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Emnemodul: Advanced Process Control

01. Nov. 2022. Time: 1400 – 1700.

Answer as carefully as possible, preferably using the available space. There are in total 6 questions. Answer all questions in English.

No printed or hand-written support material is allowed. A specific basic calculator is allowed.

Problem 1 – General questions (20%)

a) The plantwide control procedure from Skogestad is divided into two parts: top-down and bottom-up approaches. Briefly describe the goal of each part.

b) Describe the main steps of the top-down procedure for plantwide control.

c) What is self-optimizing control? Cite methods for finding self-optimizing variables.

d) What is extremum seeking control? What are the main assumptions for its implementation?

e) What is the meaning of "squeeze and shift" in the context of optimal operation?

f) In the operation of a distillation column, which purity constraint is expected to be active? When is a constraint on maximum vapor reflux expected to be active?

g) What is "snowballing" in the context of recycle processes? How can you avoid it?

h) Why do we avoid pairing CVs from the regulatory layer to MVs that may saturate?

a) The top-down approach has the goal of defining the control objectives for optimal operation, along with the TPM location. The bottom-up approach has the goal of closing the loops, from the fast, regulatory layer to the slow layers.

b) 1- Define optimization problem (cost function and constraints);
2- Identify DOFs and optimize plant for expected disturbances;
3- Define CVs for optimal operation:
- control active constraints;
- design self-optimizing CVs for unconstrained DOFs
4- Define location of TPM

c) Self-optimizing control is a procedure for finding CVs that allow for minimizing economic loss when controlled to a constant setpoint. Some methods for finding self-optimizing CVs are the nullspace method and the exact local method.

d) Extremum seeking control is a control strategy for optimal operation based on constant probing of the system. The main assumption for its implementation is that the plant is a steady-state map. It is also usually assumed that the optimization problem is convex.

e) "Squeeze and shift" refers to the necessity of tight control of hard constraints. If tight control is achieved, such that process variability is reduced ("squeeze"), the process can be operated with smaller back-off, "shifting" the setpoint closer to the constraint value, and therefore minimizing loss.

f) The purity constraint of the expensive product is expected to be active. Maximum vapor reflux constraints are expected to be active when vapor costs are low, and overpurifying is therefore inexpensive.

g) Snowballing refers to material accumulation inside a recycle loop due to disturbances. This can be avoided by setting the process TPM inside the recycle loop.

h) Usually CVs from the regulatory layer are related to process stability and cannot be given up. If the paired MV saturates, control of the CV is lost, and reconfiguring is needed.

Problem 2 – Optimal process operation (16%)

Consider a process with $n_u = 2$ steady-state degrees of freedom, $n_d = 1$ disturbance that affects economics, $n_g = 1$ inequality constraint $g = u_2 - u_1 \leq 0$, and $n_y = 2$ extra available measurements. The optimal conditions for the process for different disturbance values are given by the following table:

	$d = 0.5$	$d = 0.6$
g	0	0
y_1	0.45	0.6
y_2	0.4	0.52

a) Analyze the optimal operation for this problem, in terms of active constraints and unconstrained DOFs. Explain why the optimal CVs are $c_1 = u_2 - u_1$ and $c_2 = Hy$.

b) Calculate the optimal sensitivity matrix F for this system. Using this, calculate the selection matrix H through the nullspace method.

c) Identification of the system was performed, and it was found that the steady-state gain from the MVs to the measurements is $G^y = \begin{bmatrix} -0.8 & -1.0 \\ 1.1 & -0.6 \end{bmatrix}$, such that $\Delta y = G^y \Delta u$. With this additional information and based on the items above, determine the gain matrix G from the MVs to the CVs for optimal operation, and determine the ideal pairing between these MVs and CVs using the steady-state RGA of the system.

a) Steady-state DOFs: $n_u = 2$
Active constraints: $n_g = 1$
$\Rightarrow$ Unconstrained DOFs: $2 - 1 = 1$

$\Rightarrow$ Control active constraint ($c_1 = u_2 - u_1$) and one self-optimizing variable ($c_2 = Hy$)

b) $F = \dfrac{\Delta y^{opt}}{\Delta d} = \begin{bmatrix} \dfrac{0.6 - 0.45}{0.6 - 0.5} \\ \dfrac{0.52 - 0.4}{0.6 - 0.5} \end{bmatrix} = \begin{bmatrix} 1.5 \\ 1.2 \end{bmatrix}$

$\Rightarrow HF = [h_1 \ \ h_2] \begin{bmatrix} 1.5 \\ 1.2 \end{bmatrix} = 0$

$1.5 h_1 + 1.2 h_2 = 0 \Rightarrow h_2 = \dfrac{-1.5}{1.2} h_1$

$h_1 = 1 \Rightarrow h_2 = -1.25$

$\Rightarrow H = [1 \ \ -1.25]$, $c_2 = Hy = y_1 - 1.25\, y_2$

c) $\Delta c = G\,\Delta u$, $\Delta c_1 = \begin{bmatrix} -1 & 1 \end{bmatrix} \Delta u$

$\Delta c_2 = H \Delta y = H G^Y \Delta u$

$$HG^Y = \begin{bmatrix} 1 & -1.25 \end{bmatrix} \begin{bmatrix} -0.8 & -1.0 \\ 1.1 & -0.6 \end{bmatrix} = \begin{bmatrix} -1\times 0.8 - 1.25\times 1.1 & -1 + 1.25\times 0.6 \end{bmatrix}$$

$$= \begin{bmatrix} -2.175 & -0.25 \end{bmatrix}$$

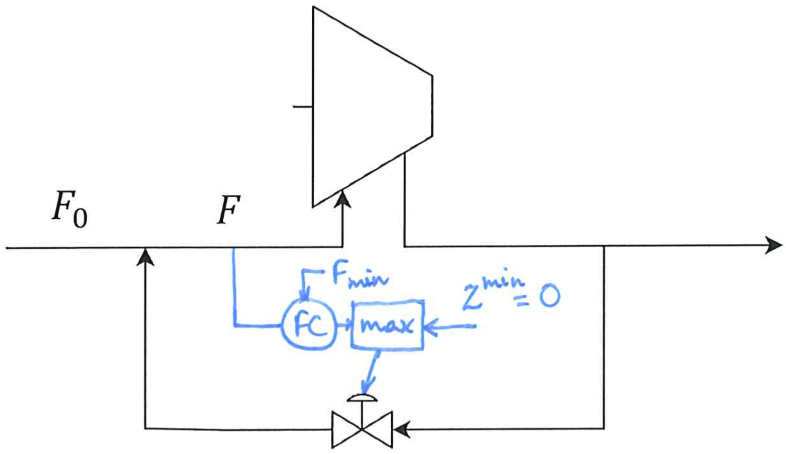
$$\Rightarrow G = \begin{bmatrix} -1 & 1 \\ -2.175 & -0.25 \end{bmatrix} \qquad \Rightarrow RGA = \begin{bmatrix} \lambda & 1-\lambda \\ 1-\lambda & \lambda \end{bmatrix}$$

$$\lambda = \frac{-1 \times (-0.25)}{-1\times(-0.25) - 1\times(-2.175)} = 0.1031 \qquad \Rightarrow RGA = \begin{bmatrix} 0.1031 & 0.8969 \\ 0.8969 & 0.1031 \end{bmatrix}$$

$\Rightarrow$ Pair u_1 to c_2 , u_2 to c_1

Problem 3 – Anti-surge control (15%)

Consider the following anti-surge system:



In this system, the compressor must be fed a minimum flow $F \geq F_{min}$ in order to avoid abnormal operation. However, the system should also operate with the recycle valve fully closed whenever possible, in order to avoid additional compression costs. The process feed F_0 is the main disturbance for the process, and the recycle valve is the only available MV.

z

a) State the possible operating regions for optimal operation of the system, in terms of the active constraints. Are the constraints related to an MV or a CV?

b) Propose a control structure that can operate optimally in all regions.

c) Can this be done with only a PID controller (i.e. without advanced control elements)?

a) $d = F_0 > F_{min}$ ⇒ Region I: $z = 0$ active (MV)

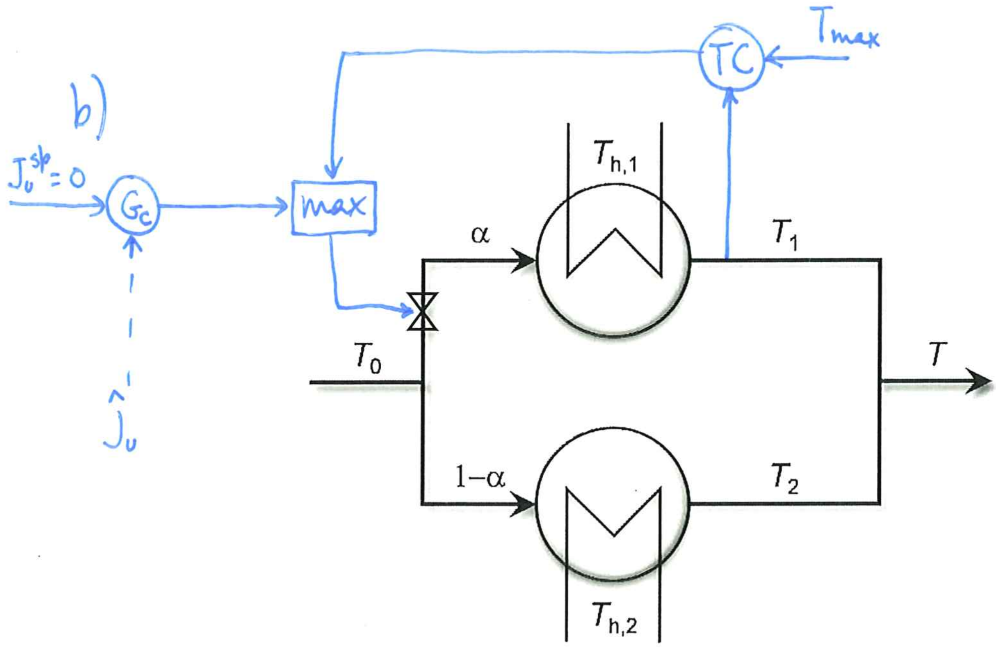
$d = F_0 < F_{min}$ ⇒ Region II: $F = F_{min}$ active (CV)

b) Here, a selector can be used to switch between objectives.

c) Yes. The selector is unnecessary, since the MV saturates when the paired CV should be given up.

Problem 4 – Heat exchanger networks (15%)

Consider the optimal operation of the following heat exchanger network:



The objective of the operation is to maximize the outlet temperature ($J = T$). In Exercise 1 we derived a simple analytical expression for the cost gradient, $J_u = \frac{(T_2 - T_0)^2}{T_{h,2} - T_0} - \frac{(T_1 - T_0)^2}{T_{h,1} - T_0}$, with the MV being the split ratio α.

Assume that the system is subject to a constraint on the maximum allowed temperature on the top branch, $T_1 \leq T_{max}$, which can be active or inactive due to disturbances.

a) What are the possible operating regions for optimal operation? What are the corresponding CVs for each region?

b) Propose a feedback control structure that operates optimally in all scenarios.

c) Why is $c = T$ not a good self-optimizing variable?

a) Region I: unconstrained ($c = J_u$)
Region II: $T_1 = T_{max}$ active ($c = T_1$)

c) Controlling the cost function to a fixed setpoint in an unconstrained problem is bad for a number of reasons:

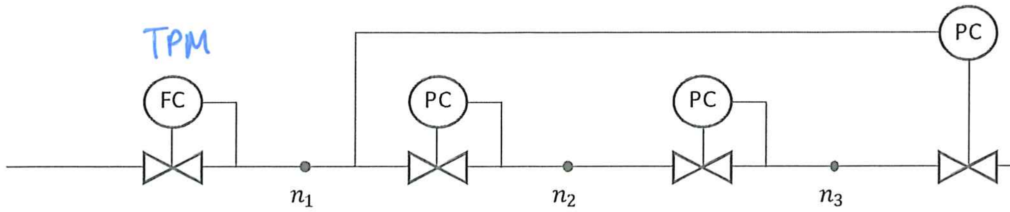
- The correct setpoint is usually unknown, and therefore the system will be subject to either infeasible operation, or multiplicity of steady states;

- Even if the correct setpoint is known, the process gain is zero at the optimum, creating problems for controller tuning.

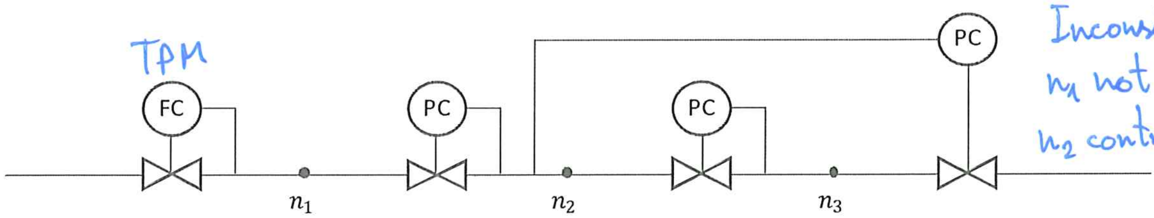
Problem 5 – TPM and inventory control (10%)

a) What are the conditions for local consistency and global consistency of an inventory control structure? How are they related?

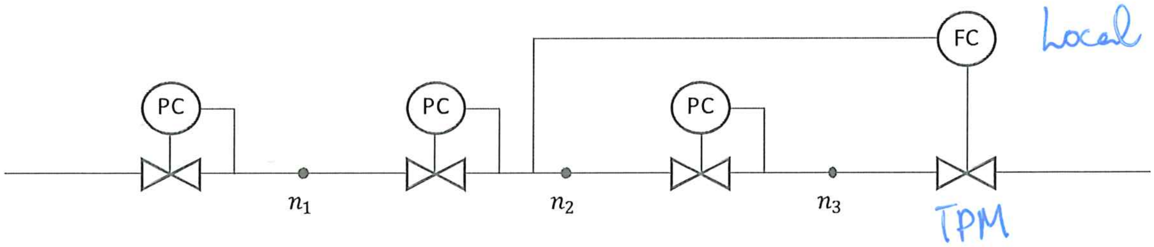
b) Analyze the 6 control structures below. Indicate the location of the TPM and if they are locally and/or globally consistent. Justify your answers.



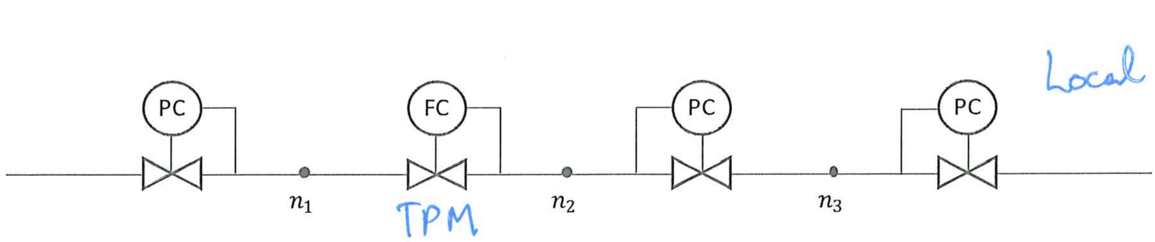
Global consistent, not local. n_1 is associated to a long loop.



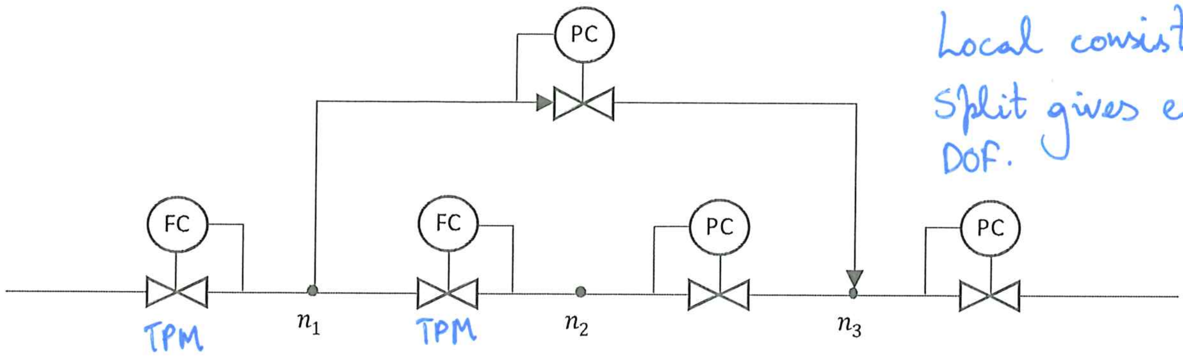
Inconsistent. n_1 not controlled, n_2 controlled twice.



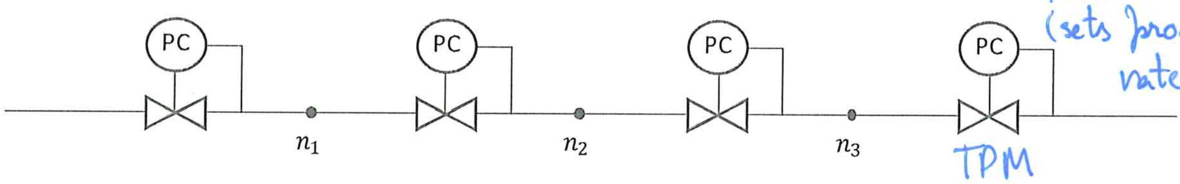
Local consistent.



Local consistent.



Local consistent. Split gives extra DOF.



Local consistent. PC acts as TPM (sets production rate)

a) Global consistency is attained when the steady-state mass balances of the plant are satisfied by the inventory control layer. Local consistency is attained when those balances are satisfied for each inventory independently. Local consistency results in global consistency, but the reverse is not true.

Problem 6 – Controller tuning (20%)

Consider the system described by the following model, with time constants in seconds:

$$y = \frac{2\,(-0.5\,s+1)}{(5\,s+1)(2\,s+1)}\,u + \frac{8\,e^{-2\,s}}{(5\,s+1)(10\,s+1)}\,d_1 + \frac{1}{2\,s+1}\,d_2$$

The measurement of d_1 is available with a delay of 1 second, and we wish to use this measurement of d_1 to improve control performance.

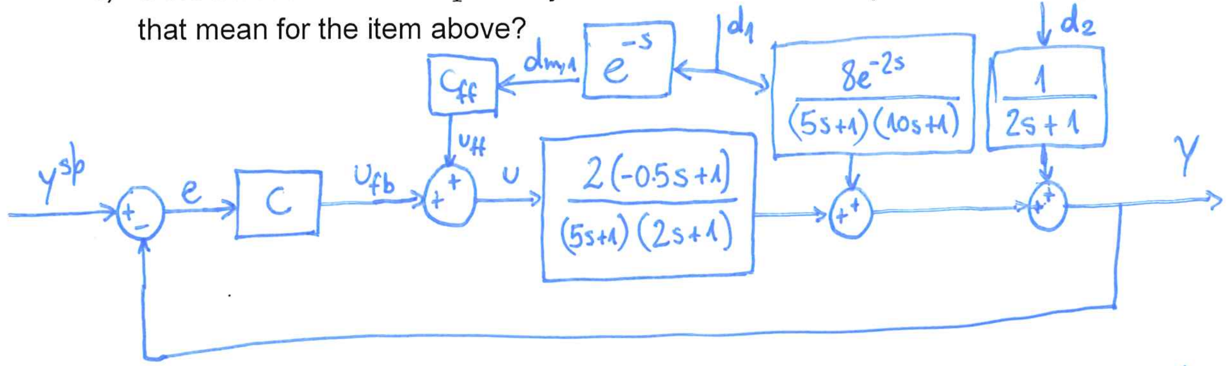
a) What is the control structure that should be used in this case? Draw the block diagram, along with all process transfer functions, of the proposed control structure.

b) Tune the feedback controller from the structure you proposed using the SIMC rules. Use the half-rule when necessary to reduce the model to a first order plus time delay form and choose the respective tuning parameter such that tight control is achieved.

c) Find the ideal controller for rejecting the effect of d_1 on y. Is this controller realizable? If not, propose a realizable solution.

d) If the measurement of d_1 is subject to an additional delay of 10 seconds, what would that mean for the item above?

a)



b) Half-rule approximation: $G(s) = \dfrac{2(-0.5s+1)}{(5s+1)(2s+1)} \cong \dfrac{k\,e^{-\theta s}}{\tau_1 s+1}$

$\tau_1 = 5 + \frac{2}{2} = 6$

$\theta = 0.5 + \frac{2}{2} = 1.5$

$\Rightarrow G_{HR}(s) = \dfrac{2\,e^{-1.5s}}{6s+1}$ $\Rightarrow$ choose $\tau_c = 1.5$ for tight control

SIMC rules: $C = K_c\left(1+\dfrac{1}{\tau_I s}\right)$, $K_c = \dfrac{1}{k}\cdot\dfrac{\tau_1}{\theta+\tau_c} = \dfrac{1}{2}\cdot\dfrac{6}{\underbrace{1.5+1.5}_{3}} = 1$

$\tau_I = \min(\tau_1, 4\cdot(\tau_c+\theta)) = \min(6, \underbrace{4\times(1.5+1.5)}_{12}) = 6$

c) Feedforward control design: $y = G u + G_{d,1} d_1 = 0$

$u = u_{ff} = c_{ff} \cdot d_m = c_{ff} \cdot g_{d,m} \cdot d_1 \Rightarrow (G \cdot c_{ff} \cdot g_{d,m} + G_{d,1}) d_1 = 0$

$$\Rightarrow c_{ff} = \frac{-G_{d,1}}{G \cdot g_{d,m}} = \frac{\dfrac{-8e^{-2s}}{\cancel{(5s+1)}(10s+1)}}{\dfrac{2(-0.5s+1)}{\cancel{(5s+1)}(2s+1)} \cdot e^{-s}} = \frac{-4 \cdot (2s+1)}{10s+1} \cdot \frac{e^{-s}}{-0.5s+1}$$

unstable! (not realizable)

Approximate $-0.5s + 1 \approx e^{-0.5s} \Rightarrow c_{ff} = \dfrac{-4(2s+1)}{10s+1} e^{-0.5s}$

(realizable)

d) This would mean that feedforward control would have a poorer performance. The ideal controller would become $c_{ff} = \dfrac{-4(2s+1)}{10s+1} \dfrac{e^{-0.5s}}{e^{-10s}}$

$\Rightarrow c_{ff} = \dfrac{-4(2s+1)}{10s+1} e^{9.5s}$, which is non-realizable. The possible solutions are either using $c_{ff} = -4$, or acting aggressively with a high lead on c_{ff}.