$	$M_d \leftrightarrow D$	$M_r \leftrightarrow F$	$x_b \leftrightarrow V$	$L/F \leftrightarrow L$
D/L	$M_b \leftrightarrow B$	$M_d \leftrightarrow D$	$M_r \leftrightarrow F$	$x_b \leftrightarrow V$	$D/L \leftrightarrow L$
D/V	$M_b \leftrightarrow B$	$M_d \leftrightarrow D$	$M_r \leftrightarrow F$	$x_b \leftrightarrow V$	$D/V \leftrightarrow L$
F	$M_b \leftrightarrow B$	$M_d \leftrightarrow L$	$M_r \leftrightarrow D$	$x_b \leftrightarrow V$	F
D	$M_b \leftrightarrow B$	$M_d \leftrightarrow L$	$M_r \leftrightarrow F$	$x_b \leftrightarrow V$	D

All six alternatives show good controllability.

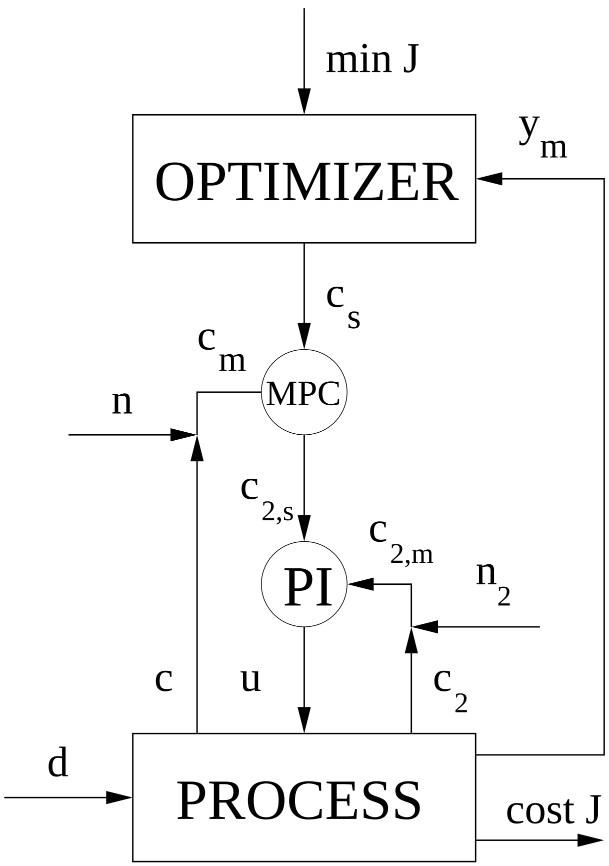
Robust optimal setpoints

Disturbance: $\Delta F_0 = +20\%$



Control: All alternatives OK

Plantwide control (Chap. 5-6)



Important tasks:

- Controlled variables
- Manipulated variables
- Measurements
- Control configuration
- Controller type

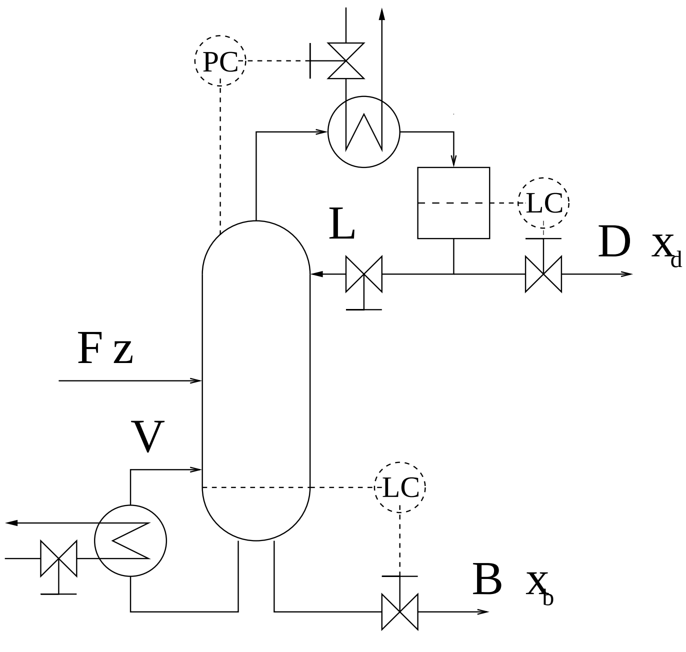
Plantwide control procedure (Larsson et.al.,2001):

- Top-down analysis
- Bottom-up design

Case-studies:

- Combined-cycle power plant
- Heat-integrated distialltion column

Two-point composition control in distillation: Optimal number of stages wrt. controllability



Fixed setpoints:

- Two competing factors:
  - Interaction:
    Smallest with many stages
    Reference tracking
  - Internal flows:
    Largest with few stages
    Disturbance rejection

Fixed energy
(constant internal flows):

- Best with many stages

Further work

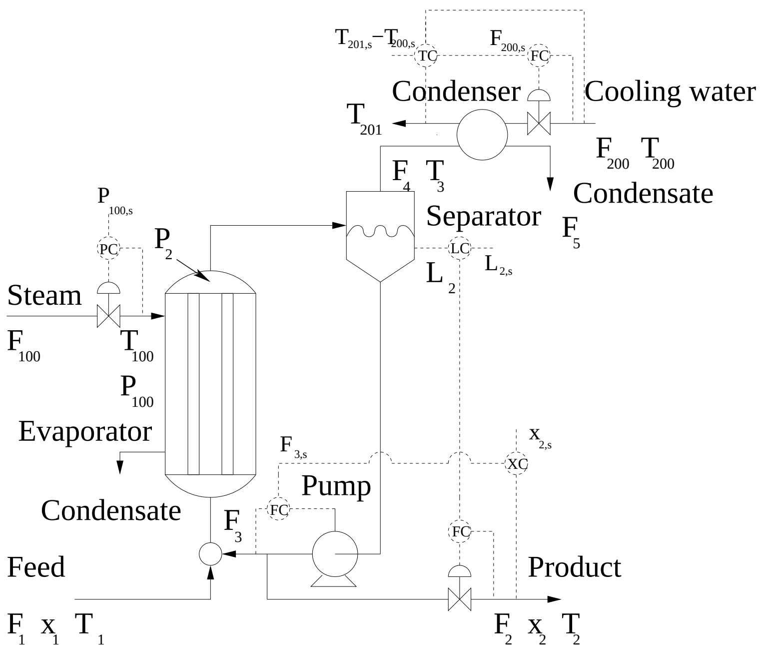
- Identifying candidate controlled variables
- Model uncertainty
- Plantwide control procedure: Bottleneck, degree of freedom, bottom-up design.
- Case-studies

Concluding remarks

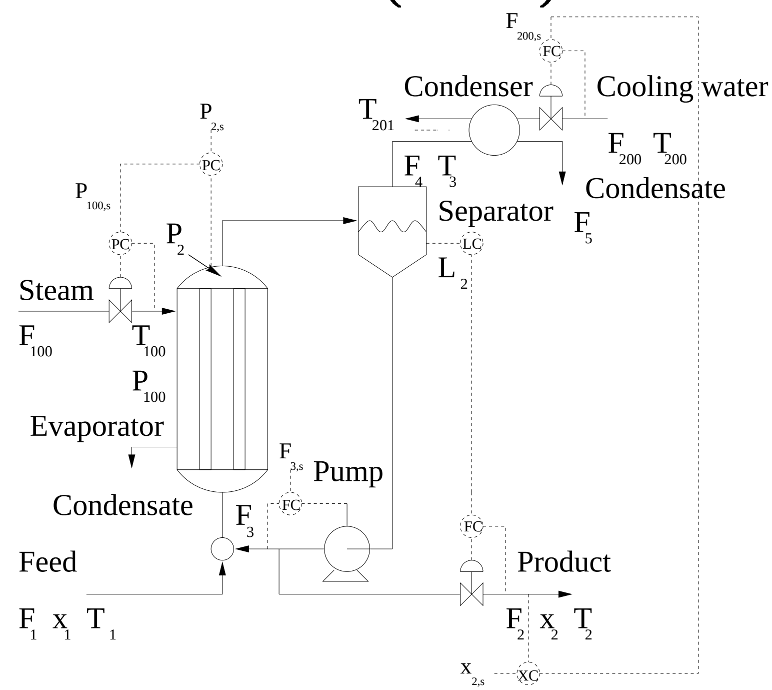
- Self-optimizing control and feasibility
- Several detailed case-studies based on a systematic method.

Example 3: Evaporation process (Newell,1989)

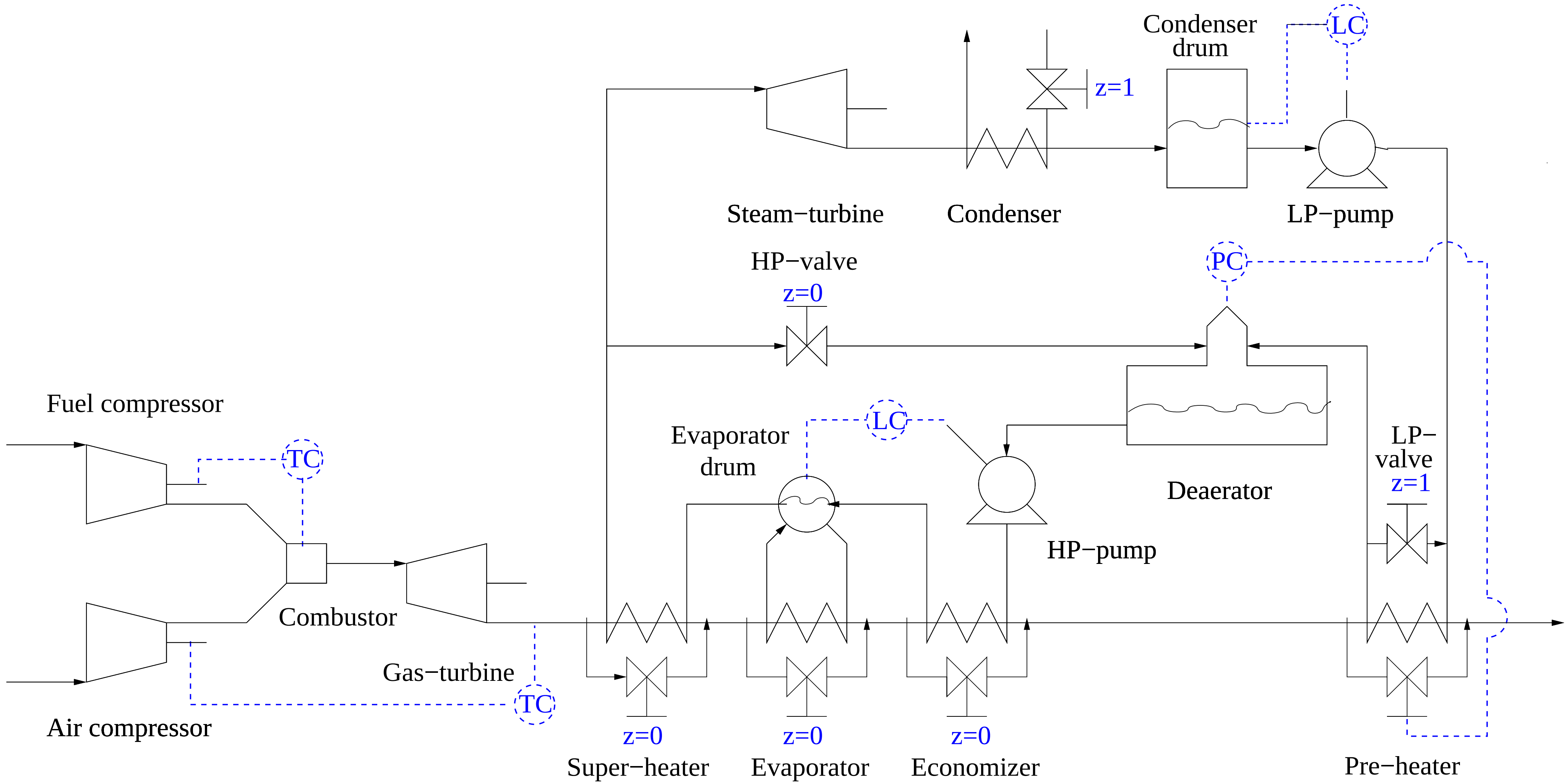
$T_{201} - T_{200}$



Kookos et.al.(2001)

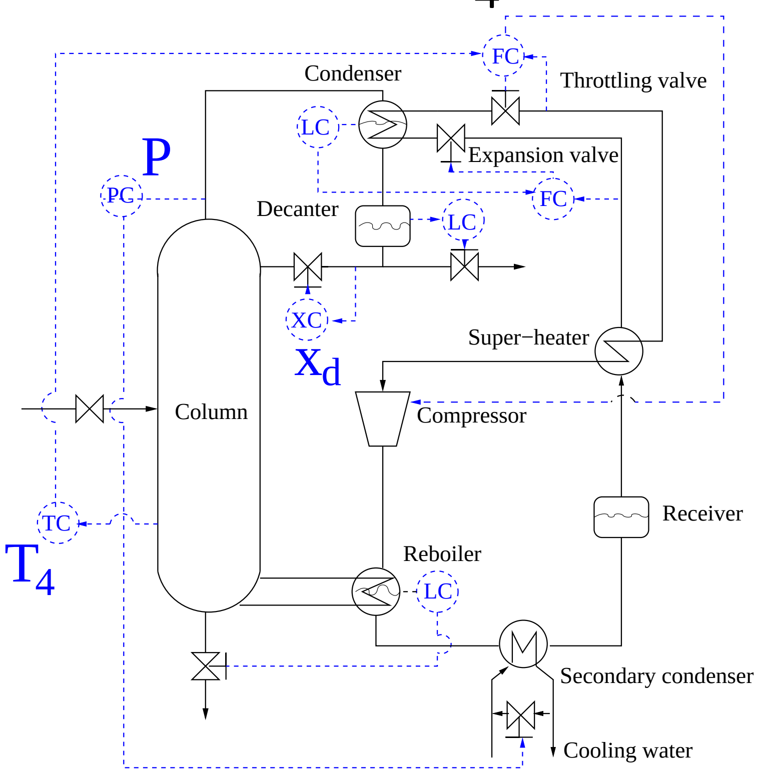


Case study 1: Combined cycle power plant



Case study 2: Heat-integrated distillation column

T_4



Li et.al.(2003)