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Model Predictive Control for Bottleneck Isolation with Unmeasured Faults

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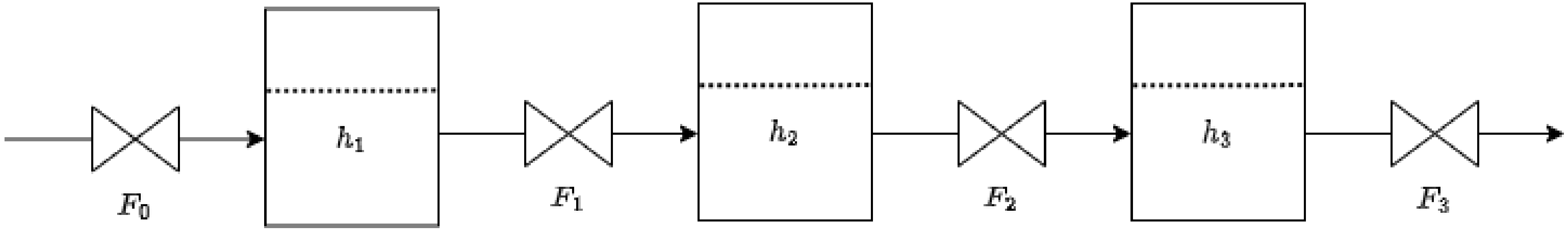
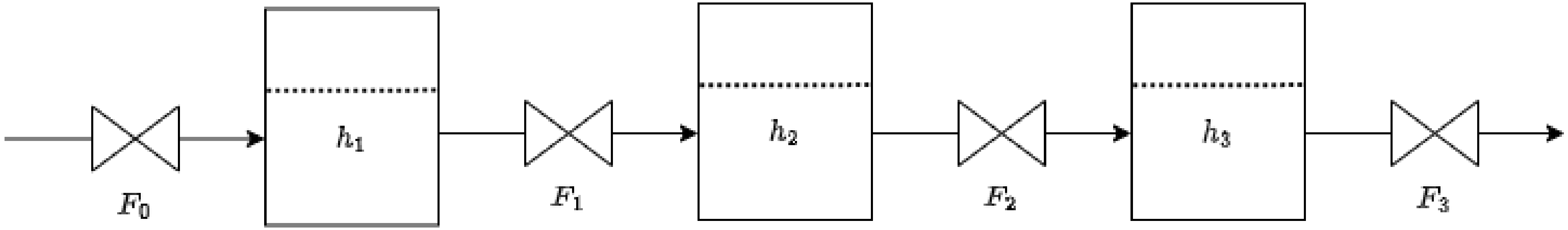
Inventory control (level, pressure)

- All inventories (level, pressure) must be regulated by
  - Controller, or
  - “self-regulated” (e.g., overflow for level, open valve for pressure)
  - Exception closed system: Must leave one inventory (level) uncontrolled



Inventory control objectives

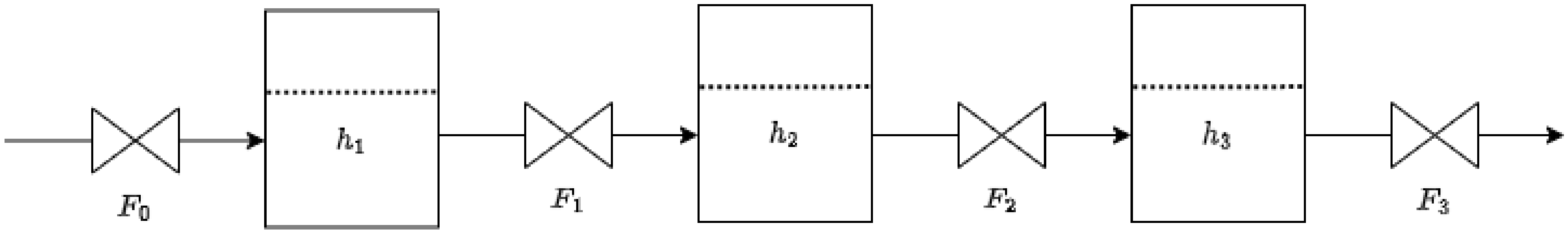
1. Keep inventories (levels h_i) constant ("normal level control")
2. Reduce variations in flows F_i ("averaging level control")



Zotica, C., Forsman, K., and Skogestad, S. (2022). Bidirectional inventory control with optimal use of intermediate storage. Computers & Chemical Engineering, 159,107677.

Inventory control objectives

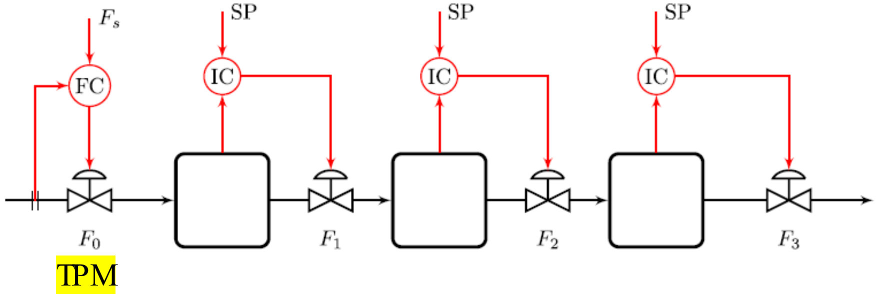
1. Keep inventories (levels) constant (“normal level control”)
2. Reduce variations in flow (“averaging level control”)
3. Rearrange loops when TPM (bottleneck) moves
4. Maximise throughput by bottleneck isolation



TPM = throughput manipulator = «gas pedal of proces»

Zotica, C., Forsman, K., and Skogestad, S. (2022). Bidirectional inventory control with optimal use of intermediate storage. Computers & Chemical Engineering, 159,107677.

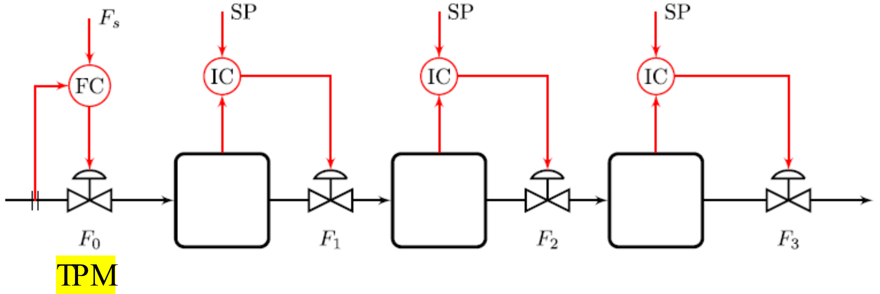
Inventory control for units in series



(a) Inventory control in direction of flow (for given feed flow, TPM = F_0)

TPM = throughput manipulator

Inventory control for units in series



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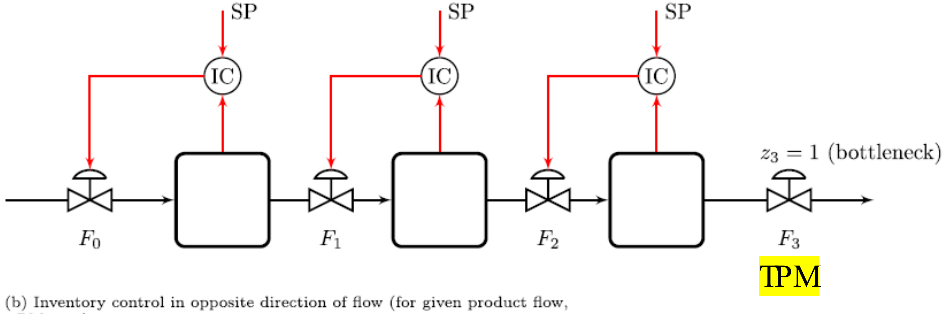
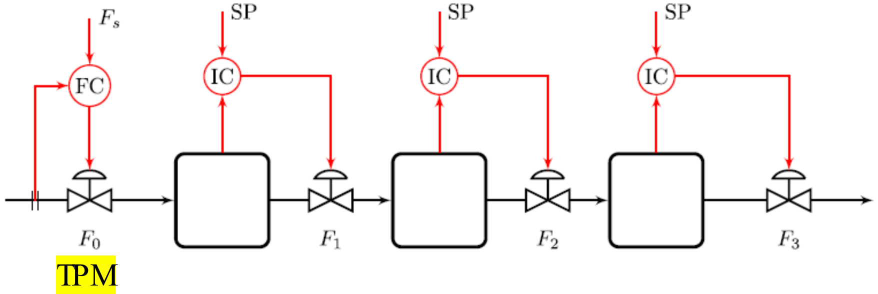


(b) Inventory control in opposite direction of flow (for given product flow, TPM= F_3)

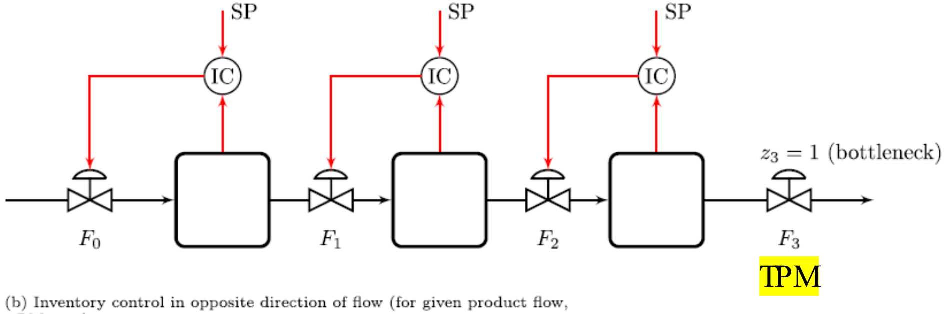
TPM = throughput manipulator

Inventory control for units in series

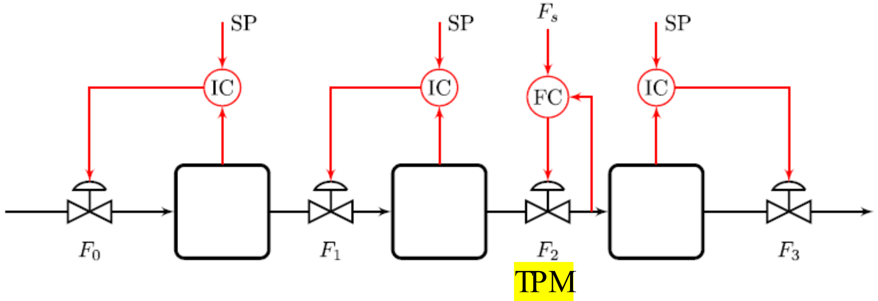
Radiating rule (Price et al, 1994):
Inventory control should be "radiating" around a given flow (TPM).



(a) Inventory control in direction of flow (for given feed flow, TPM = F_0)



(b) Inventory control in opposite direction of flow (for given product flow, TPM= F_3)



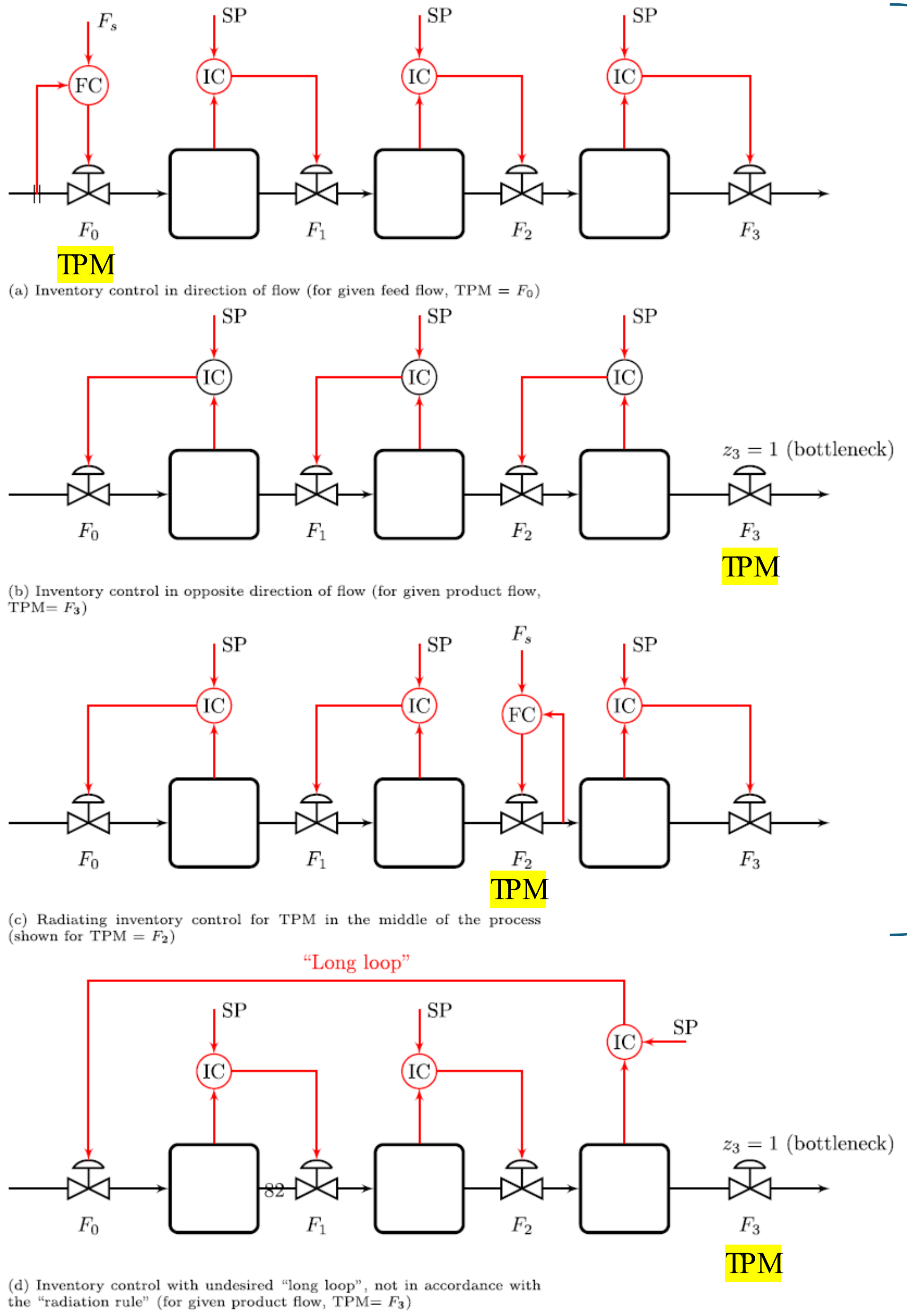
(c) Radiating inventory control for TPM in the middle of the process (shown for TPM = F_2)

)

TPM = throughput manipulator

Inventory control for units in series

Radiating rule (Price et al, 1994): *Inventory control should be "radiating" around a given flow (TPM).*

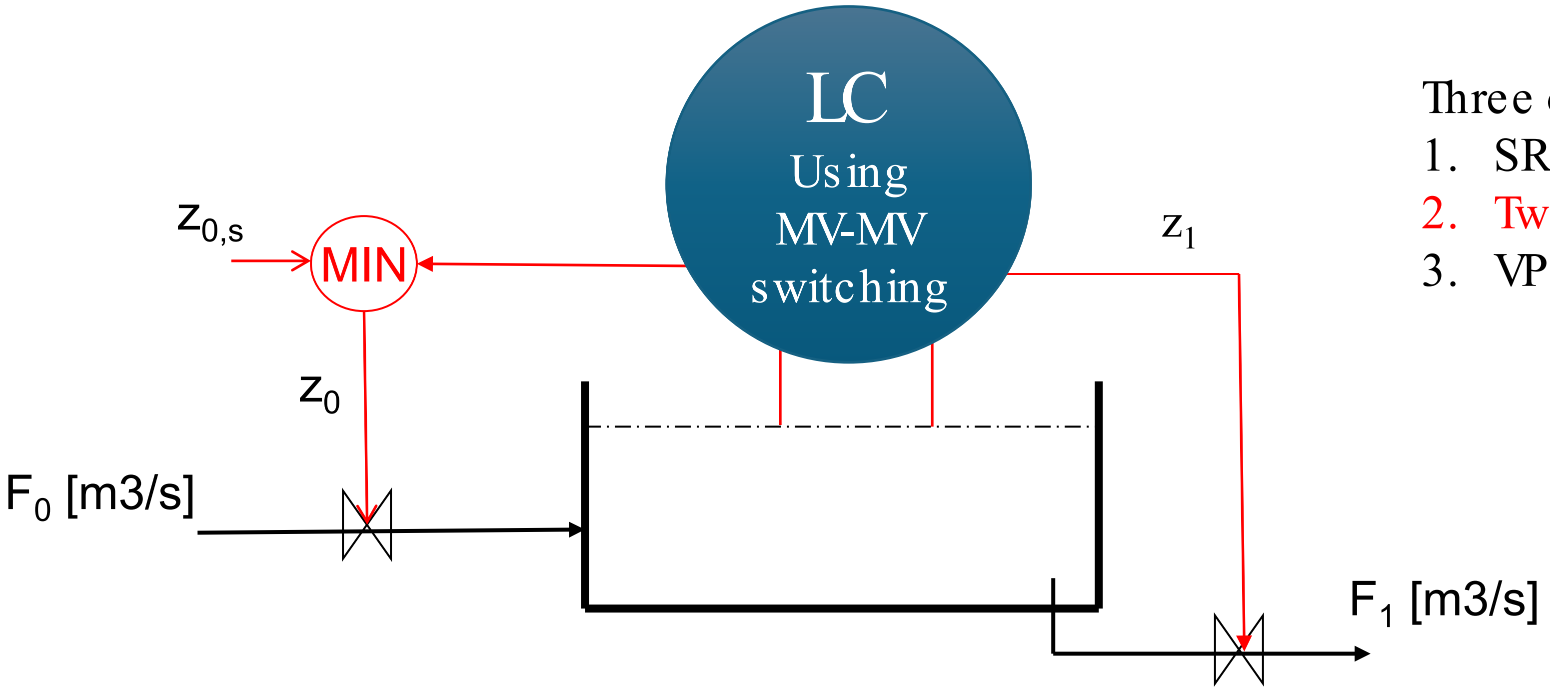


Follows radiation rule

Does NOT follow radiation rule

TPM = throughput manipulator

"Bidirectional inventory control"



Three options for MV-MV switching

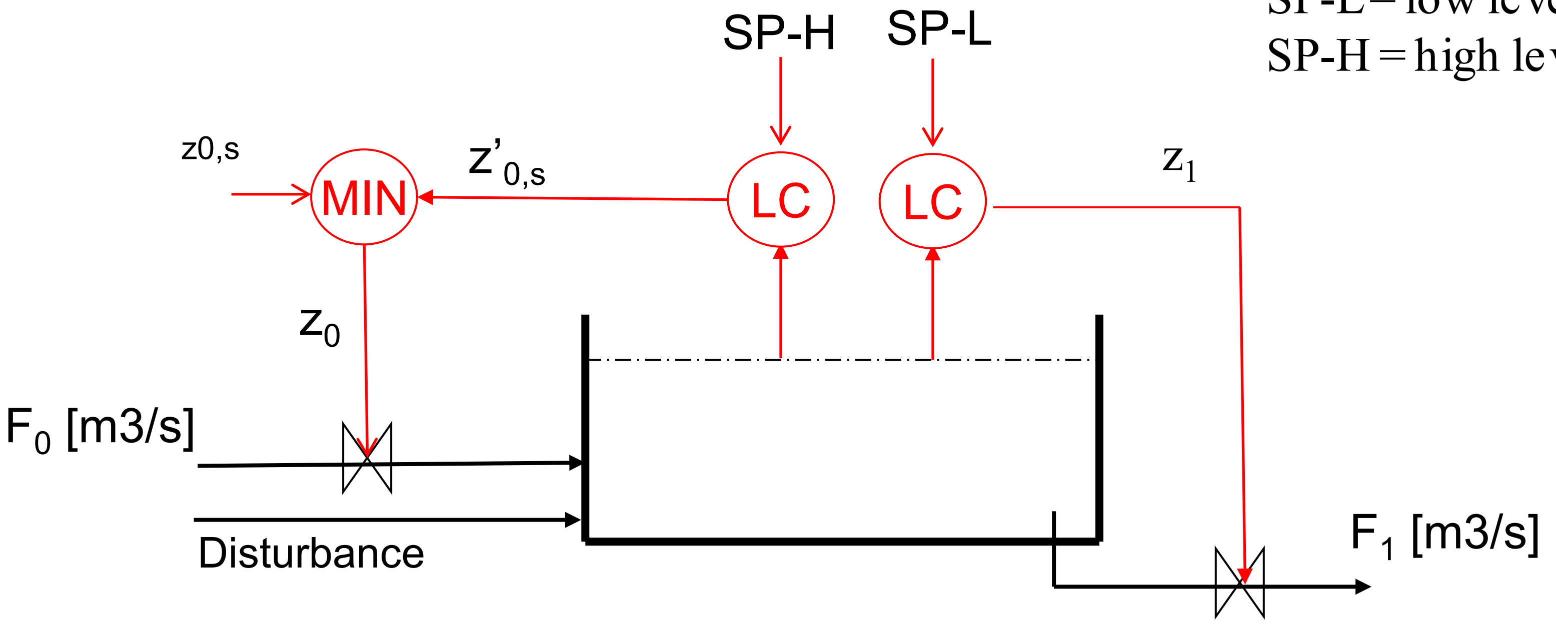
1. SRC (problem since F_{0s} varies)
2. Two controllers
3. VPC ("Long loop" for z1, backoff)

MV = manipulated variable

SRC = split range control

VPC = valve position control

Alt. 2: Two controllers (recommended)



SP-L = low level setpoint (10%)
SP-H = high level setpoint (90%)

Use of two setpoints is good for using buffer dynamically to isolate bottleneck!!

Generalization of bidirectional inventory control

Reconfigures automatically with optimal buffer management!!

Maximize throughput:
$F_s = \infty$

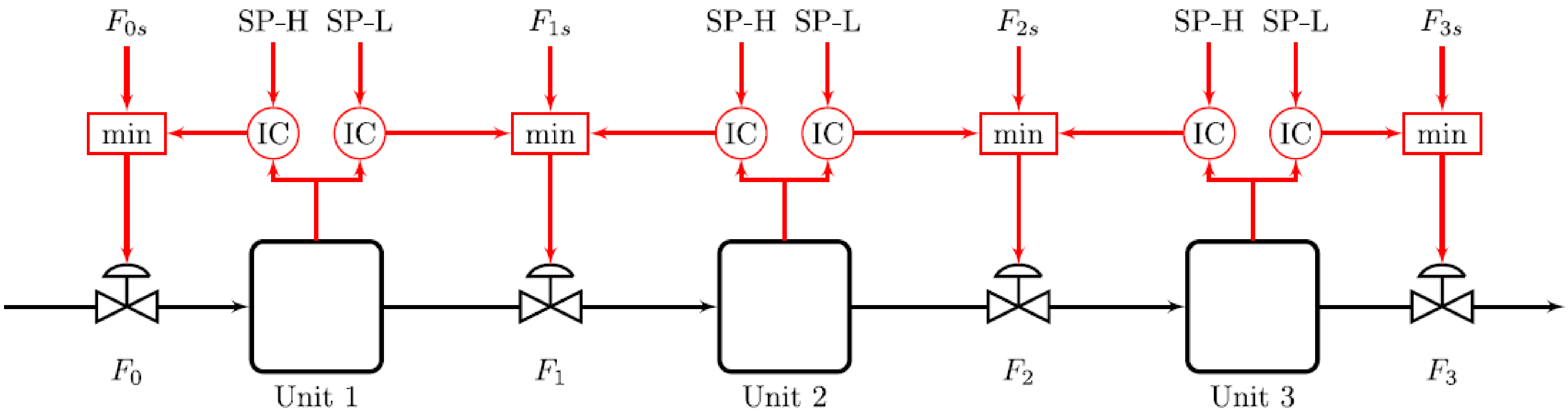


Fig. 36. Bidirectional inventory control scheme for automatic reconfiguration of loops (in accordance with the radiation rule) and maximizing throughput. Shinskey (1981) Zotică et al. (2022).
SP-H and SP-L are high and low inventory setpoints, with typical values 90% and 10%.
Strictly speaking, with setpoints on (maximum) flows ($F_{i,s}$), the four valves should have slave flow controllers (not shown). However, one may instead have setpoints on valve positions (replace $F_{i,s}$ by $z_{i,s}$), and then flow controllers are not needed.

F.G. Shinskey, «Controlling multivariable processes», ISA, 1981, Ch.3

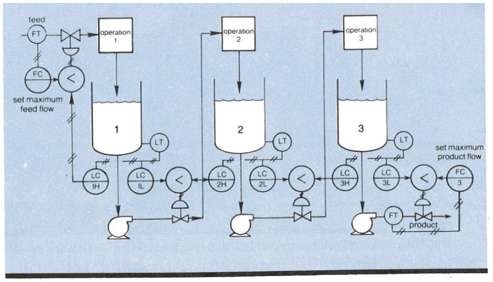
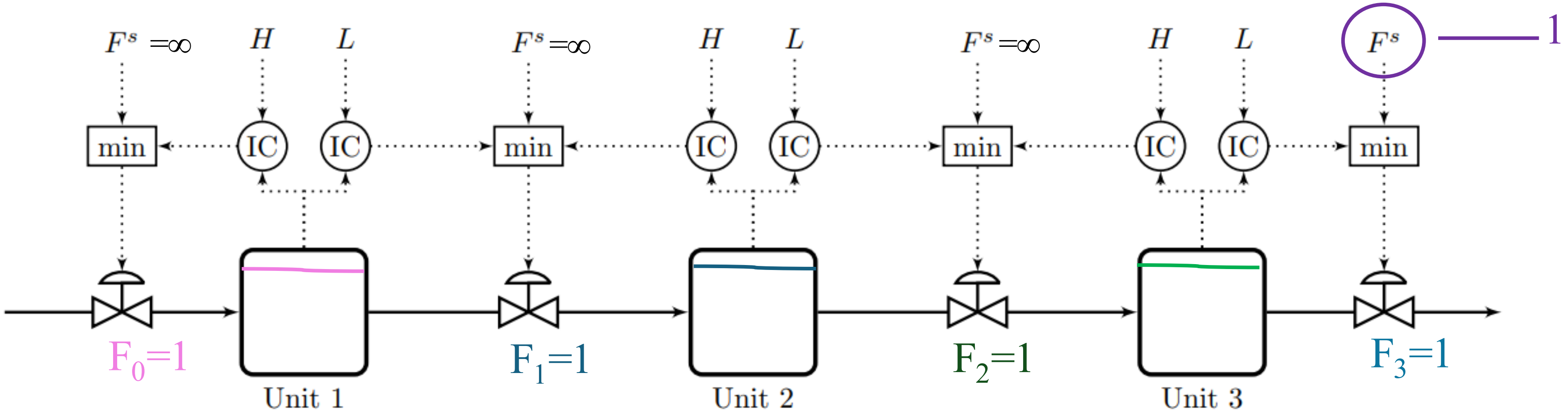
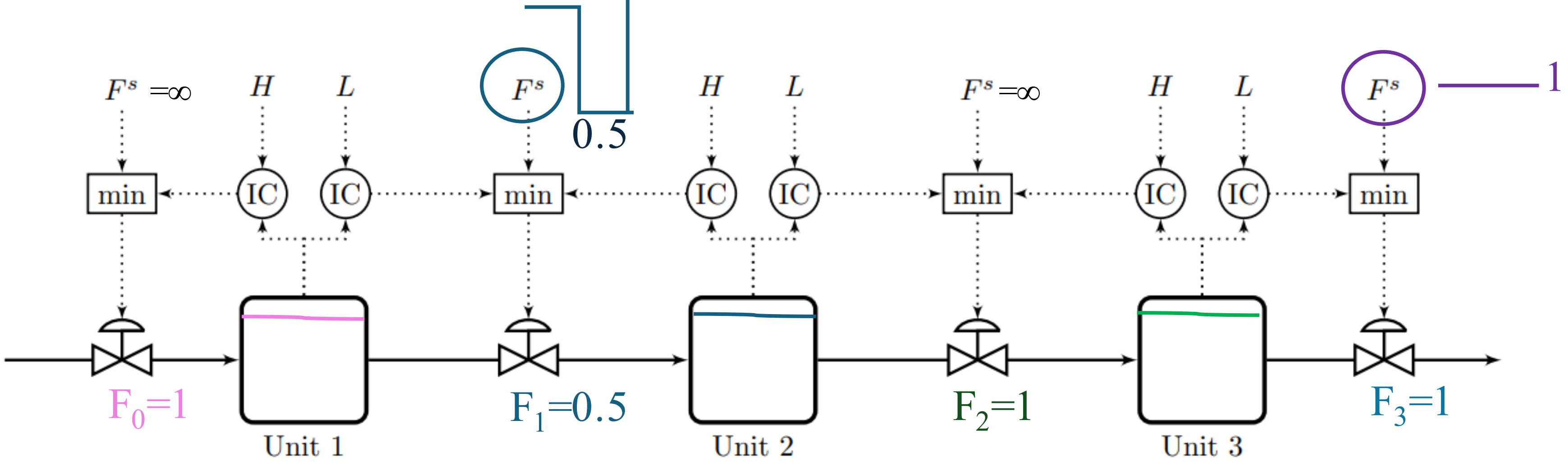


Fig. 3-7. Production rate can be set at either end of the process or constrained at any intermediate point without loss of inventory control.

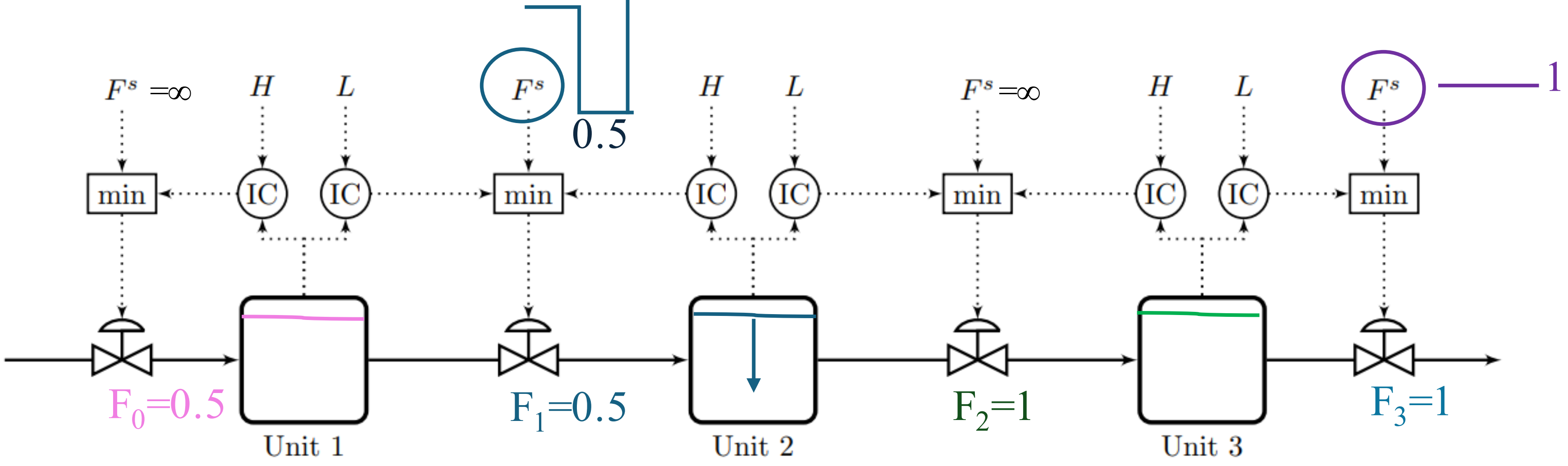
Cristina Zotica, Krister Forsman, Sigurd Skogestad ,»Bidirectional inventory control with optimal use of intermediate storage», Computers and chemical engineering, 2022



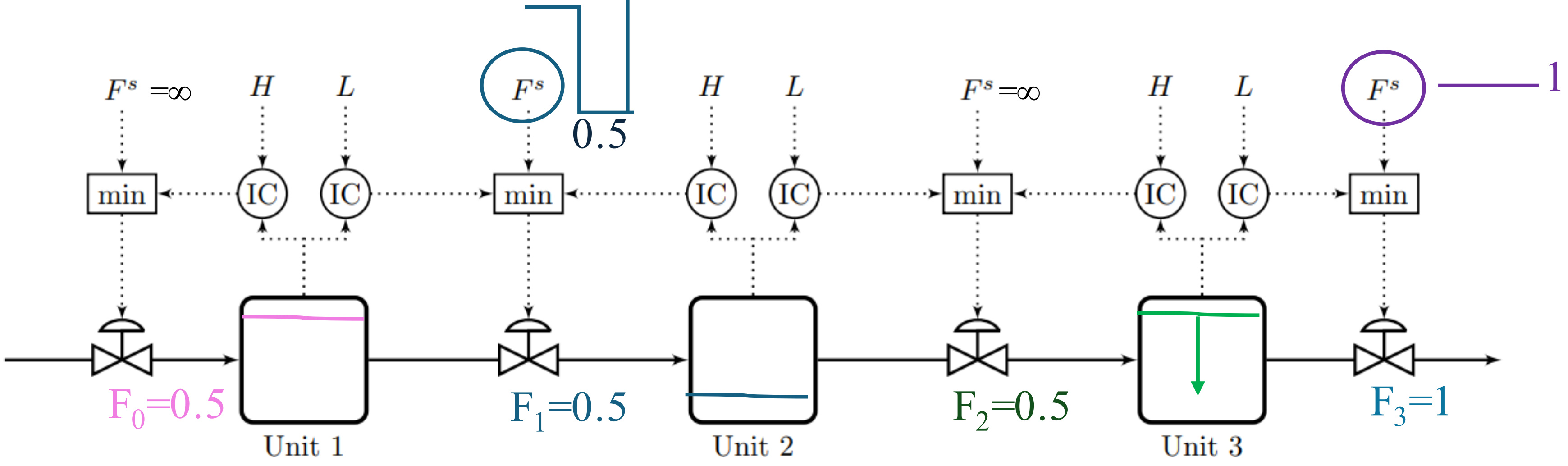
$F^s = \infty$
H
L
min
IC
IC
$F^s = \infty$
H
L
min
IC
IC
$F^s = \infty$
H
L
min
IC
IC
F^s
1
min
$F_0=1$
Unit 1
$F_1=1$
Unit 2
$F_2=1$
Unit 3
$F_3=1$



F^s =∞
H
L
min
IC
IC
F^s
0.5
min
IC
IC
H
L
F^s=∞
min
IC
IC
H
L
F^s
1
min
F_0=1
Unit 1
F_1=0.5
Unit 2
F_2=1
Unit 3
F_3=1



$F^s = \infty$
H
L
F^s
0.5
H
L
$F^s = \infty$
H
L
F^s
1
min
IC
IC
min
IC
IC
min
IC
IC
min
$F_0 = 0.5$
Unit 1
$F_1 = 0.5$
Unit 2
$F_2 = 1$
Unit 3
$F_3 = 1$



$F^s = \infty$
H
L
F^s
0.5
H
L
$F^s = \infty$
H
L
F^s
1
min
IC
IC
min
IC
IC
min
IC
IC
min
F_0=0.5
Unit 1
F_1=0.5
Unit 2
F_2=0.5
Unit 3
F_3=1

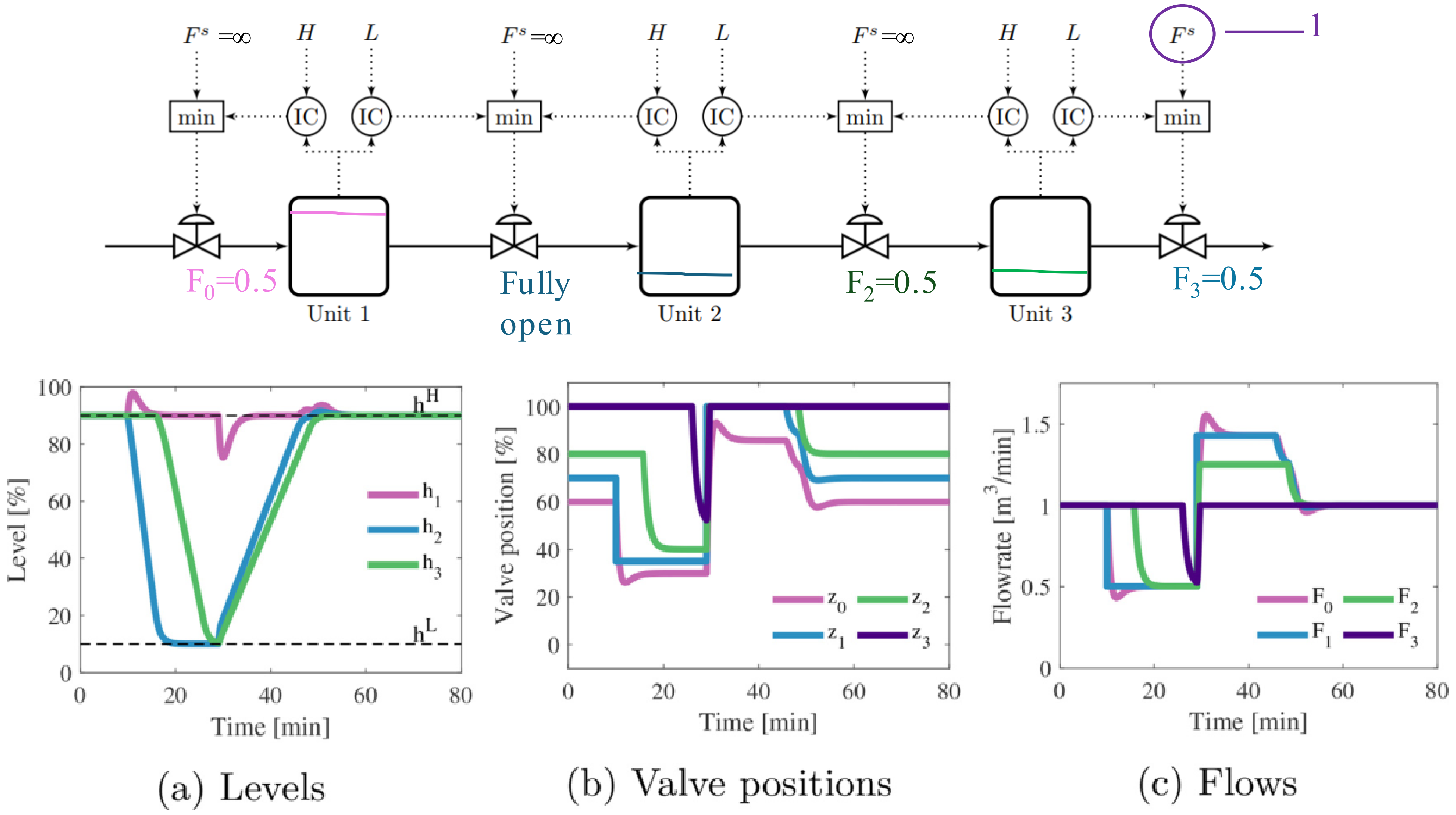
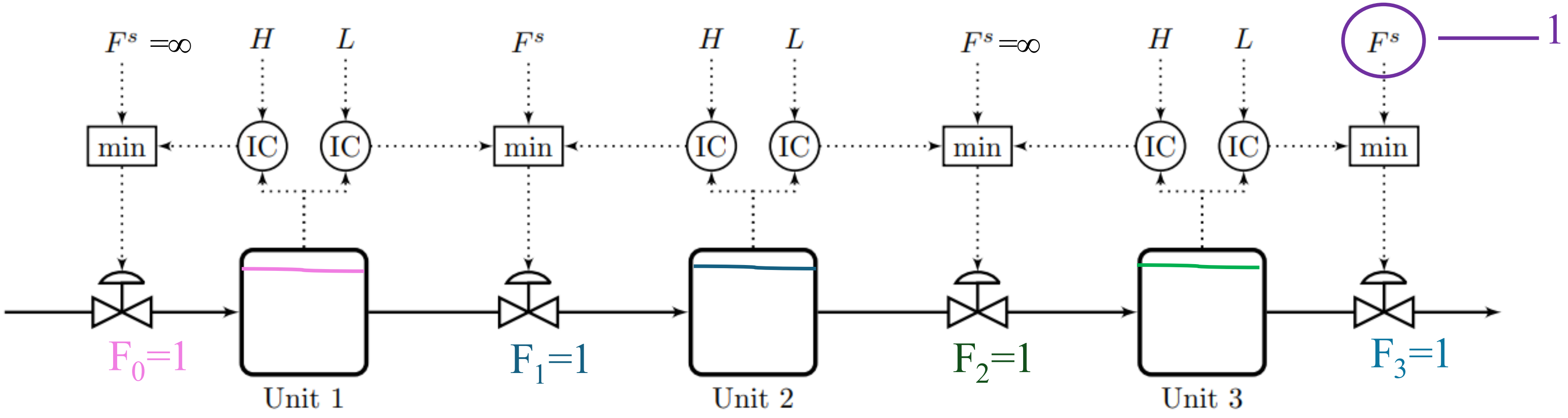


Fig. 13. Simulation of a temporary (19 min) bottleneck in flowrate F_1 for the proposed control structure in Fig. 10. The TPM is initially at the product (F_3).



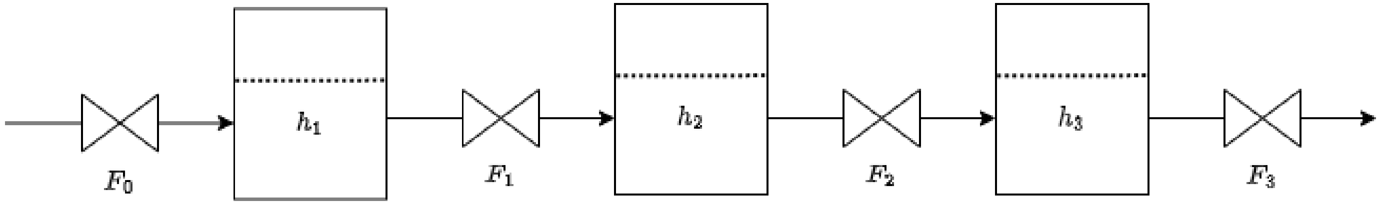
Challenge: Can MPC be made to do his? Optimally reconfigure loops and find optimal buffer?

MPC for inventory control

Challenges:

1. No knowledge of future bottlenecks/disturbances
2. Inaccurately identified bottlenecks (off-set free behaviour)
3. Maintain computational tractability

MPC formulation



- Mass balance for inventory (series of integrators)
- Choice of objective (cost J) ??

$$\min_{h,F} \ J$$

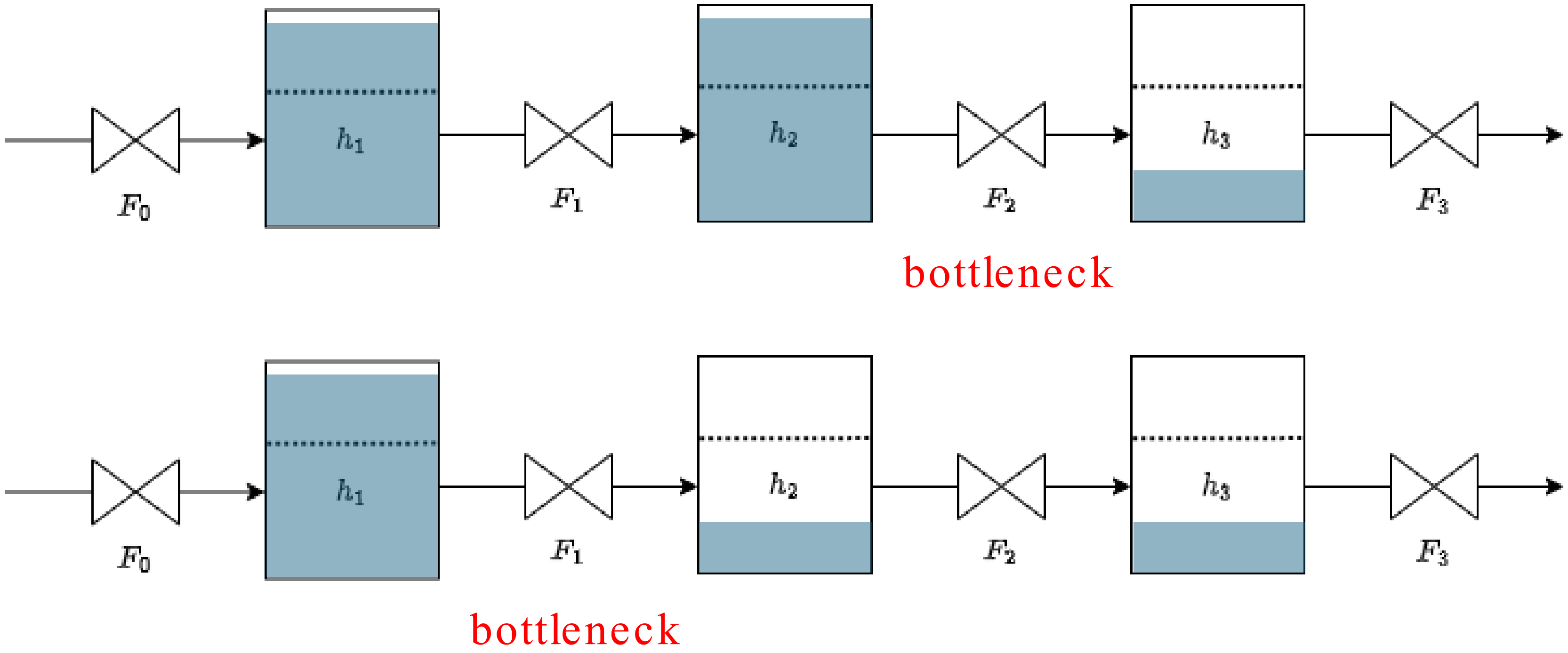
$$h(t_{k+1}) = h(t_k) + \frac{M}{a} F(t_k)$$
$$h_{\min} \le h(t_k) \le h_{\max}$$
$$0 \le F(t_k) \le F_{\max}$$ (4 manipulated variable)

$$M_{ij} = \begin{cases} 1 \text{ if } F_j \text{ enters vessel } i \\ -1 \text{ if } F_j \text{ exits vessel } i \\ 0 \text{ otherwise} \end{cases}$$

e.g. F_1 relation to h_2 & h_1
$M_{21} = 1\ , M_{11} = -1$

Desired behaviour: bottleneck isolation

- the inventory before the bottleneck should be *high*, and those after should be *low*



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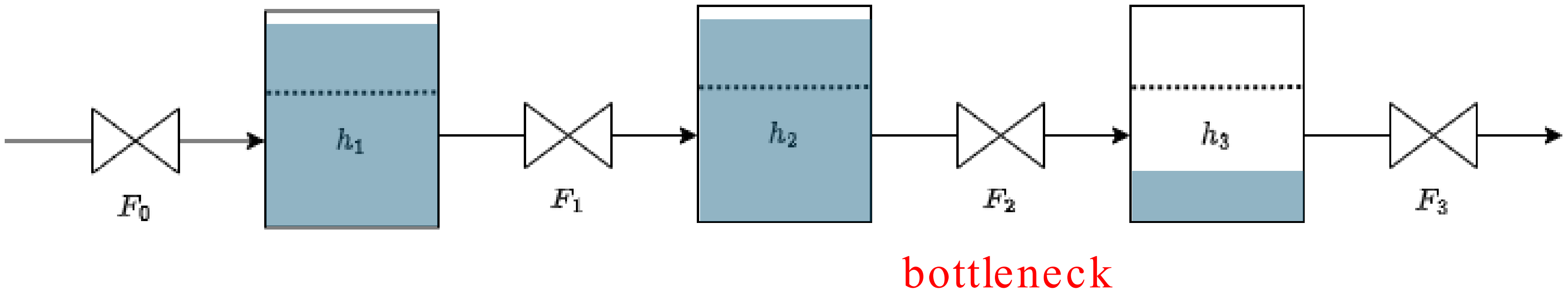


Objective?

Option 1: maximize flows between tanks

Option 2: maximize outflow and weighted inventories

Choice of MPC objective

1. "Trick": Unreachable setpoints

$$J = \sum_{k=0}^{N_k} \gamma^k \|F(t_k) - F_{sp}\|_2^2$$

Maximizes the flow out of tanks

2. Maximize outflow & inventories

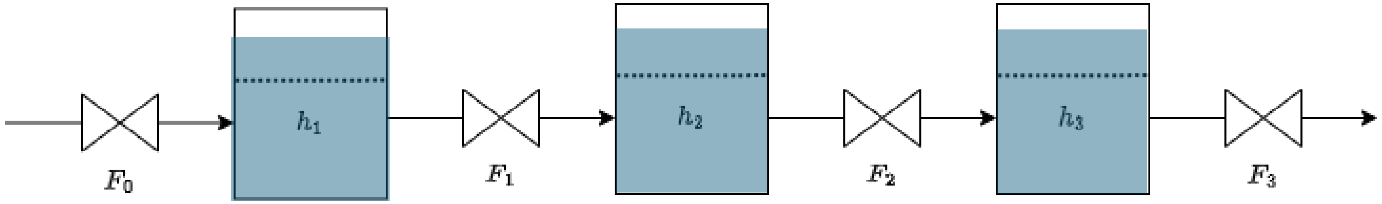
$$J = -\sum_{k=0}^{N_k} \gamma^k \left(F_N(t_k) + \sum_{i=1}^{N_I} \alpha_i h_i(t_k) \right)$$

Tanks closer to exit have higher α

$$0 < \alpha_i < 1$$

(easy to use for more complex topologies)

objectives give same behaviour & match decentralised approach

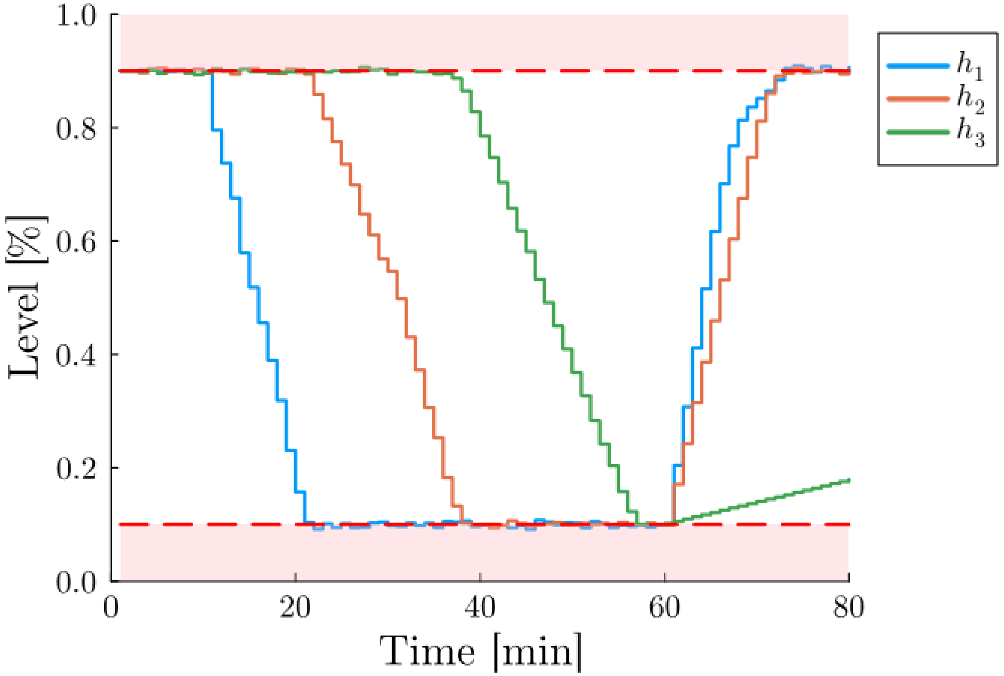


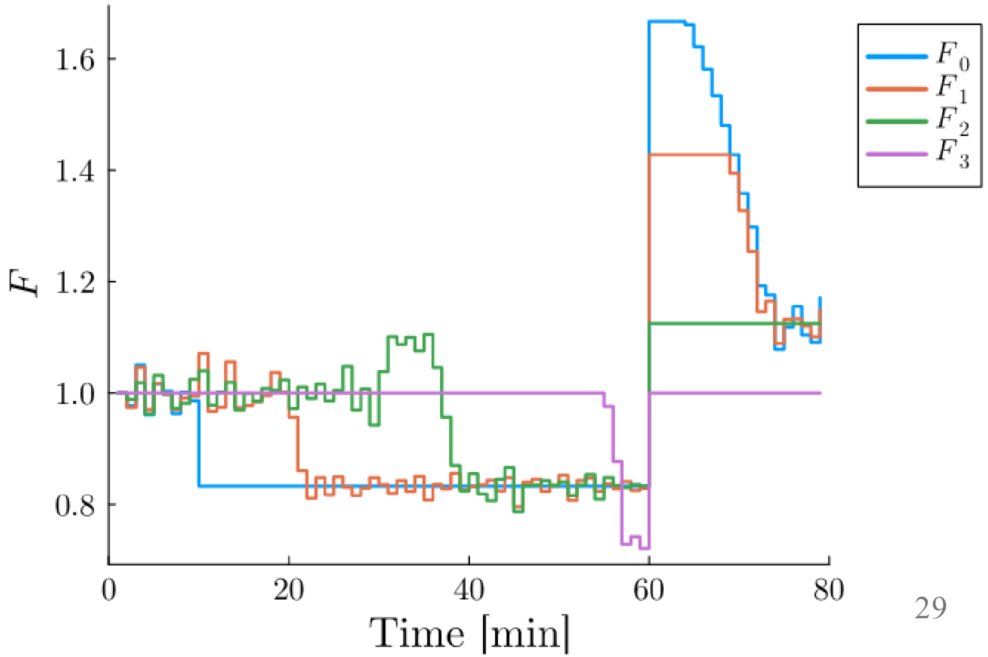
Example 1

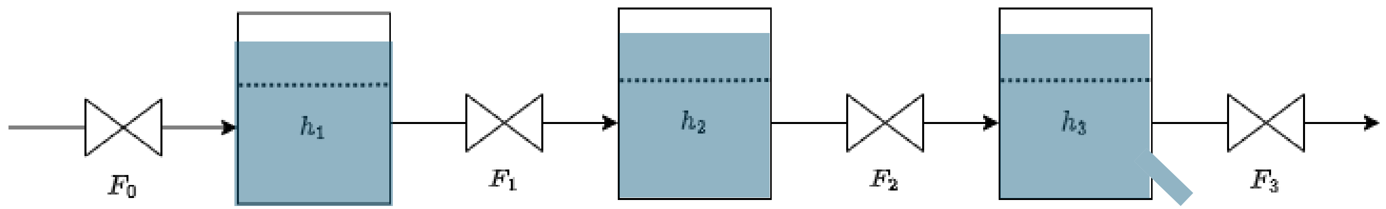
Disturbance: bottleneck shifts

- F_3 for 10 min
- F_0 for 50 min
- F_3 for 10 min

What happens if the disturbance is not known?







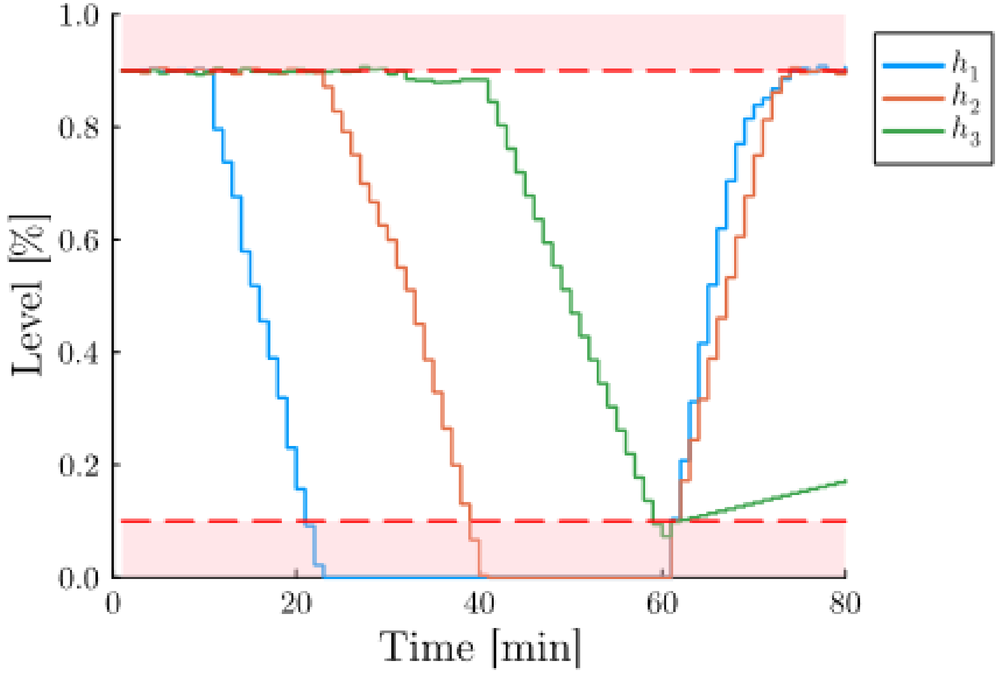
Example 2

Disturbance: new bottleneck:

- F_3 for 10 min
- F_0 for 50 min
- F_3 for 10 min

Disturbance: leak in Tank 3

Disturbances are unknown



(MPC continuously allocates an unreachable F0)

Disturbance model

Augmented model

$$x_{k+1} = Ax_k + Bu_k + B_d d_k$$
$$d_{k+1} = d_k$$
$$y_k = Cx_k + C_d d_k$$
$$x_0 = \hat{x}_{0|0}, \;\; d_0 = \hat{d}_{0|0}$$

Update equations

$$e_k = y_k - C\hat{x}_{k|k-1} - C_d\hat{d}_{k|k-1}$$
$$\hat{x}_{k|k} = \hat{x}_{k|k-1} + K_x e_k$$
$$\hat{d}_{k|k} = \hat{d}_{k|k-1} + K_d e_k$$

Goal: desired response in y_k despite model mismatch

Need to chose B_d, C_d, K_x, K_d

This is difficult!

Pannocchia, G. (2015). Offset-free tracking mpc: A tutorial review and comparison of different formulations. In 2015 European control conference (ECC).

Disturbance models: simple choices

Deadbeat output

- the disturbance directly enters the output

$$B_d = 0, C_d = I, K_x = 0, K_d = I$$

$$y_k = Cx_k + Id_k$$

- (most common)

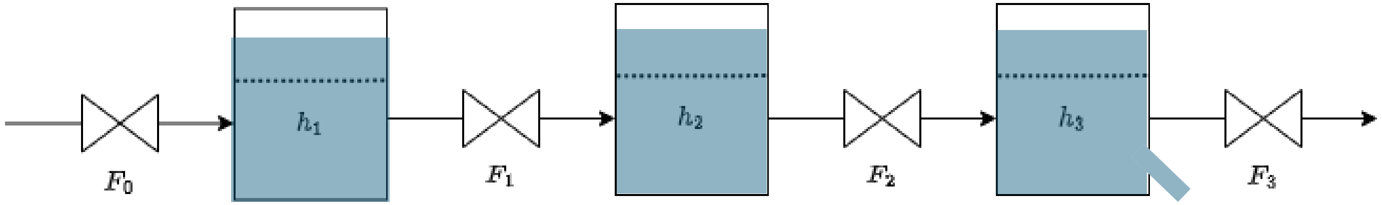
Deadbeat input

- the disturbance acts as an input

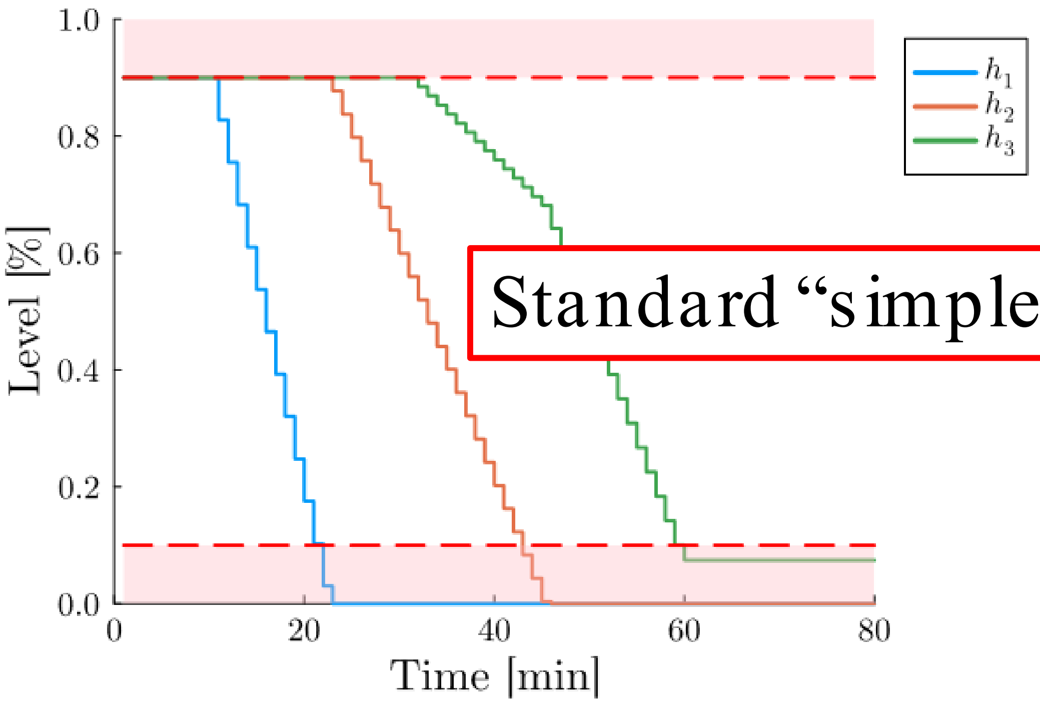
$$B_d = I, C_d = 0, K_x = 0, K_d = I$$

$$x_{k+1} = Ax_k + Bu_k + Id_k$$

Example 2:

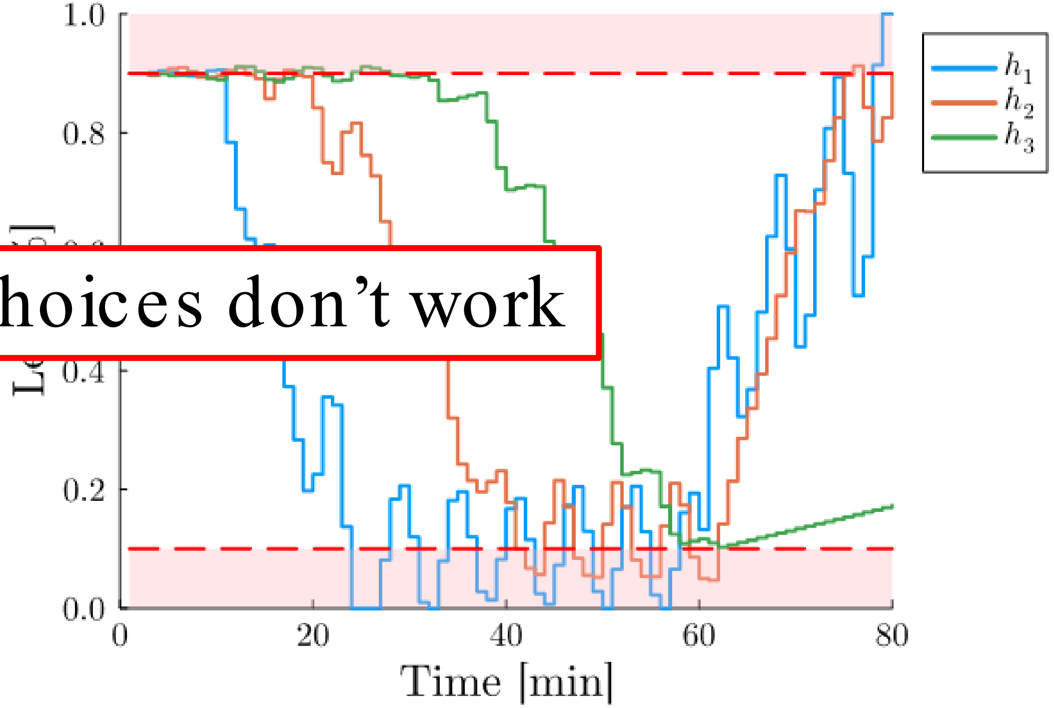


Augment the output ($\boldsymbol{C_d}$)



Augmented system is not detectable!

Augment the input ($\boldsymbol{B_d}$)



Augmented observer has + eigenvalue, system matrix eigenvalues at 1

Standard "simple" choices don't work

Youla-Kucera parameterisation

Instead of picking 4 matrices, tune a single matrix Q

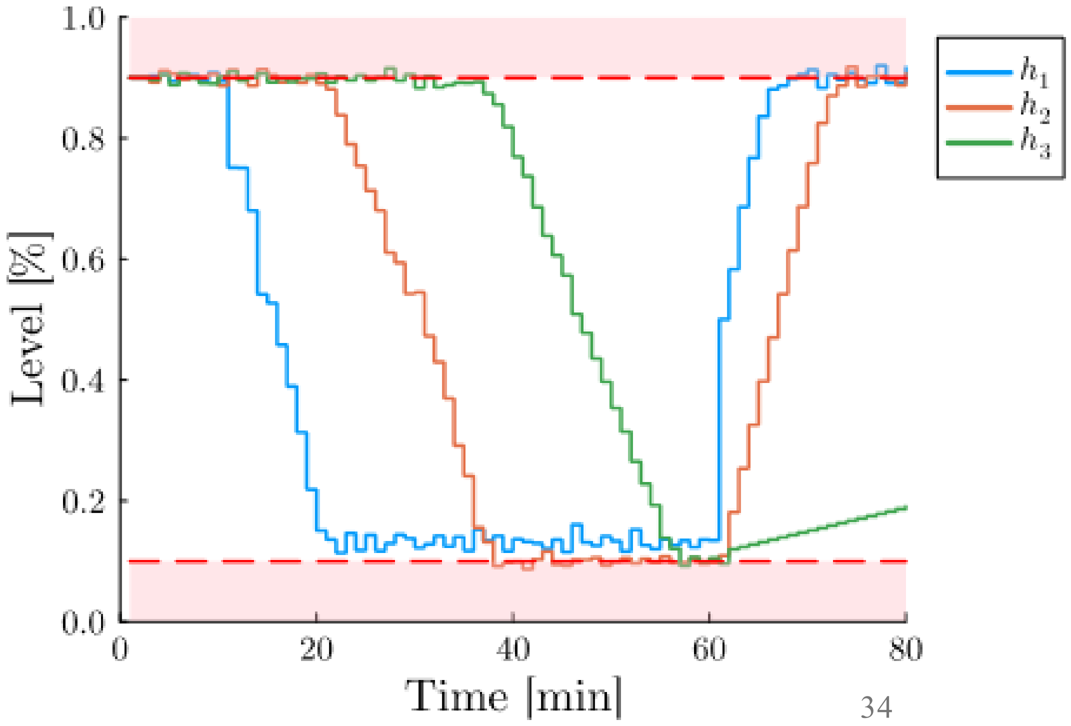
$$B_d = Q, C_d = I - CQ, K_x = Q, K_d = I$$

If $(A - QCA)$ has negative eigenvalues

- Augmented system detectable
- Observer is asymptotically stable

e.g. $Q = 1.1\, I$

Simpler tuning problem



I made this example to find a case where MPC does not work; Bidirectional inventory control with minimum flow for F_2

Max flow: $F_s = \infty$

L = 10%,

M_L = 40%,

M_H = 60%

H = 90%.

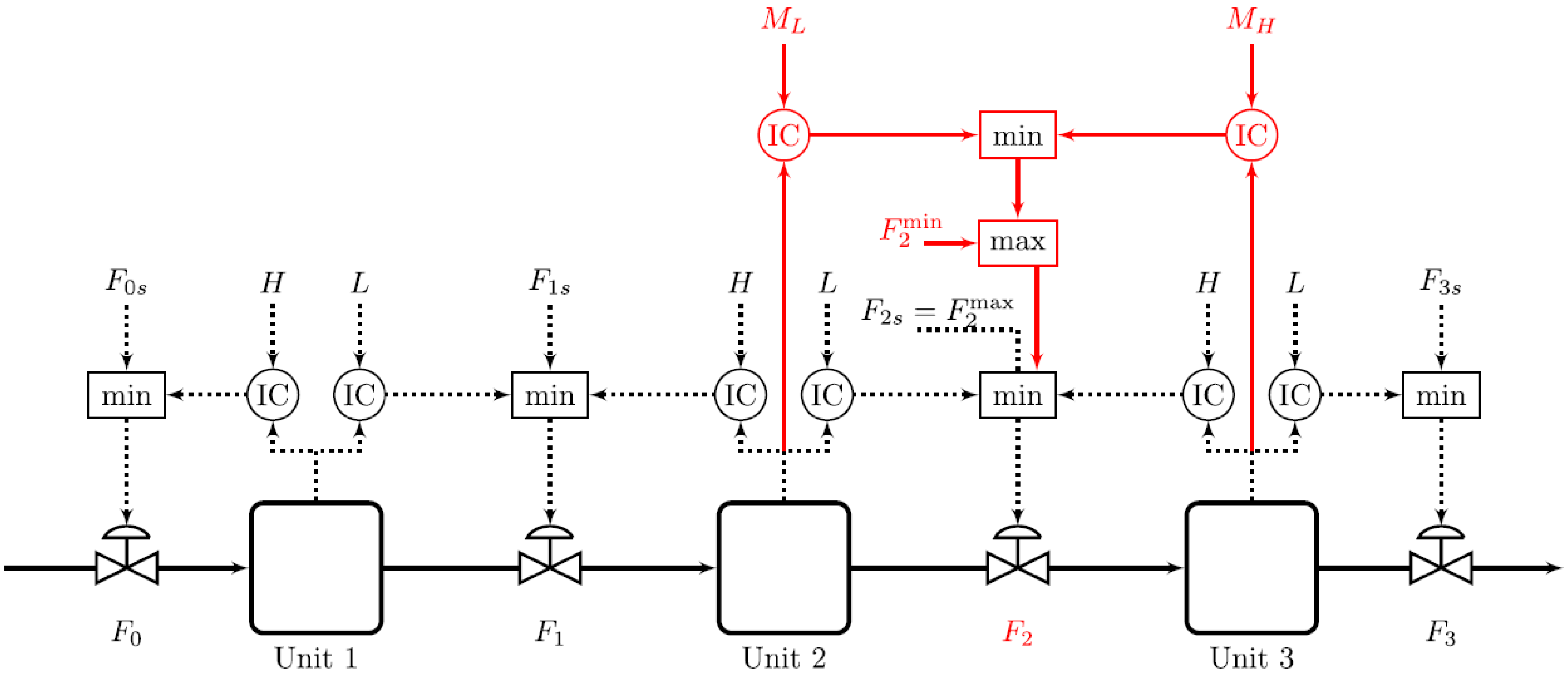
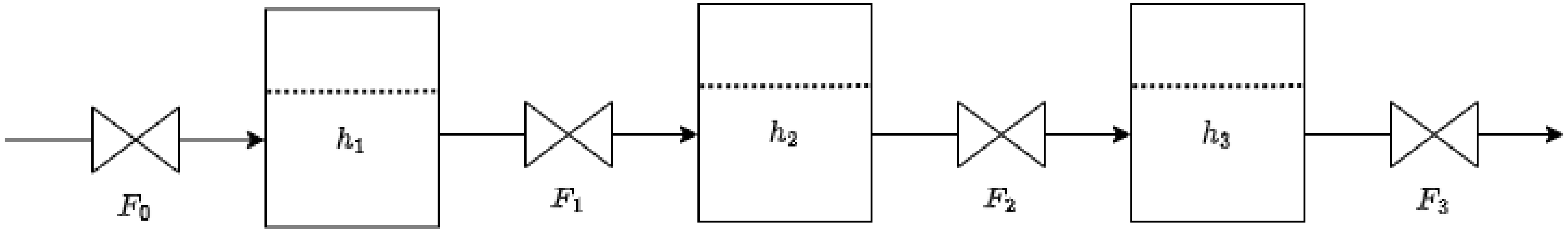


Fig. 37. Bidirectional inventory control scheme for maximizing throughput (dashed black lines) while attempting to satisfy minimum flow constraint on F_2 (red lines). H, L, M_L and M_H are inventory setpoints.

The control structure in Fig. 37 may easily be dismissed as being too complicated so MPC should be used instead. At first this seems reasonable, but a closer analysis shows that MPC may not be able to solve the problem (Bernardino & Skogestad, 2023).[8] Besides, is the control structure in Fig. 37 really that complicated? Of course, it is a matter of how much time one is willing to put into understanding and studying such structures. Traditionally, people in academia have dismissed almost any industrial structure with selectors to be ad hoc and difficult to understand, but this view should be challenged.

Conclusions



MPC can be used to isolate bottlenecks without:

- Requiring forecast of bottlenecks
- Correct identification of bottlenecks

The scheme can readily be extended to account for:

- Delays in transportation
- Tunings of transients
- More complex topologies

Thank you for your attention!