Studies on Selection of Controlled Variables

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Norwegian University of Science and Technology

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Thesis outline

1. Introduction
2. Overview of control structure design and optimizing control
3. The null space method for selecting controlled variables
4. Measurement selection in the null space method
5. Disturbance discrimination in self-optimizing control
6. Effect of non-optimal nominal setpoints in self-optimizing control
7. Dynamics of controlling measurement combinations
8. Self-optimizing control structures for a Petlyuk distillation column
9. Energy savings by over-fractionation in the Petlyuk column
10. Control structure selection for oil and gas production networks
11. Control structure selection for an evaporator example
12. Appendices A-E

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Presentation outline

- Introduction
- Part I: (Chapters 3 and 4)
  - Self-optimizing control
  - The null space method
  - Measurement selection
- Part II: (Chapters 8,10 and 11)
  - The Petlyuk Column
  - Oil & gas production networks
  - Evaporator
- Part III: (Chapters 5, 6 and 7)
  - Effect of nominal setpoint error
- Concluding remarks and further work

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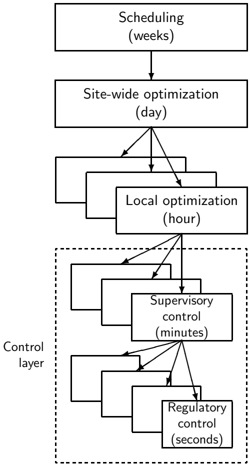
Control structure hierarchy in chemical plants



- Each layer in the control hierarchy operates at different time scales
- Layers connected through the controlled variables
- Focus on the interaction between the local optimization layer and the control layer
- Economics primarily decided by steady-state

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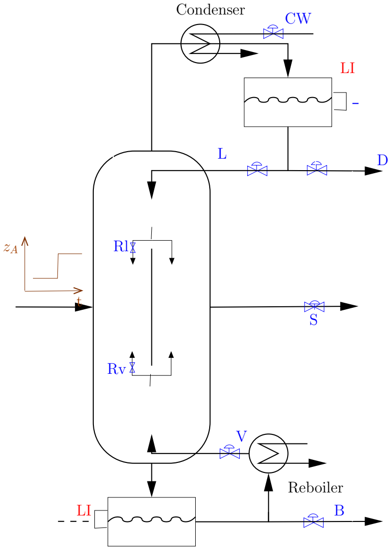
Introduction - Selection of controlled variables: Petlyuk column



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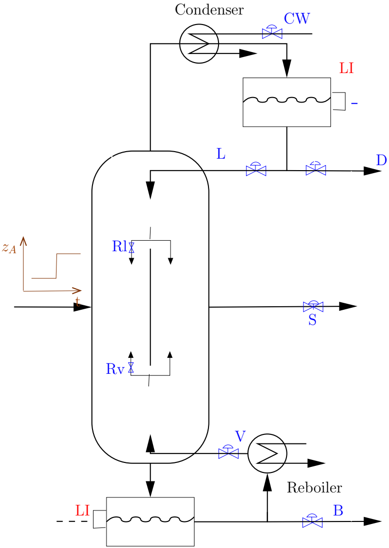

- Persistent disturbance z_A.

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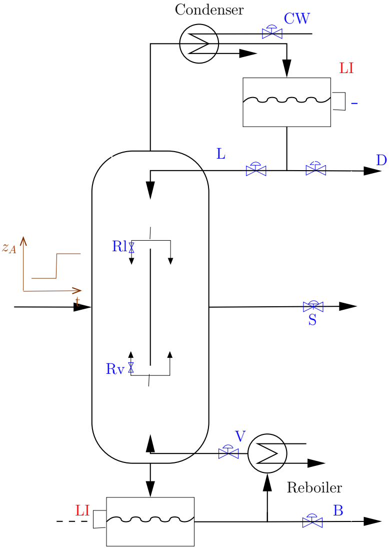

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- 7 degrees of freedom: $\mathbf{u}^T = [S, D, B, L, V, R_L, R_V]$

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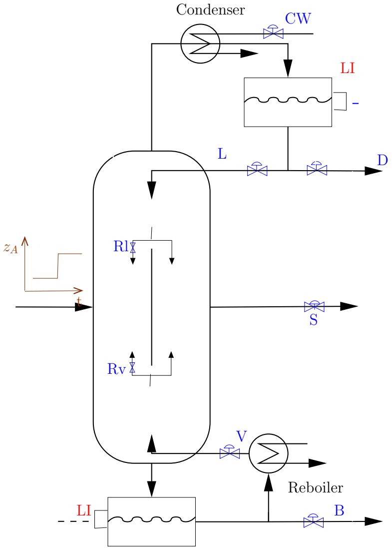

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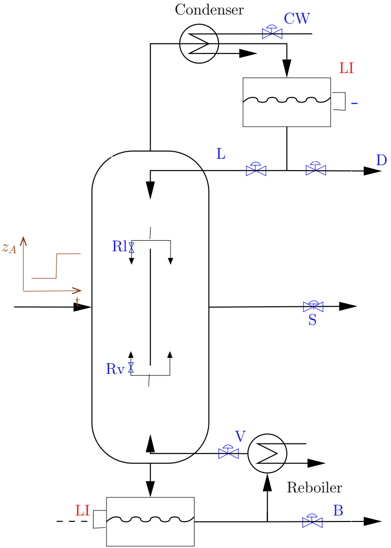

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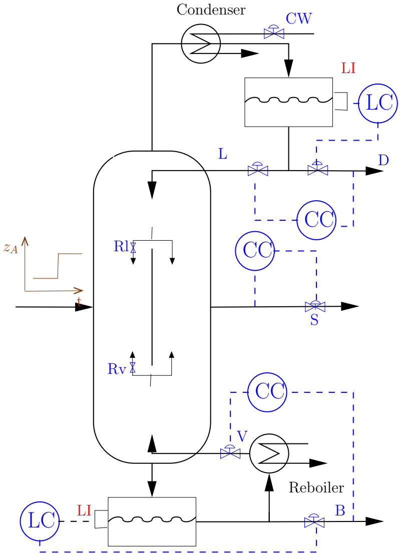

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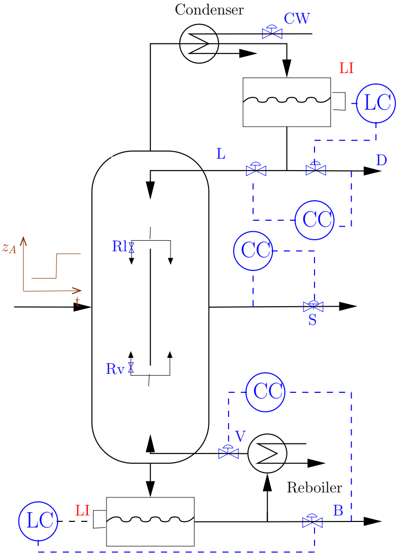

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- $= 2$ DOF left. What to control?

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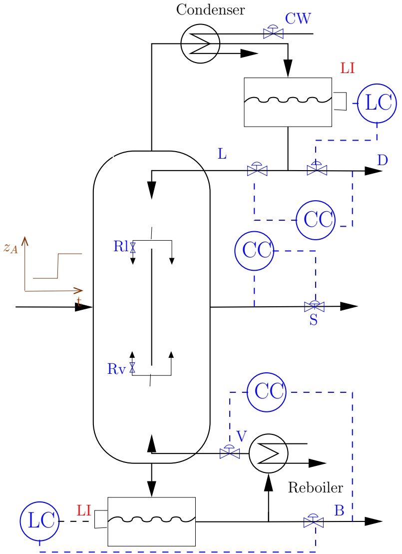

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- $= 2$ DOF left. What to control?
- Optimize the operation!

$$\min_{R_L, R_V} J(R_L, R_V, z_A, \ldots)$$

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Introduction - Strategies for ensuring optimal operation

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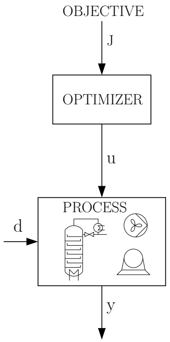
Open loop implementation



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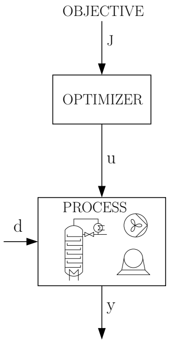
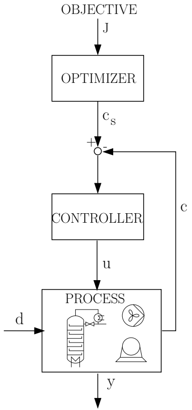


Closed loop implementation with separate control layer



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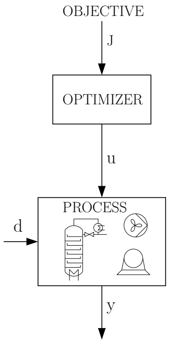

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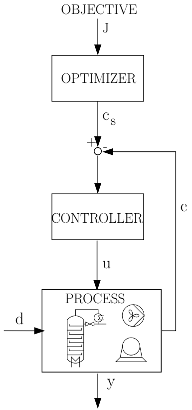
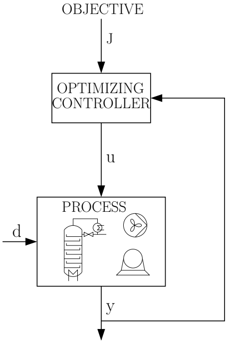


Optimizing controller



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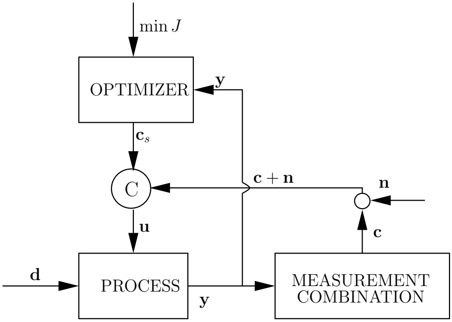
Part I: Self-optimizing control



- Which variables to measure? $\mathbf{y}$
- Which variables to control? $\mathbf{c}$
- What setpoints to use? $\mathbf{c}_s$

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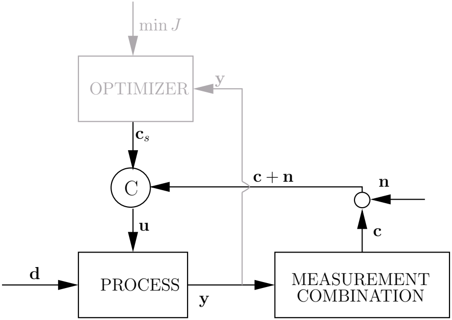
Part I: Self-optimizing control



- Which variables to measure? $\mathbf{y}$
- Which variables to control? $\mathbf{c}$
- What setpoints to use? $\mathbf{c}_s$
- Can we achieve acceptable steady-state economic performance with constant setpoints?

- $\Rightarrow$ Self-optimizing control

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Example: How to keep your wife happy!

- Objective: $J =$ "wife happines"

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  - $c =$ "smiles (by wife)"

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Mathematical formulation

- How to find the best set of controlled variables c?

$$\{c(x, u_0, d)\} = \arg\min_{c} \int_{\substack{d \in \mathcal{D} \\ n_c \in \mathcal{N}_c}} J(c, d, n)$$

$$\mathbf{f}(\mathbf{x}, \mathbf{u}_0, \mathbf{d}) = 0 \qquad \text{Model equations}$$

$$\mathbf{g}(\mathbf{x}, \mathbf{u}_0, \mathbf{d}) \leq 0 \qquad \text{Inequality constraints}$$

$$\mathbf{c}(\mathbf{x}, \mathbf{u}_0, \mathbf{d}) = \mathbf{c}_s + \mathbf{n} \qquad \text{Controlled variables}$$

Mathematical formulation

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- Simplify

$$\min_{\mathbf{u}_0} J(\mathbf{x}, \mathbf{u}_0, \mathbf{d})$$
$$\mathbf{f}(\mathbf{x}, \mathbf{u}_0, \mathbf{d}) = 0$$
$$\mathbf{g}(\mathbf{x}, \mathbf{u}_0, \mathbf{d}) \leq 0$$
$$\mathbf{y}_0 = \mathbf{f}_{y_0}(\mathbf{x}, \mathbf{u}_0, \mathbf{d})$$

$$\mathbf{g}' = 0 \ \forall \ \mathbf{d}$$

Active for all disturbances

$\Longrightarrow$

$\mathbf{u}$ DOF left

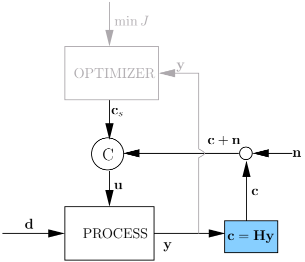
$$\min_{\mathbf{u}} J(\mathbf{x}, \mathbf{u}, \mathbf{d})$$
$$\begin{bmatrix} \mathbf{f}(\mathbf{x}, \mathbf{u}, \mathbf{d}) \\ \mathbf{g}'(\mathbf{x}, \mathbf{u}, \mathbf{d}) \end{bmatrix} = 0$$
$$\mathbf{y}_0 = \mathbf{f}_{y_0}(\mathbf{x}, \mathbf{u}, \mathbf{d})$$

The null space method

- Method for selecting self-optimizing controlled variables
- Assume as many c's as u's given disturbances $\mathbf{d}$
- Select a subset of measurements $\mathbf{y}$
- Proposal: Controlled variables as linear combination of measurements

$$\begin{bmatrix} c_1 \\ c_2 \\ \vdots \\ c_{n_c} \end{bmatrix} = \begin{bmatrix} h_{1,1}y_1 + h_{1,2}y_2 + \ldots + h_{1,n_y}y_{n_y} \\ h_{2,1}y_1 + h_{2,2}y_2 + \ldots + h_{2,n_y}y_{n_y} \\ \vdots \\ h_{n_c,1}y_1 + h_{n_c,2}y_2 + \ldots + h_{n_c,n_y}y_{n_y} \end{bmatrix}$$

- $$\mathbf{c} = \mathbf{H}\mathbf{y}$$



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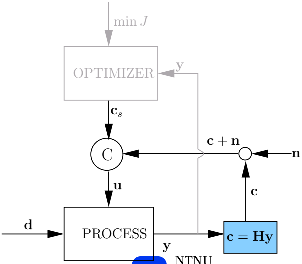
The null space method - Continued

How to find $\mathbf{H}$?

- Simple insight: $\Delta \mathbf{c}^{opt}(\mathbf{d})$ should be small

Reduced space optimization problem

$$\min_{\mathbf{u}} J(\mathbf{u}, \mathbf{d})$$
$$\mathbf{y}_0 = \mathbf{f}_{y0}(\mathbf{u}, \mathbf{d})$$



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- Find optimal sensitivity matrix:

$$\Delta\mathbf{y}^{opt} = \left(\frac{\mathrm{d}\mathbf{f}_y}{\mathrm{d}\mathbf{d}}\right)_{|\mathbf{u}^{opt}} \Delta\mathbf{d} = \mathbf{F}\Delta\mathbf{d}$$

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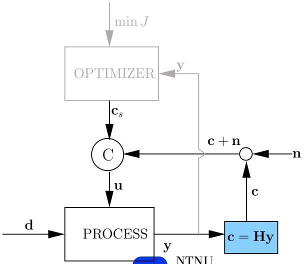

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- Select $\mathbf{c}$ such that

$$\Delta \mathbf{c}^{opt} = \mathbf{H}\Delta \mathbf{y}^{opt} = \mathbf{HF}\Delta \mathbf{d} = 0$$

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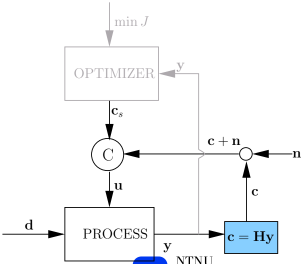

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- Achieved if

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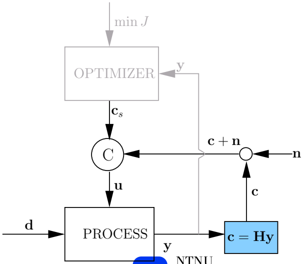

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- Select $\mathbf{H}$ in the left null space of $\mathbf{F}$

Reduced space optimization problem

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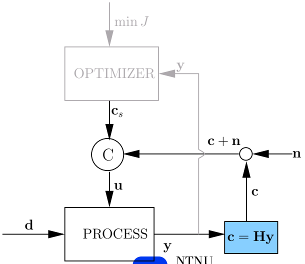

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- Need

$$\#y \geq \#u + \#d$$

Reduced space optimization problem

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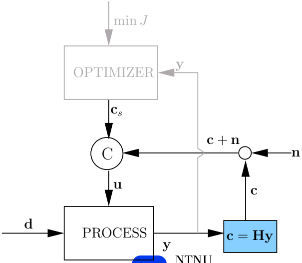

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Self-optimizing control - Simple example

- Objective: $\min_u J = (u-d)^2 \quad d^* = 0$
- Measurements:

$$y_1 = 0.9u + 0.1d$$
$$y_2 = 0.5u - d$$

- Optimal input:

$$\frac{\partial J}{\partial u} = 2(u^{opt} - d) = 0$$

$$\Rightarrow u^{opt} = d$$

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- Optimal change:

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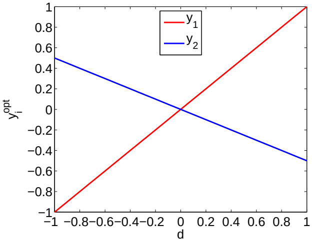

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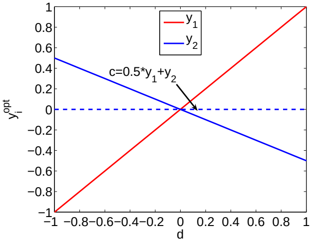
- Select $c = 0.5y_1 + y_2$



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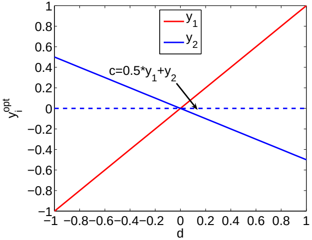
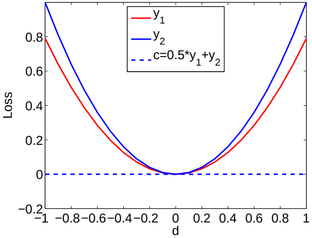
- Select $c = 0.5y_1 + y_2$
- Loss: $L = J(u,d) - J^{opt}(d)$





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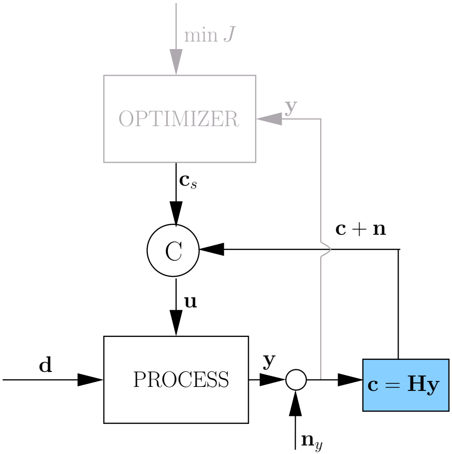
Self-optimizing control - How to select measurements?

- Dealt with disturbances $\mathbf{d}$
- How about measurement errors n_y?



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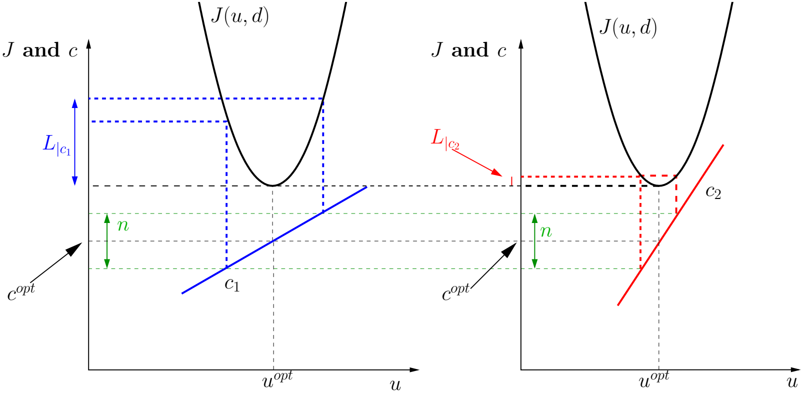
Self-optimizing control - How to select measurements?

- Implementation error



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Self-optimizing control - How to select measurements?

- Optimal selection criteria

$$y_{j|j=\{1,..,n_y\}} = \arg\min_{y_{0_i}} \bar{\sigma}\left(\tilde{\mathbf{J}}[\tilde{\mathbf{G}}^y]^{-1}\right)$$

- Suboptimal

$$y_{j|j=\{1,..,n_y\}} = \arg\max_{y_{0_i}} \underline{\sigma}(\tilde{\mathbf{G}}^y)$$

- Methods for handling too few and using all measurements

Models

- All measurements $\mathbf{y}_0$:

$$\Delta\mathbf{y}_0 = \mathbf{G}^{y_0}\Delta\mathbf{u} + \mathbf{G}_d^{y_0}\Delta\mathbf{d}$$

- Selected measurements $\mathbf{y}$:

$$\Delta\mathbf{y} = \mathbf{G}^{y}\Delta\mathbf{u} + \mathbf{G}_d^{y}\Delta\mathbf{d}$$

- $\tilde{\mathbf{J}} = \begin{bmatrix}\mathbf{J}_{uu}^{1/2} & \mathbf{J}_{uu}^{1/2}\mathbf{J}_{uu}^{-1}\mathbf{J}_{ud}\end{bmatrix}$ where $\mathbf{J}_{uu} = \frac{\partial^2 J}{\partial \mathbf{u}^2}$ and $\mathbf{J}_{ud} = \frac{\partial^2 J}{\partial \mathbf{u}\partial \mathbf{d}^T}$

Part II: Petlyuk column

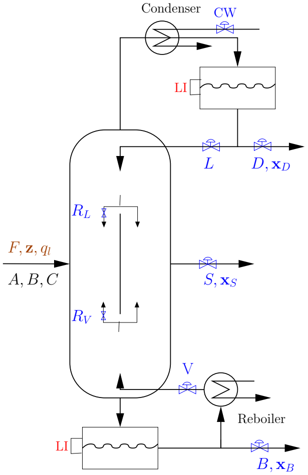
- Manipulated variables:

$$\mathbf{u}^T = [S, D, B, L, V, R_L, R_V]$$

- Steady-state degrees of freedom: 5
- Minimize cost: $\min_u V$
- Constraints:

$$x_{A,D} \geq 0.97 \quad \text{active}$$
$$x_{B,S} \geq 0.97 \quad \text{active}$$
$$x_{C,B} \geq 0.97 \quad \text{active}$$
$$\text{Flows} \geq 0 \text{ kmol/h}$$
$$0 \leq R_L, R_V \leq 1$$

- Disturbances: $[F\ z_A\ z_B\ q_l] =$ $[1\pm0.1\text{kmol/h}\ 1/3\pm0.1\ 1/3\pm0.1\ 0.477\pm0.1]$



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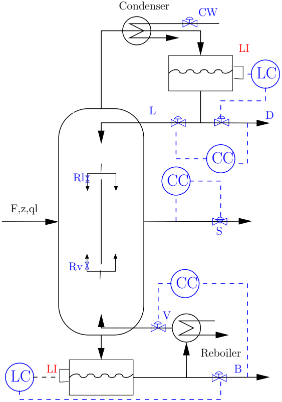
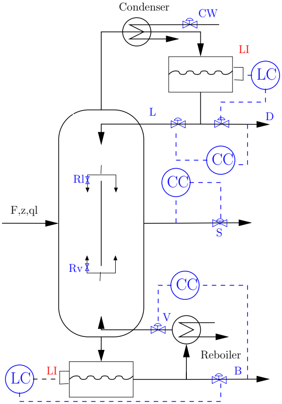
Petlyuk column

- Goal with case study two-fold:
    1. Compare NSM with previously proposed method for selecting self-optimizing controlled variables
    2. Compare with previously proposed structures (DT_S)



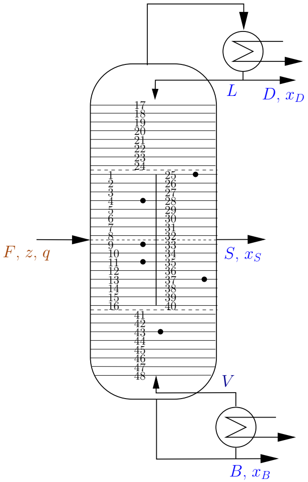
Petlyuk column

- Goal with case study two-fold:
    1. Compare NSM with previously proposed method for selecting self-optimizing controlled variables
    2. Compare with previously proposed structures (DT_S)
- Two new proposed structures
    - NSM using both R_V and R_L ⇒ using 7 temperatures
    - NSM using only R_L ⇒ using 7 temperatures



Petlyuk column - Continued - Loss

CS #	c_4	c_5	Disturbances $L_a[\%]$	Disturbances $L_w[\%]$	Noise $L_a^n[\%]$	Noise $L_w^n[\%]$
1	c_{tdf}^1	c_{tdf}^2	0.0252	0.2082	0.0117	0.0213
2	R_V	c_{odf}	0.0607	0.2247	0.0206	0.0847
3	R_V	DT_S	1.4916	11.88	0.0475	0.2108
4	R_V	R_L	12.9508	95.16	3.6254	9.3142
7	R_V	T_{34}	0.4063	2.8982	0.1034	0.1215
11	R_V	T_4	4.1310	42.029	0.0589	0.1046



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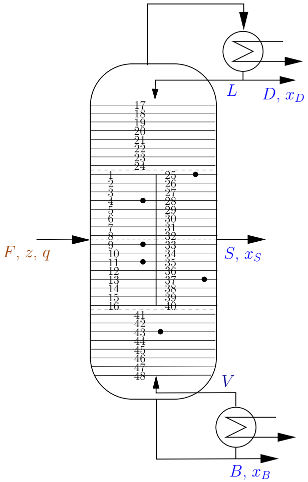

- Dynamic simulation
  - Decentralized control structure using PI(D) controllers
  - All PI(D) controllers tuned using Skogestad's IMC tuning rules

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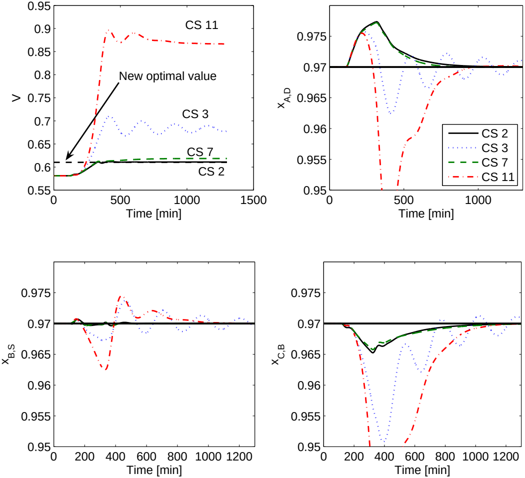
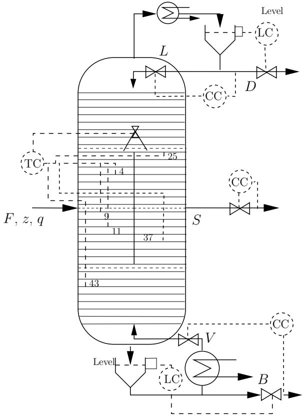
Petlyuk column - Dynamic simulations

- Step in feed composition $z_A : 0.33 \rightarrow 0.43$





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Other case studies

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Other case studies

Chapter 10, Case I:

Gas lifted wells: Save $0.34 - 0.65\%$ (USD $1.7 - 3.7$ million/year).

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Chapter 9:
: Energy savings by over-fractionation

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Part III: Topics in self-optimizing control

- Chapter 5: Disturbance classification:
  Propose several rules for disturbance classification

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- Chapter 5: Disturbance classification:
  Propose several rules for disturbance classification
- Chapter 6: Non-optimal nominal point:
  Show that non-optimal nominal point does not influence candidate ranking.

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Effect of non-optimal nominal point

- Nominal optimal point: $(\mathbf{u}^*, \mathbf{d}^*) = (\mathbf{u}^{opt}(\mathbf{d}^*), \mathbf{d}^*)$
- Actual nominal point: $(\mathbf{u}^0, \mathbf{d}^*) \neq (\mathbf{u}^*, \mathbf{d}^*)$

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Example: Nominal optimum $(u^*, d^*) = (0, 0)$

- Objective:

$$\min_u (u-d)^2$$

- Candidate controlled variables:

$$y_1 = 0.1(u-d)$$
$$y_2 = 2u - d$$
$$y_3 = 2u - 0.5d$$
$$y_4 = u - 3d$$

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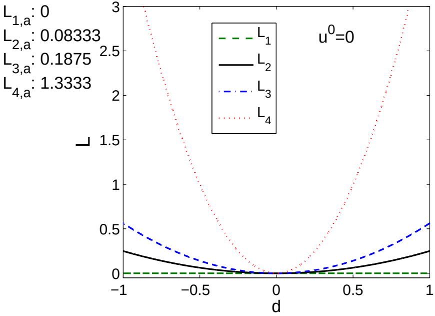

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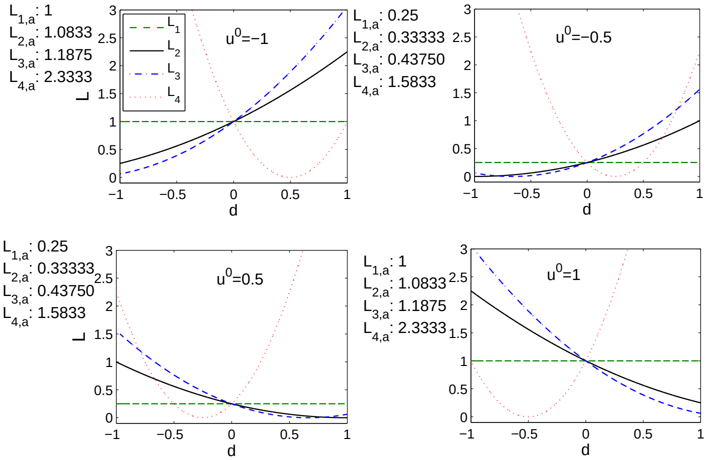
Effect of non-optimal nominal point: Example cont.



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Effect of non-optimal nominal point cont.

- Average increase in loss independent of what we control
- Non-nominal point no effect on candidate rank
- True for linear plant and quadratic objective

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Part III: Topics in self-optimizing control

- Chapter 5: Disturbance classification:
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- Chapter 7: Measurement combinations and control:
  - Use freedom in NSM to shape plant
  - Filter measurements to avoid RHZ

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- Appendix C: Perfect steady-state indirect control:
  E. Hori, S. Skogestad, V. Alstad

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Concluding remarks and further work

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  - Proposed a systematic method for selecting self-optimizing controlled variables
  - Generalized to handle measurement errors
  - Disturbance discrimination
  - Effect of nominal setpoint error in self-optimizing control
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- Acknowledgments: ABB, Norsk Hydro and The Research Council of Norway

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Petlyuk column: Energy savings by over-fractionation

- Energetically optimal to over-fractionate one product stream

Problem formulation

$$\min_{\mathbf{u}} V$$
$$x_{A,D} \geq x^0_{A,D}$$
$$x_{B,S} \geq x^0_{B,S}$$
$$x_{C,B} \geq x^0_{C,B}$$

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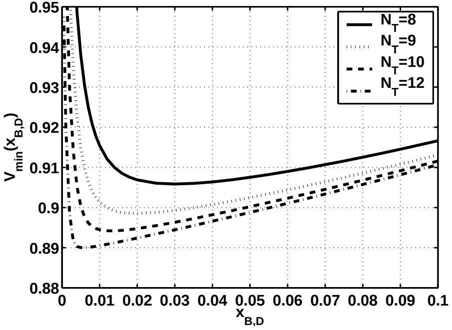
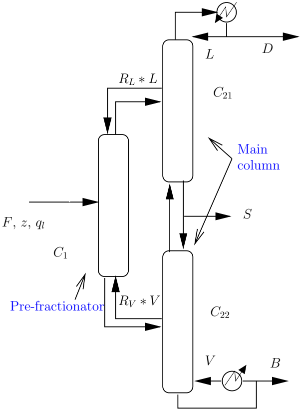
- Energetically optimal to over-fractionate one product stream
- Same vapor flow in main column





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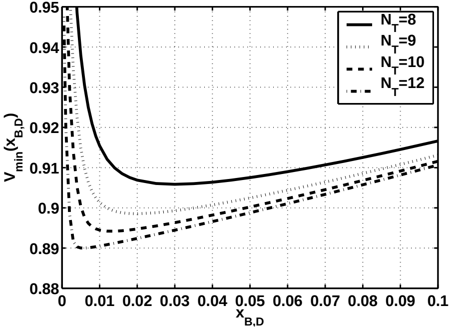

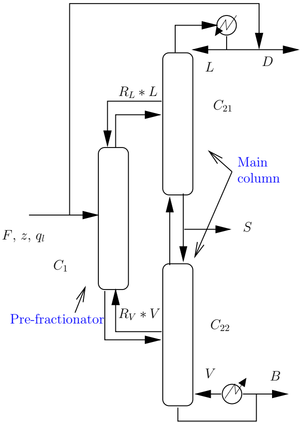

- Increased savings bypassing a portion of the feed

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Petlyuk column - Loss

CS #	Loss [%]							
	F_-	F_+	z_{A-}	z_{A+}	z_{B-}	z_{B+}	q_{l-}	q_{l+}
1	0.0	0.0	0.0171	0.0207	0.0166	0.0111	0.0001	0.0000
2	0.0	0.0	0.0037	0.1340	0.2247	0.1666	0.1876	0.1084
3	0.0	0.0	5.0840	11.8810	0.3469	0.8295	1.0441	1.1740
4	0.0	0.0	46.7037	6.3019	95.1660	9.8256	32.4629	6.0578
5	0.0	0.0	0.22826	2.6973	0.30078	0.40385	0.18903	0.12882
6	0.0	0.0	0.43234	inf	0.56891	1.7347	0.20494	0.17341
7	0.0	0.0	0.12667	1.3807	0.22211	0.18703	0.18794	0.11290
8	0.0	0.0	0.82264	inf	1.1556	inf	0.25233	0.31315
9	0.0	0.0	0.11772	1.7075	0.31570	0.16848	0.21236	0.10722
10	0.0	0.0	1.6053	inf	2.3873	inf	0.38058	1.0685
11	0.0	0.0	9.3786	42.029	0.22507	0.28417	0.66607	1.0851
12	0.0	0.0	inf	33.300	0.52408	0.28762	0.77086	1.0070

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	F_-	F_+	z_{A-}	z_{A+}	z_{B-}	z_{B+}	q_{l-}	q_{l+}
1	0.0	0.0	0.0171	0.0207	0.0166	0.0111	0.0001	0.0000
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CS #	Loss [%]							
	$n_{x^0_{A,D}+}$	$n_{x^0_{A,D}-}$	$n_{x^0_{C,B}+}$	$n_{x^0_{C,B}-}$	$n_{x^0_{B,S}+}$	$n_{x^0_{B,S}-}$	L_n^{max}	L_n^{avg}
1	0.0025	0.0095	0.0639	0.2082	0.0002	0.0007	0.0213	0.0117
2	0.0040	0.0110	0.0060	0.0174	0.0004	0.0004	0.0847	0.0206
3	0.0074	0.0207	0.0033	0.0034	0.0025	0.0075	0.2108	0.0475
4	0.0262	0.0253	0.0245	0.0311	0.2579	1.0198	9.3142	3.6254
5	0.0040	0.0110	0.0029	0.0035	0.3334	2.5693	0.0861	0.0673
6	0.0040	0.0110	0.0041	0.0063	0.3088	2.7112	0.0857	0.0587
7	0.0040	0.0112	0.0028	0.0026	0.4040	2.8982	0.1215	0.1034
8	0.0040	0.0110	0.0069	0.0126	0.3037	3.6569	0.0864	0.0586
9	0.0044	0.0128	0.0055	0.0042	0.7108	4.9155	0.7517	0.3805
10	0.0040	0.0110	0.0132	0.0289	0.3148	inf	0.0881	0.0667
11	0.0036	0.0108	0.0072	0.0106	0.3439	1.9349	0.1046	0.0589
12	0.0034	0.0131	0.0087	0.0130	0.3318	1.7321	0.1097	0.0963

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