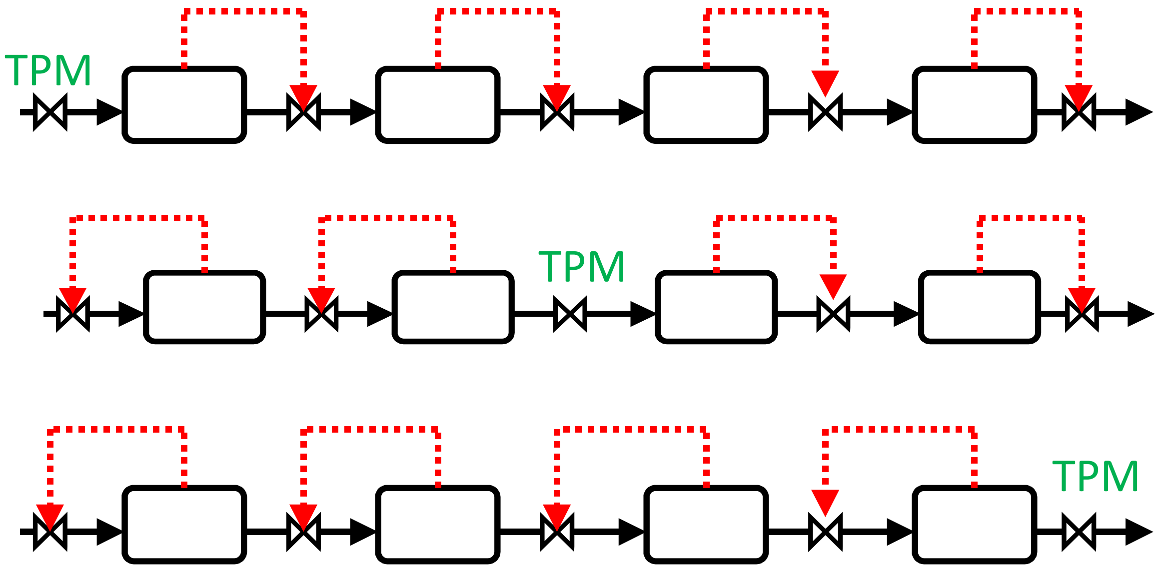
Part 4: Inventory control and optimal buffer management

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 for units in series and TPM

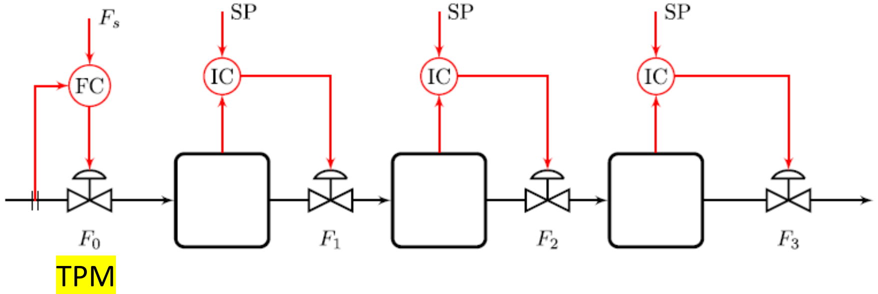
- *TPM* ("gas pedal") *= Variable used for setting the throughput/production rate (for the entire process).*
- Where is the TPM located for the process?
  - Usually at the feed, but not always!
  - Important for dynamics
  - Determines the inventory control structure
- **Rule (Price et al., 1994): Inventory control (Level and pressure) must be radiating around TPM:**



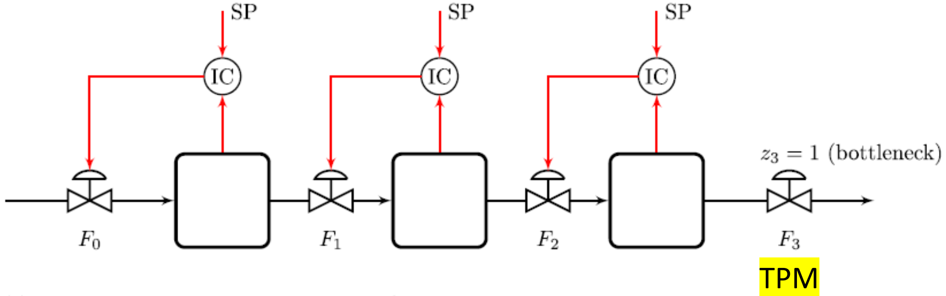
Inventory control for units in series

Radiating rule:

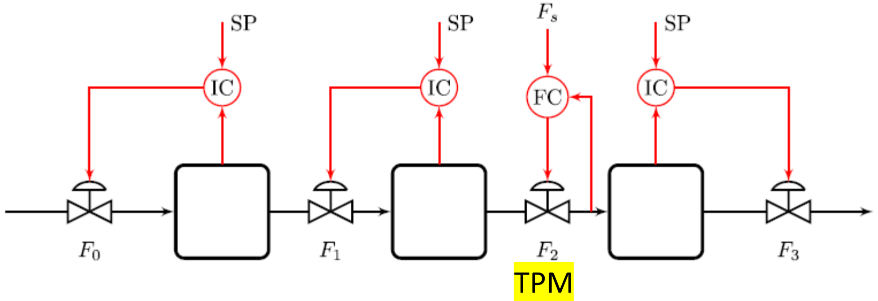
Inventory control should be "radiating" around a given flow (TPM).



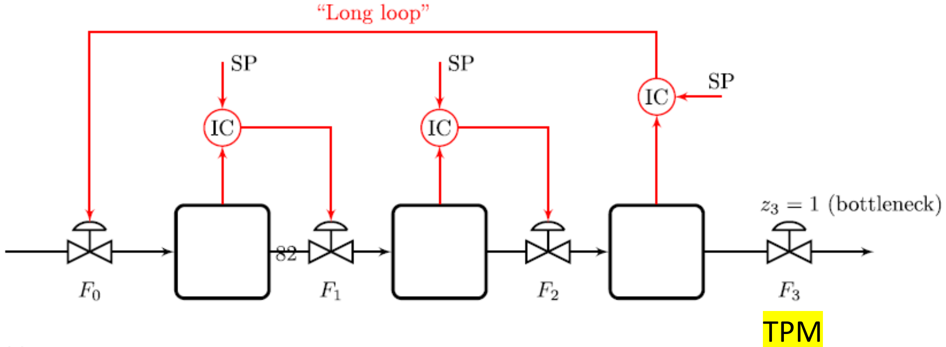
(a) Inventory control in direction of flow (for given feed flow, TPM = F_0)



(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)



(d) Inventory control with undesired "long loop", not in accordance with the "radiation rule" (for given product flow, TPM= F_3)

Follows radiation rule

Does NOT follow radiation rule

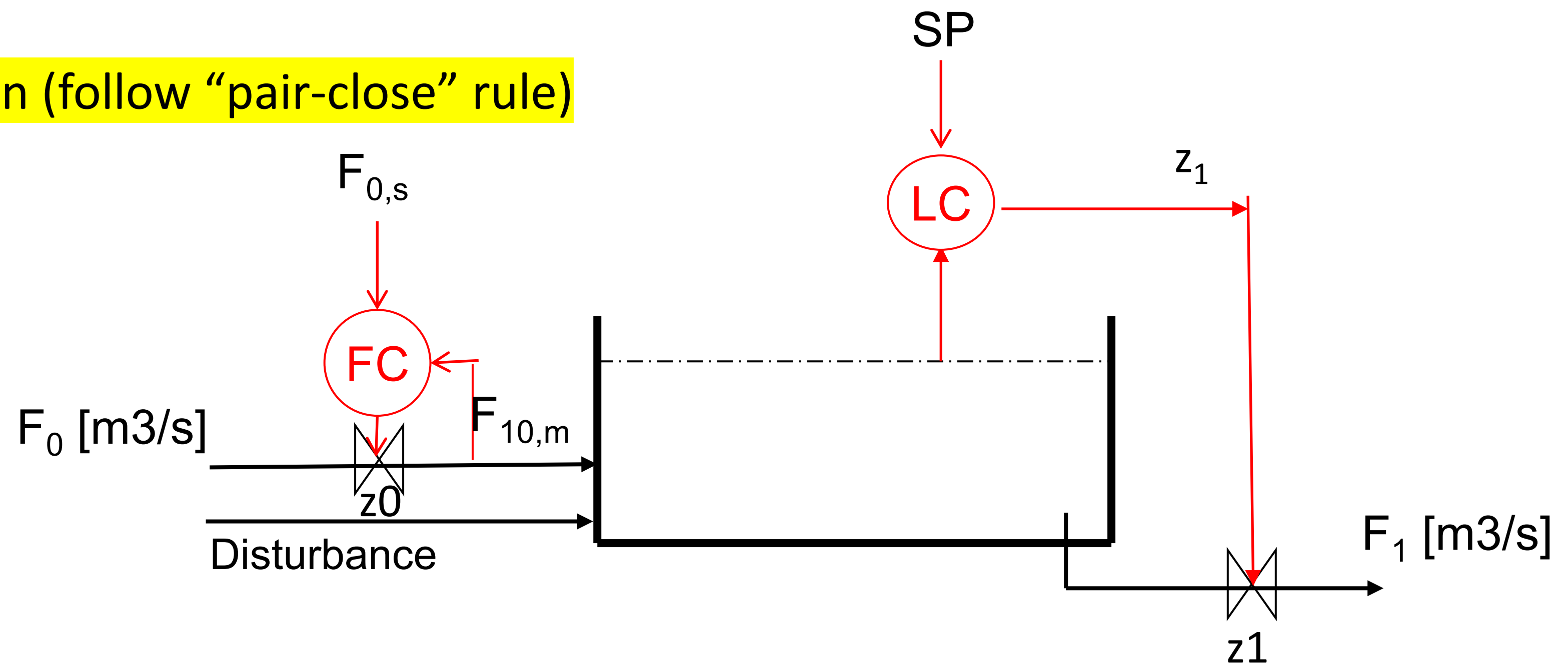
- TPM = throughput manipulator – where throughput of plant is set
- Usually only one TPM
    - To get consistent mass balance: Can only fix same flow once
    - But there are exceptions
        - Multiple feeds (they are then usually set in ratio to the “main” TPM)
        - Recycle systems often have a flow that can be set freely

- Rule for maximizing production for cases where we cannot rearrange inventory loops: Locate TPM at expected bottleneck
    - Otherwise you will need a “long loop” and you get loss in production because of backoff from constraint

Example : Level control

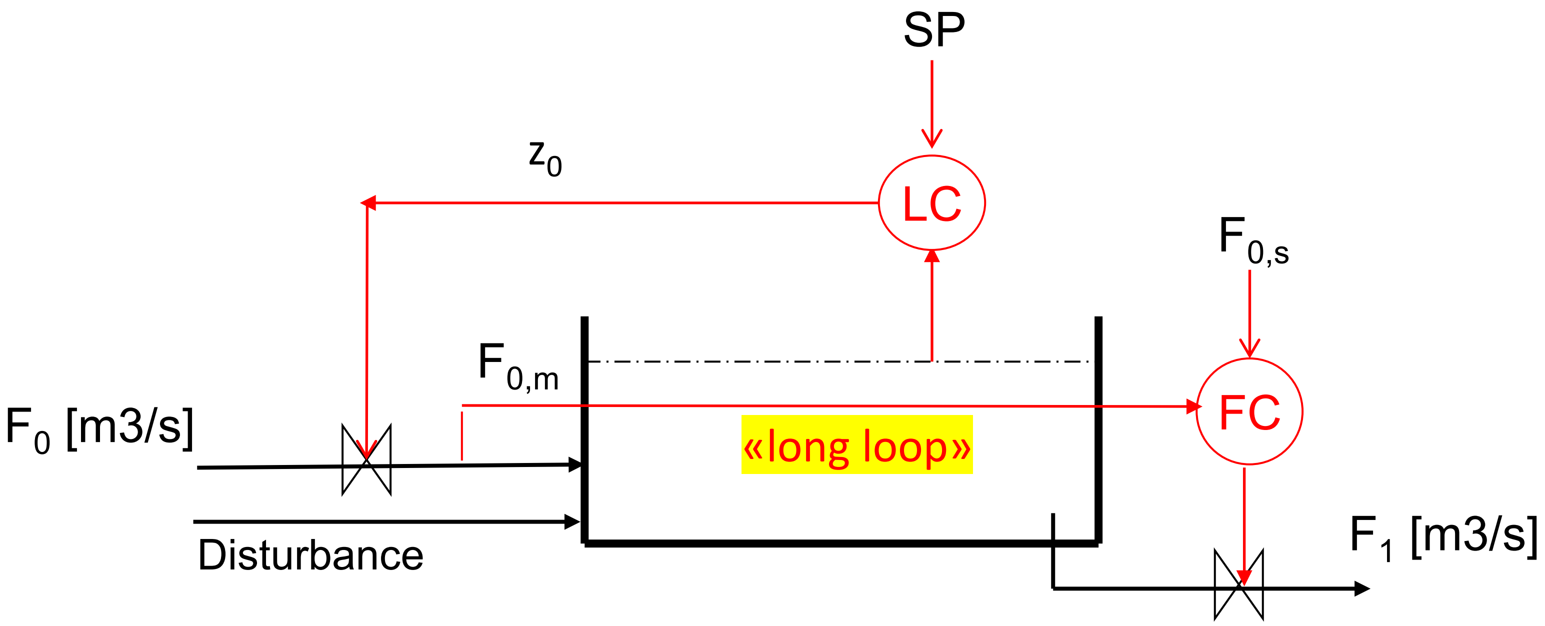
CV1 = F0 (inflow): Should be controlled at setpoint $F_{0,s}$ (if possible)
Valve z1 : Likely to saturate (potential bottleneck)

Nominal design (follow “pair-close” rule)



TPM at feed (F_0) ⇒Inventory control in the direction of flow
Problem: outflow-valve may saturate at fully open (z1=1) and then we lose level control
Note: We did not following the “input saturation rule” which says:
Pair MV that may saturate (z1) with CV that can be given up (F0)

Reverse pairing with “long loop” (follows “input saturation rule”):

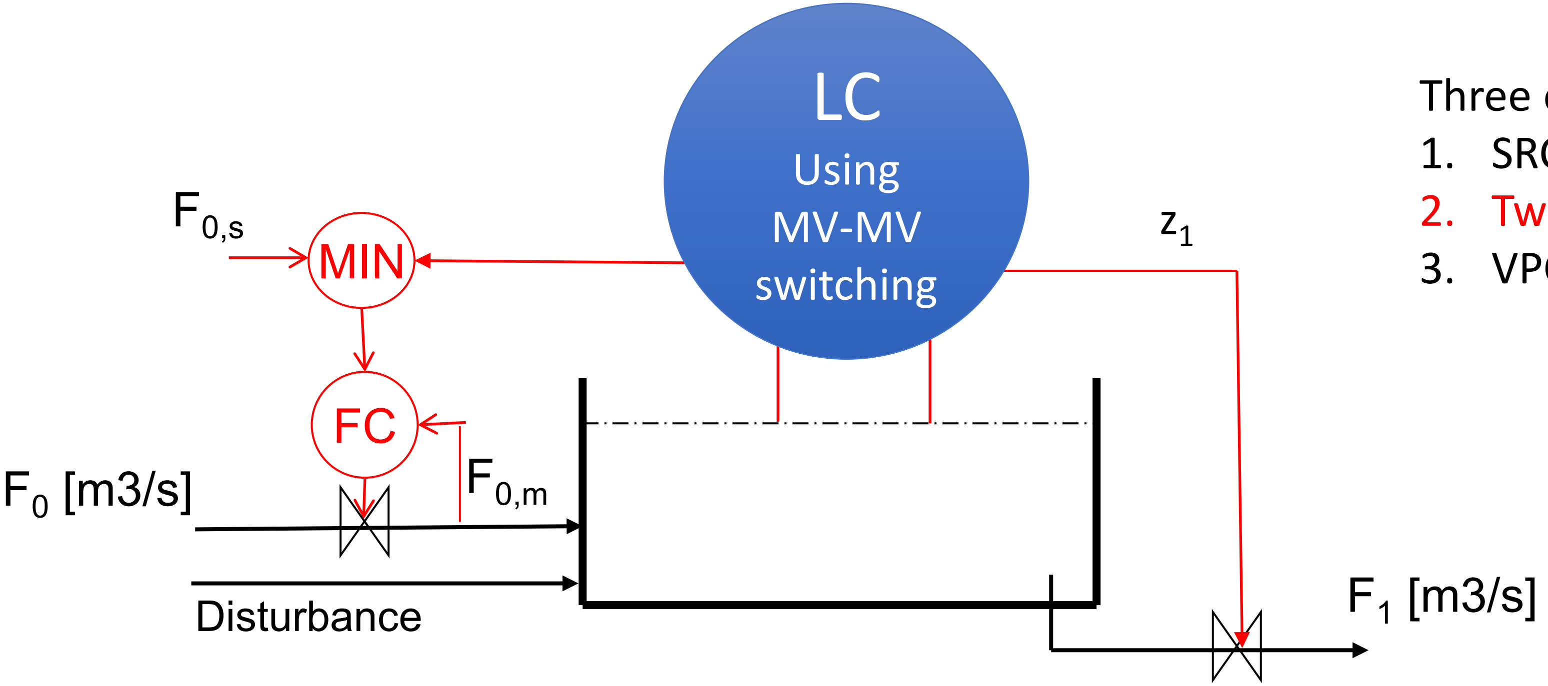


TPM at product (F_1) ⇒Inventory control opposite direction of flow

«Long loop» = Works through other loops

Alternative solution: Follow "Pair close"-rule and use Complex MV-CV switching.

Get: "Bidirectional inventory control"



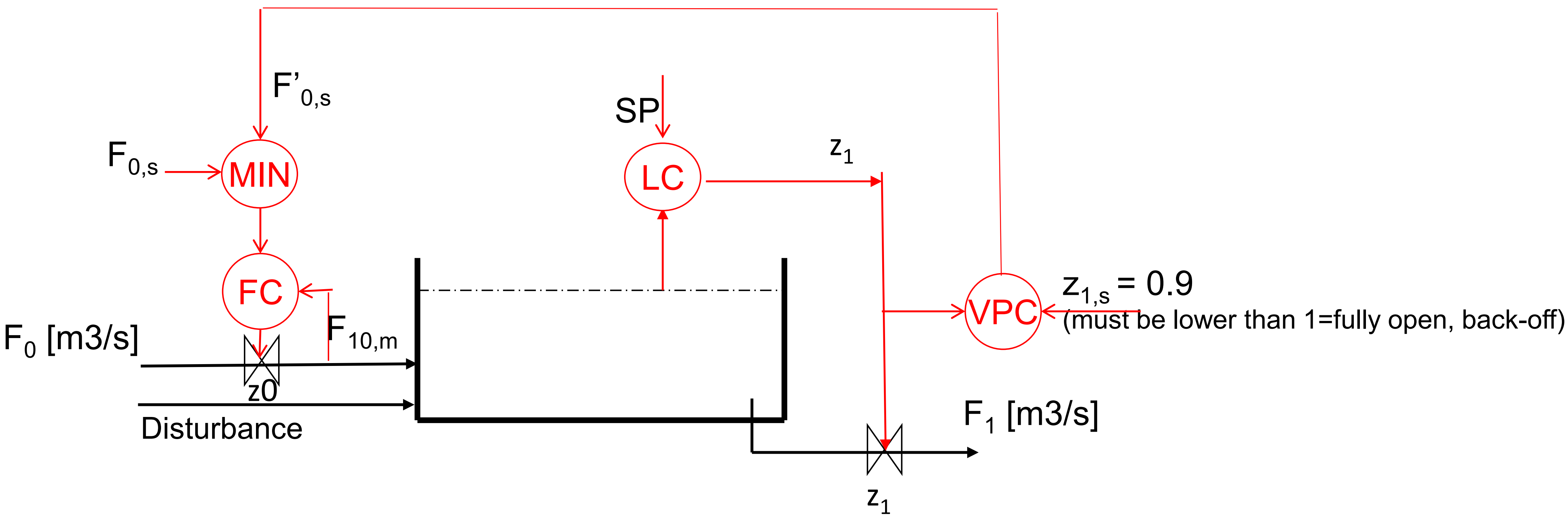
Three options for MV-MV switching

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

- TPM moves around
- Avoid long loop for control of F0
- Works both when F0-valve or F1-valve saturate at open

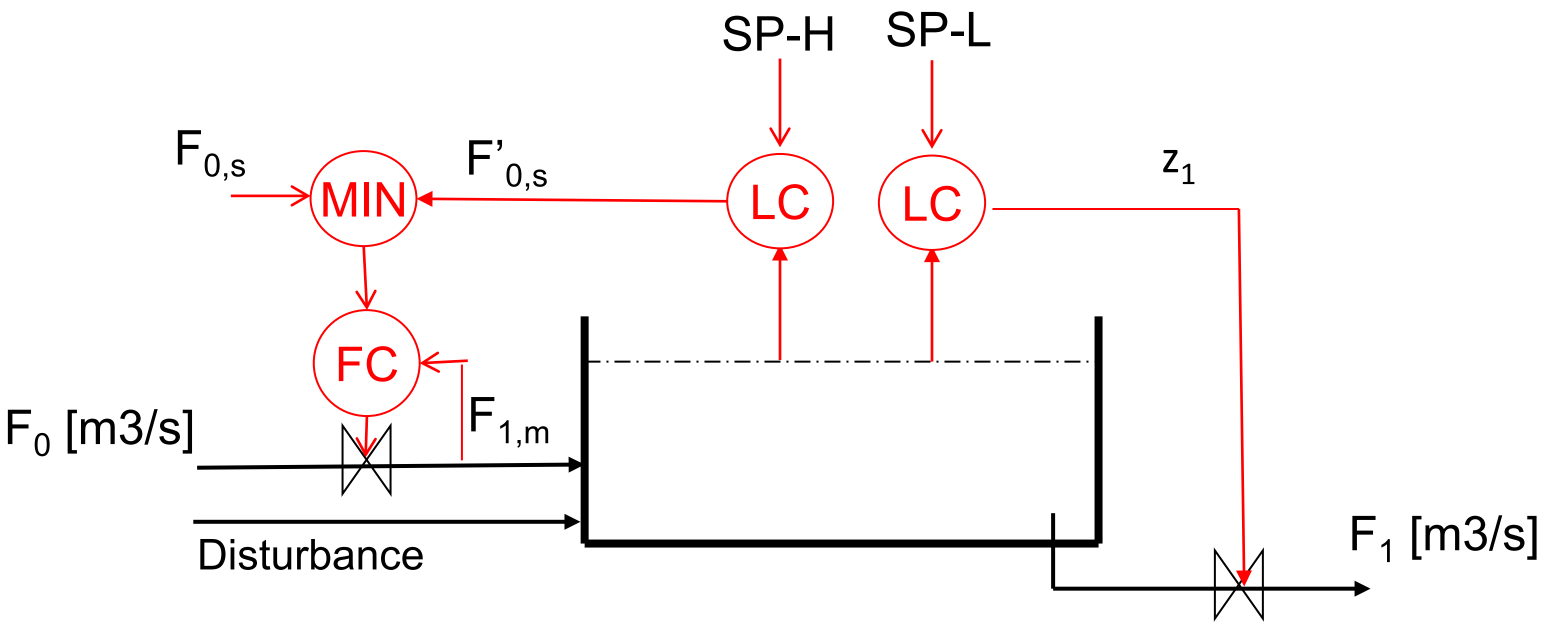
Overall: seems to be the best solution

Alt. 3. Valve position control on z_1



VPC: “reduce inflow (F_0) if outflow valve (z_1) approaches fully open”

Alt. 2: Two controllers (recommended)



SP-L = low level setpoint
SP-H = high level setpoint

In addition: Use of two setpoints is good for using buffer dynamically!!

Rule for SP for MV-MV switch using many controllers: If CV (level) increases when MV (F1) reaches constraint (fully open F1) because of a disturbance (F0) then use SP-L for this MV (otherwise (decreases) use SP-H).
Alternative: If MV reaches max-constraint for case with negative gain (from MV to CV) use SP.L.
BUT: Is such a rule useful? Probably not because it takes effort to check the conditions (gain)

Generalization of bidirectional inventory control

Reconfigures automatically with optimal buffer management!!

Maximize throughput:

$F_s = \infty$

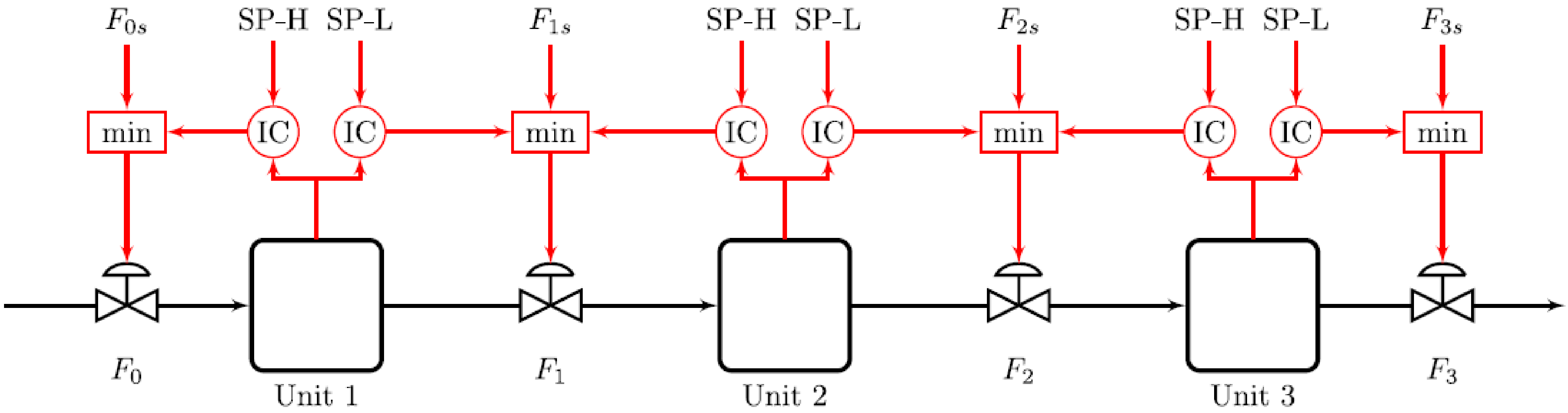
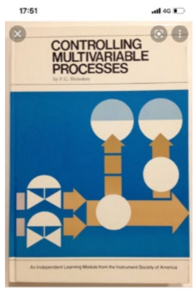


Fig. 36. Bidirectional inventory control scheme for automatic reconfiguration of loops (in accordance with the radiation rule) and maximizing throughput. Shinskey (1981) Zotică et al. (2022).
SP-H and SP-L are high and low inventory setpoints, with typical values 90% and 10%.
Strictly speaking, with 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



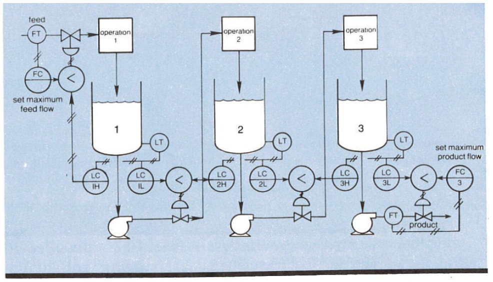
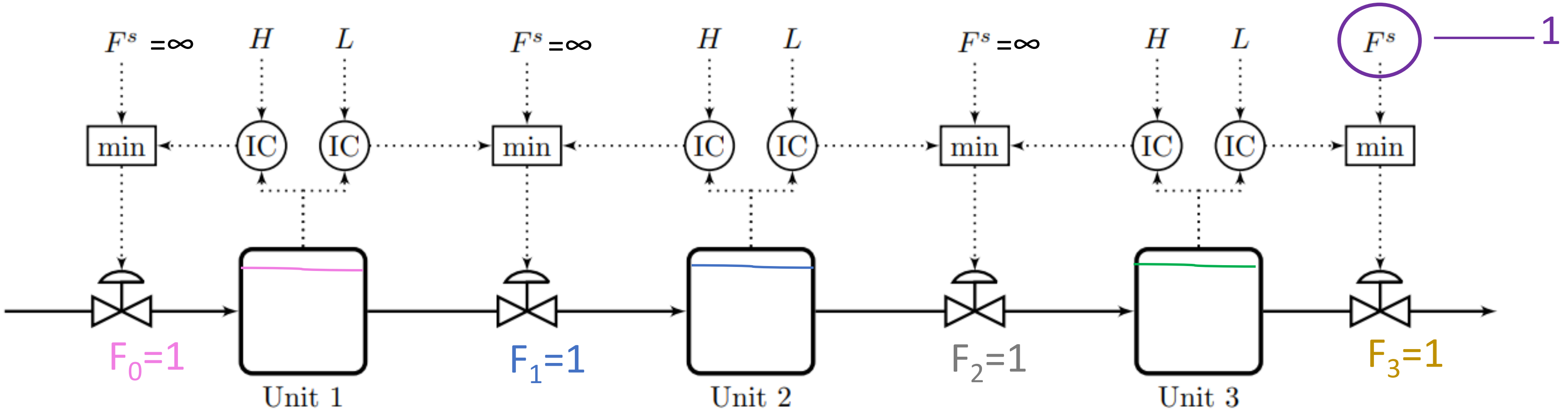
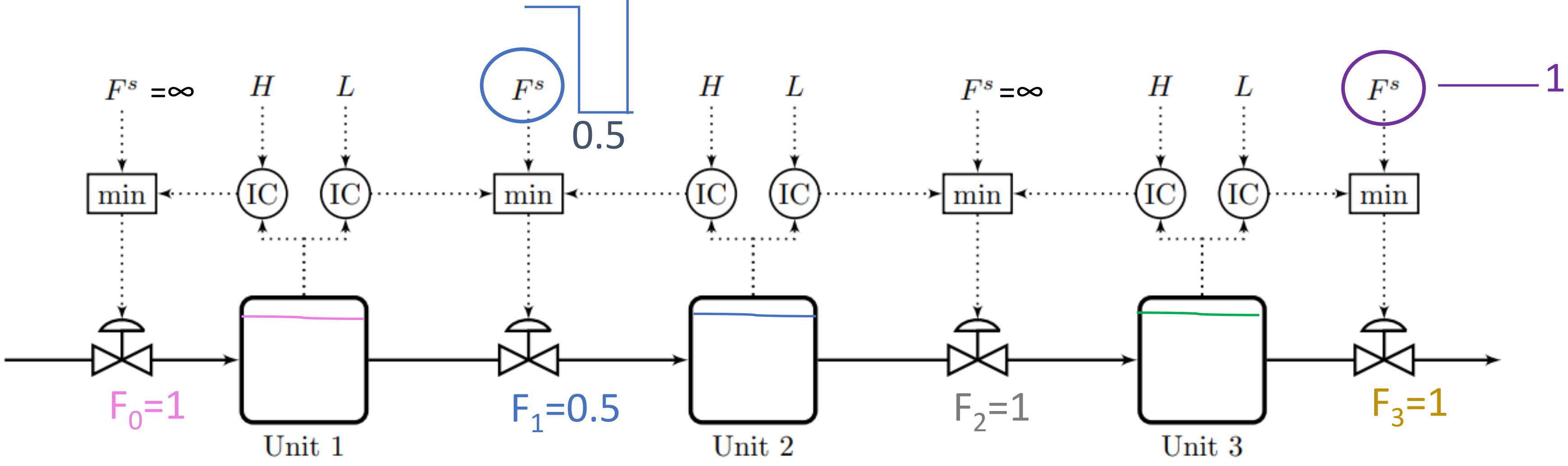
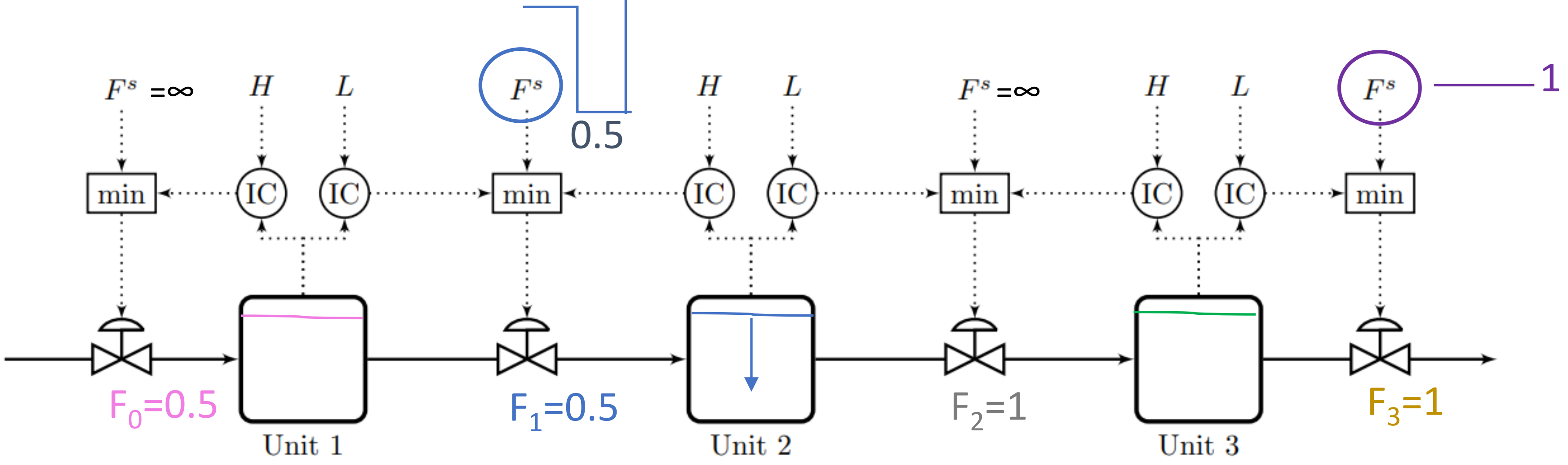


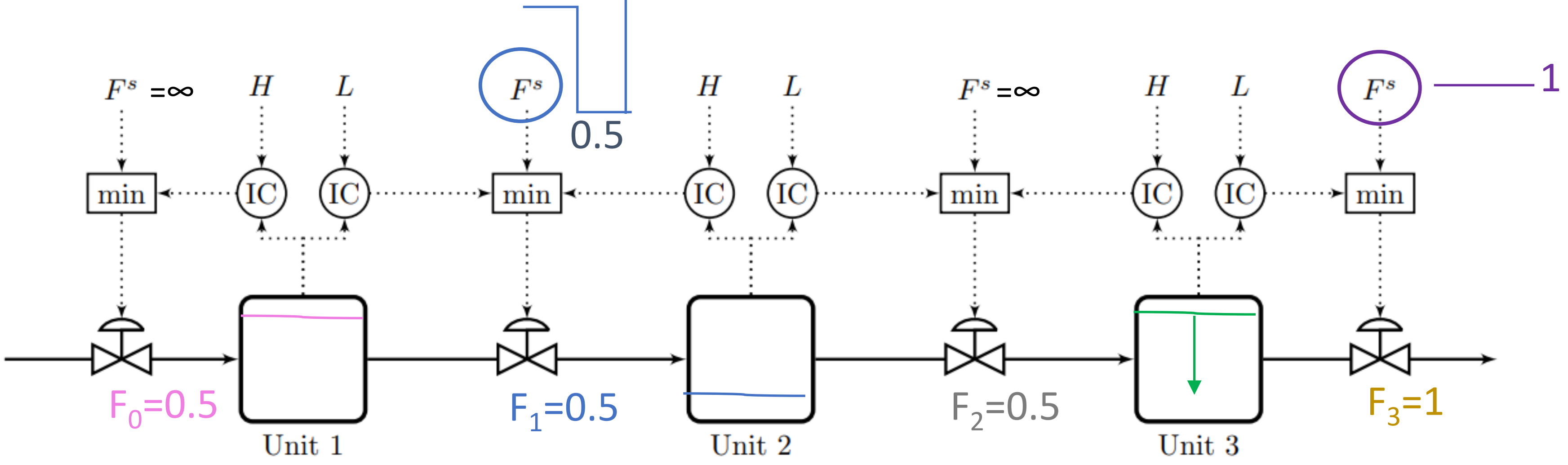
Fig. 3-7. Production rate can be set at either end of the process or constrained at any intermediate point without loss of inventory control.

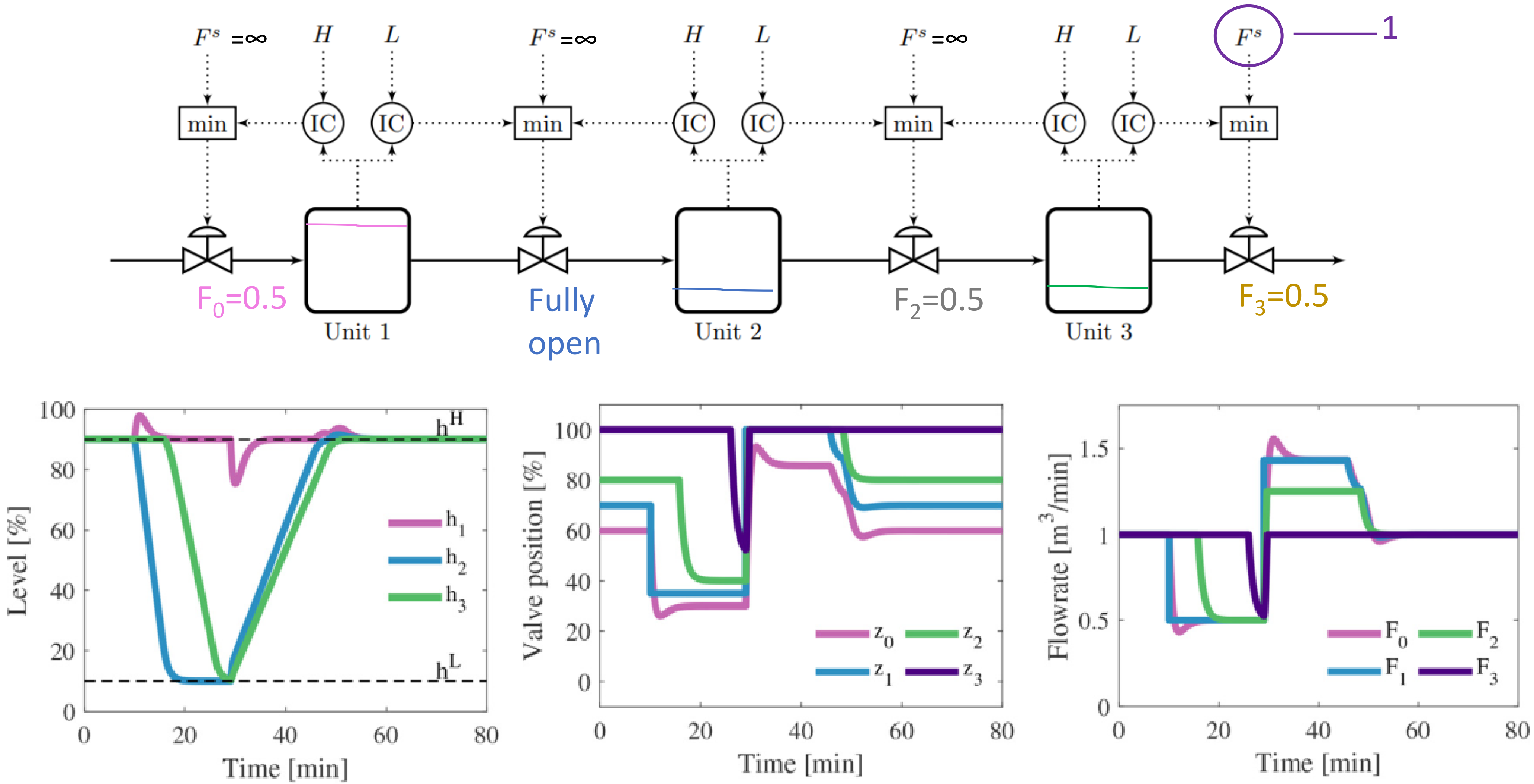
Cristina Zotica, Krister Forsman, Sigurd Skogestad ,»Bidirectional inventory control with optimal use of intermediate storage», Computers and chemical engineering, 2022


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


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

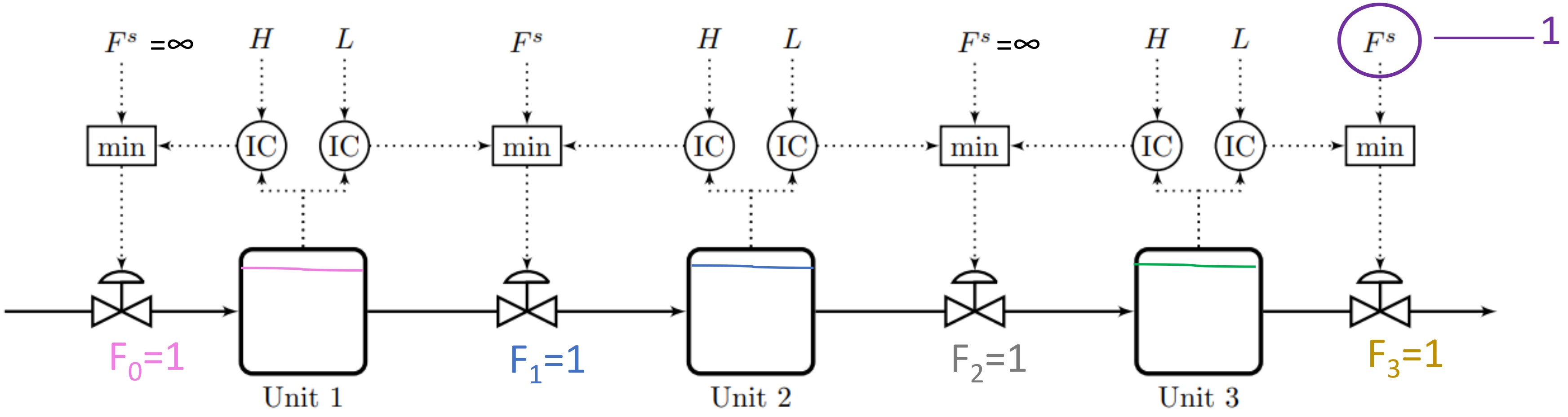

$F^s = \infty$
H
L
F^s
0.5
H
L
$F^s = \infty$
H
L
F^s
1
min
IC
IC
min
IC
IC
min
IC
IC
min
F_0=0.5
F_1=0.5
F_2=1
F_3=1
Unit 1
Unit 2
Unit 3


$F^s = \infty$
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
$F_3=1$



(a) Levels (b) Valve positions (c) Flows

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?

YES. Use «trick»/insight of unachievable high setpoints on all flows

Industrial Case (Perstorp)

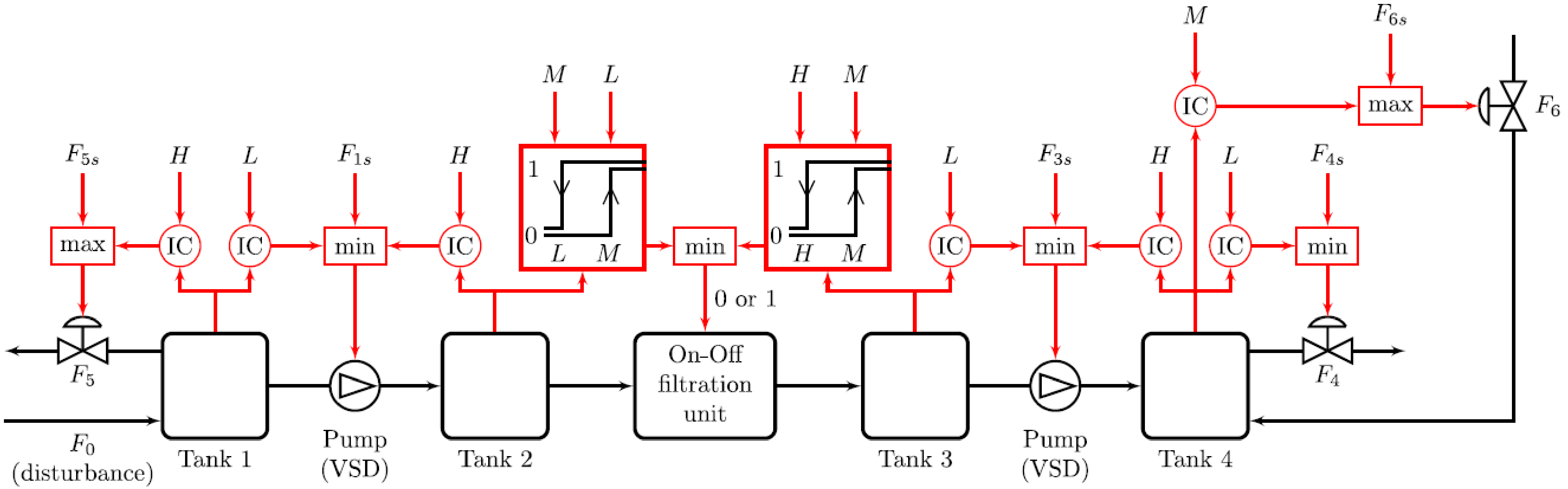


Fig. 38. Bidirectional inventory control structure for industrial plant with on/off (1/0) control of filtration unit.
H, L and M are inventory setpoints with typical values 90%, 10% and 50%.
If it is desirable to set a flowrate (F_s) somewhere in the system, then flow controllers must be added at this location.

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%.

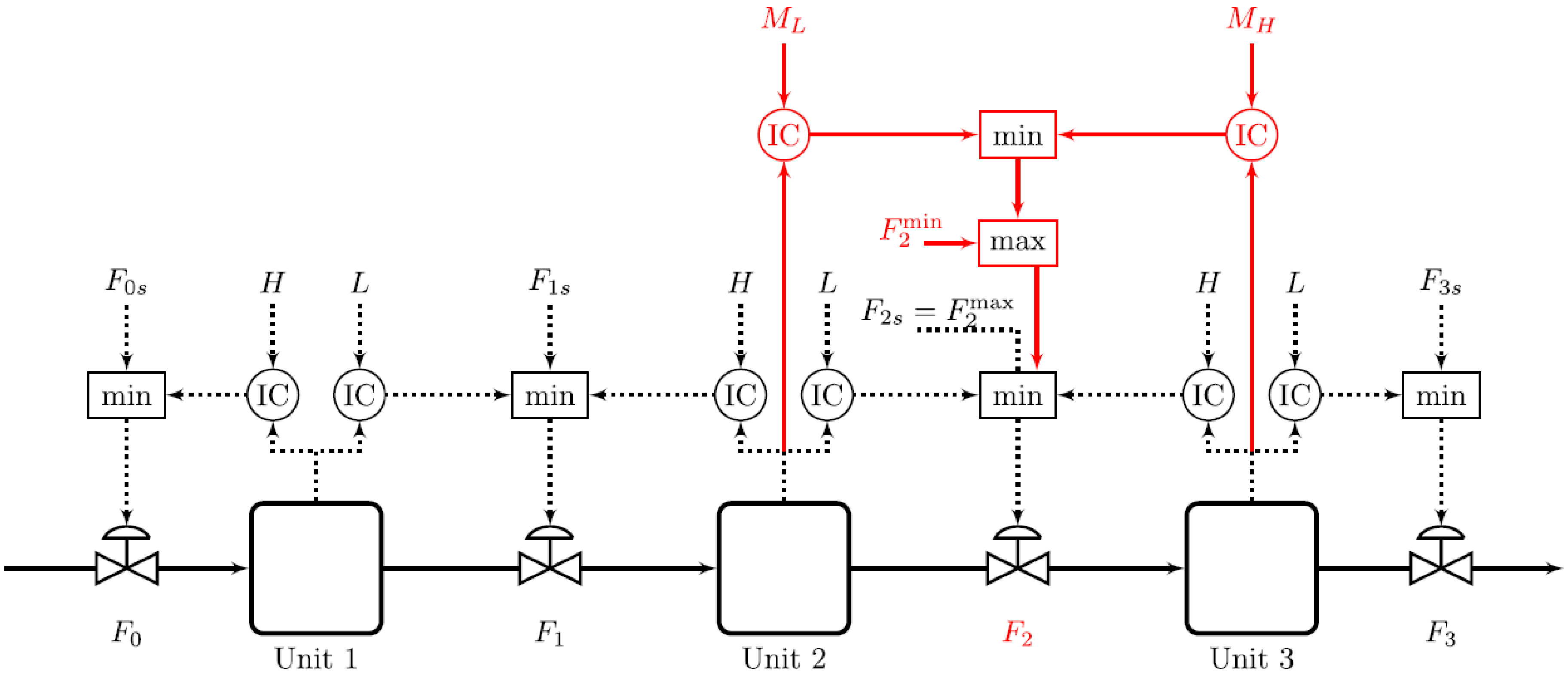
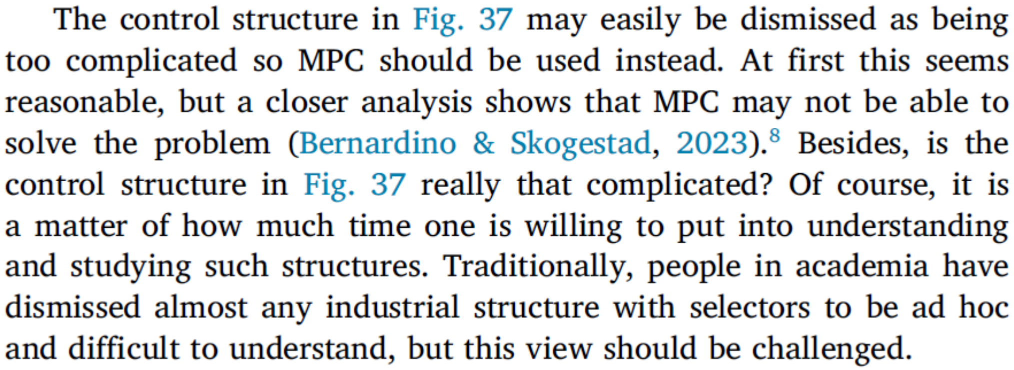
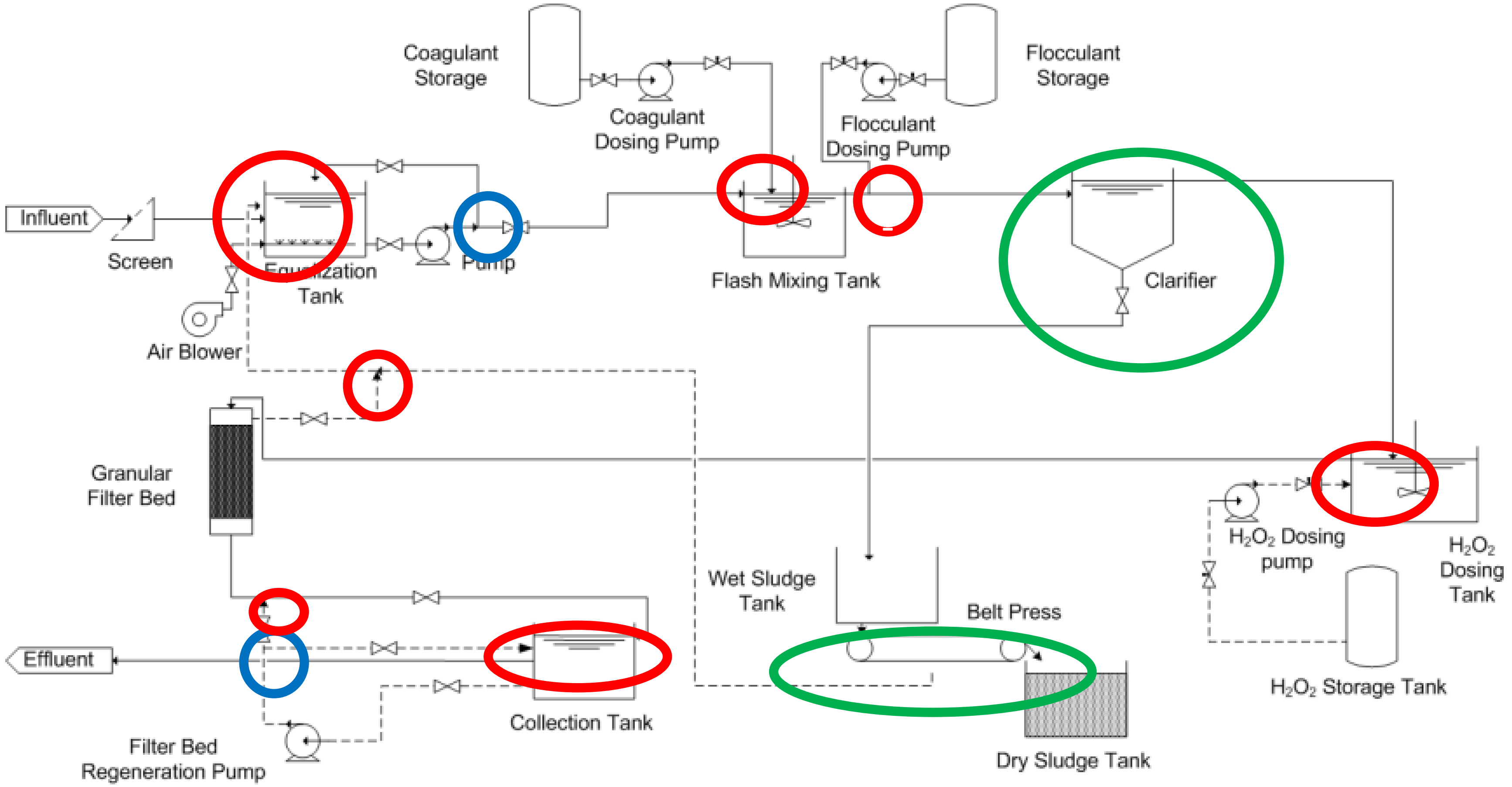


Fig. 37. Bidirectional inventory control scheme for maximizing throughput (dashed black lines) while attempting to satisfy minimum flow constraint on F_2 (red lines). H, L, M_L and M_H are inventory setpoints.



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.

Bidirectional control for plants with recycle (new from this week!)



○ Mixing (use ratio control for feeds)

○ Separator («fixed» split)

○ Adjustable split (same composition)

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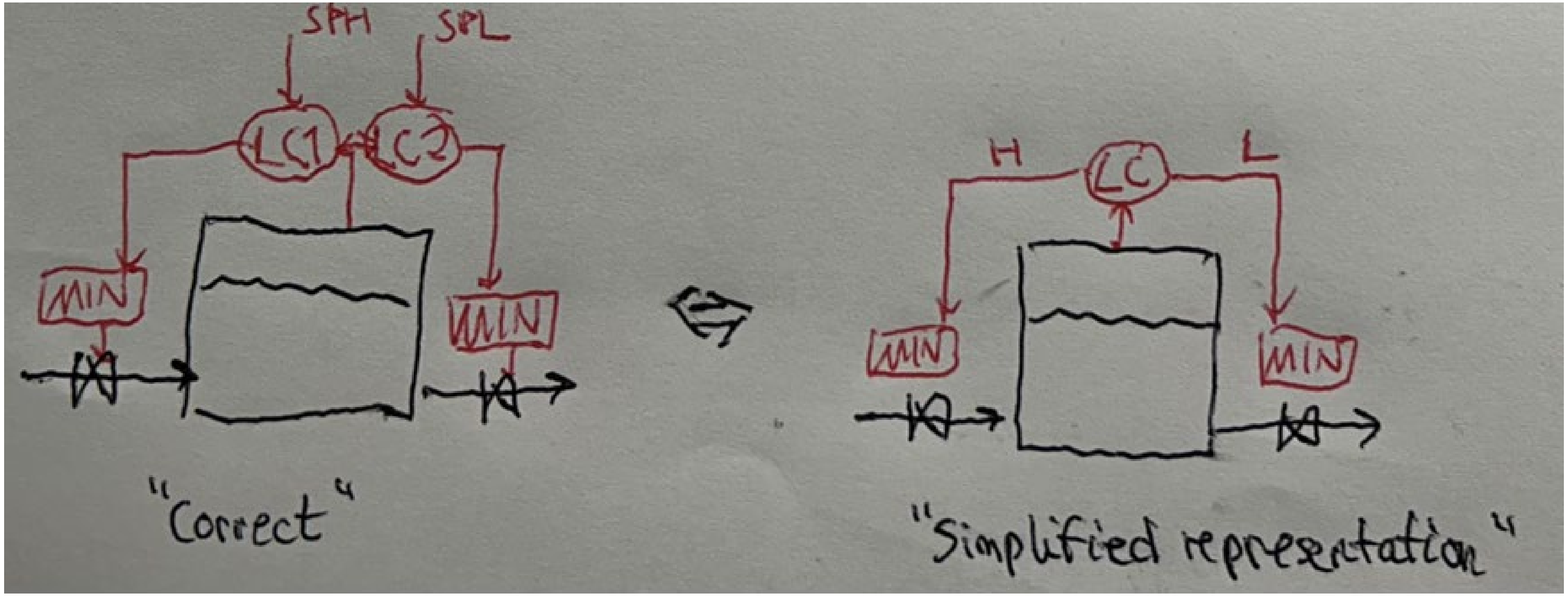
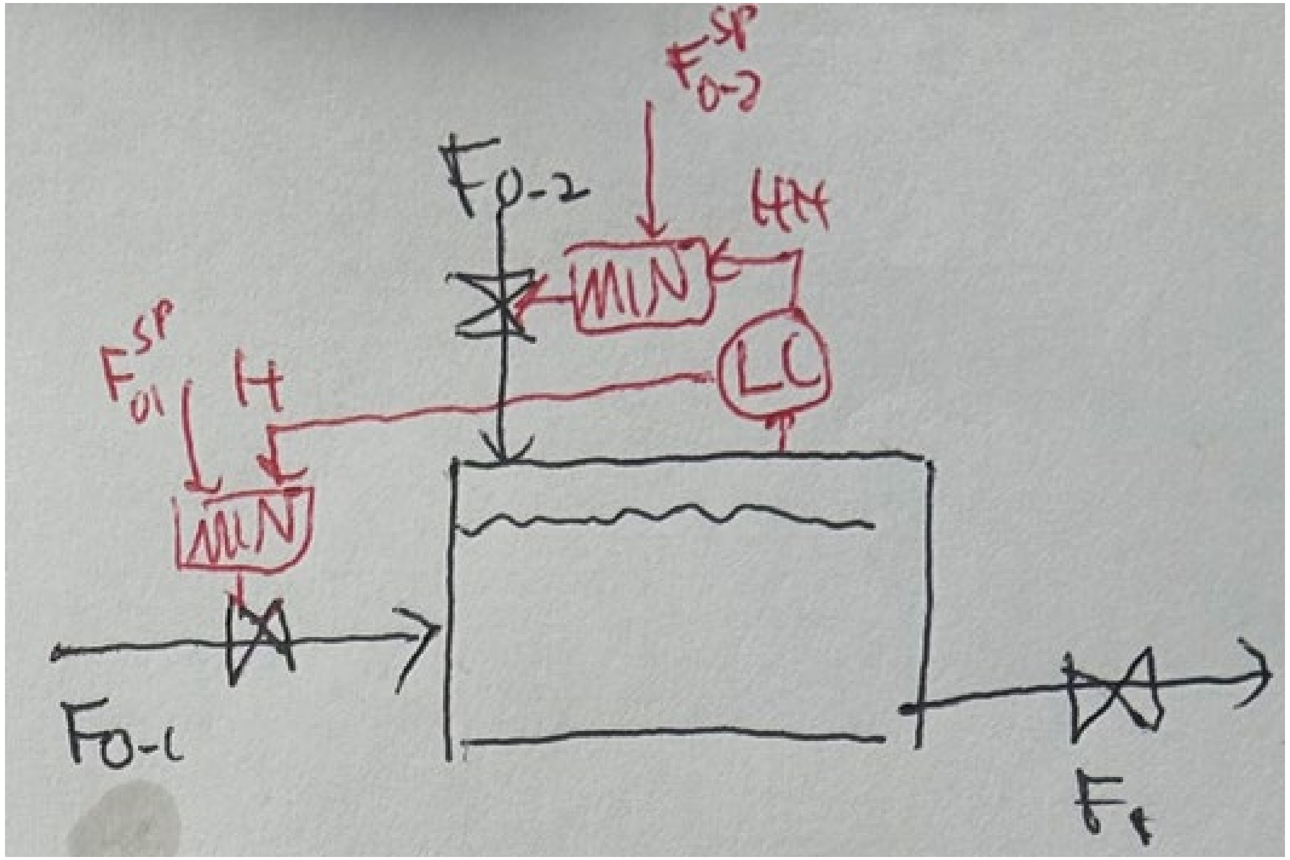
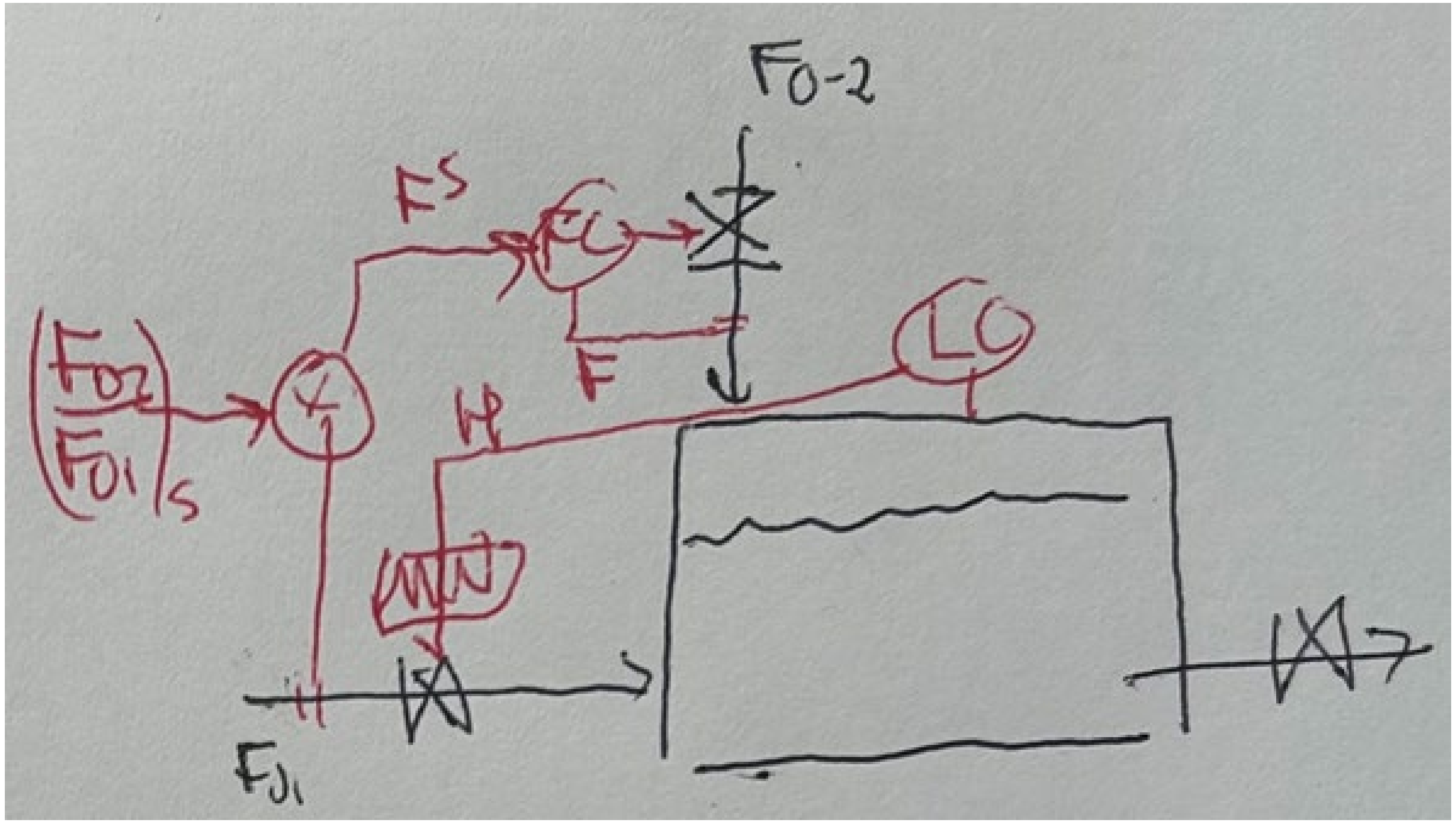
Notation bidirectional control



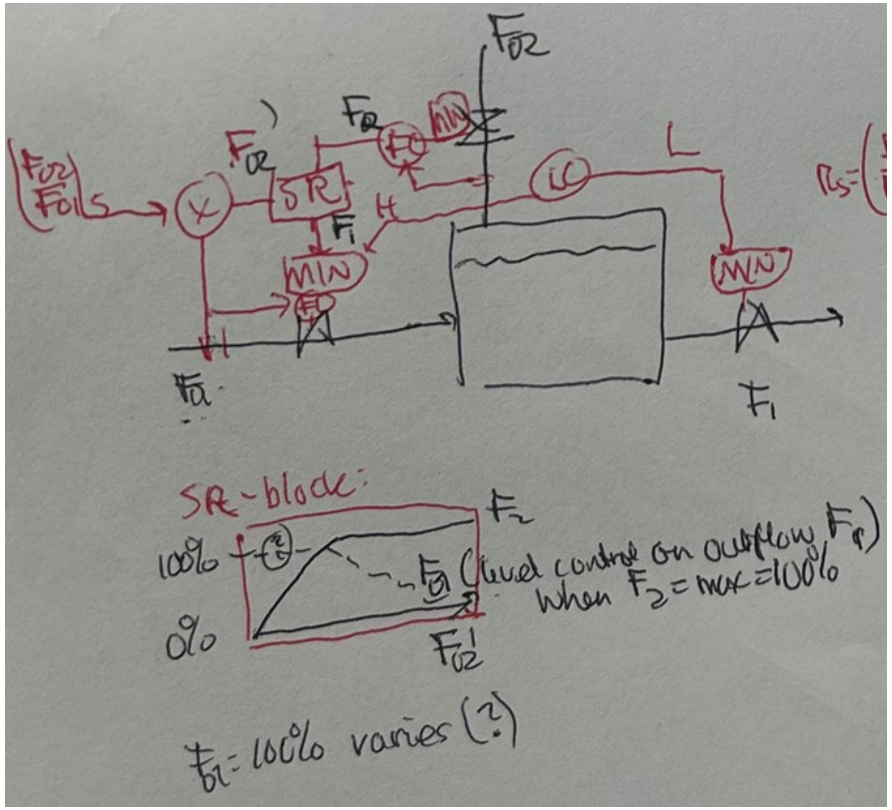
Mixing = Stream merging (junction)



Mixer with ratio control

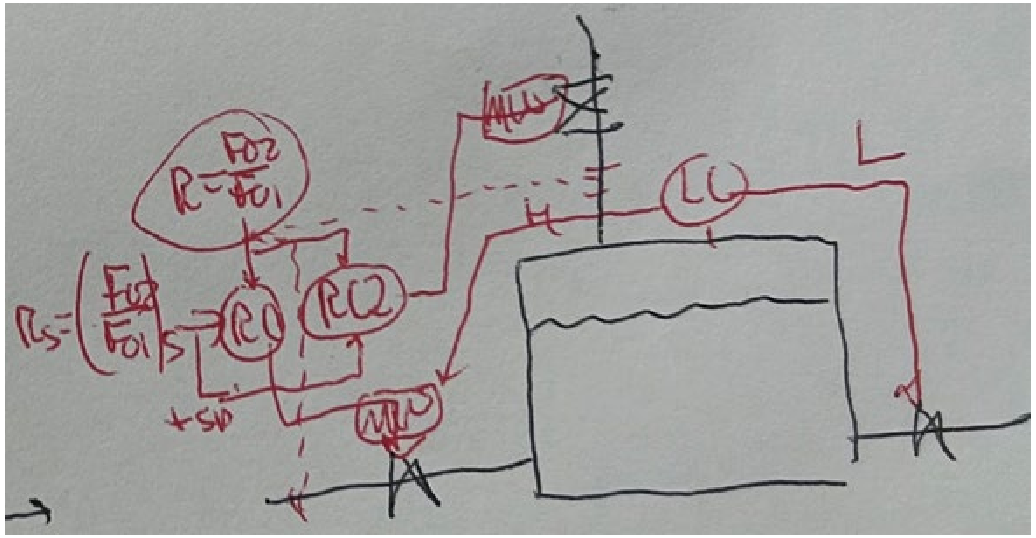


Mixer with ratio control – for case when one flow may saturate



With split range block.

Problem: 100% for reference flow varies



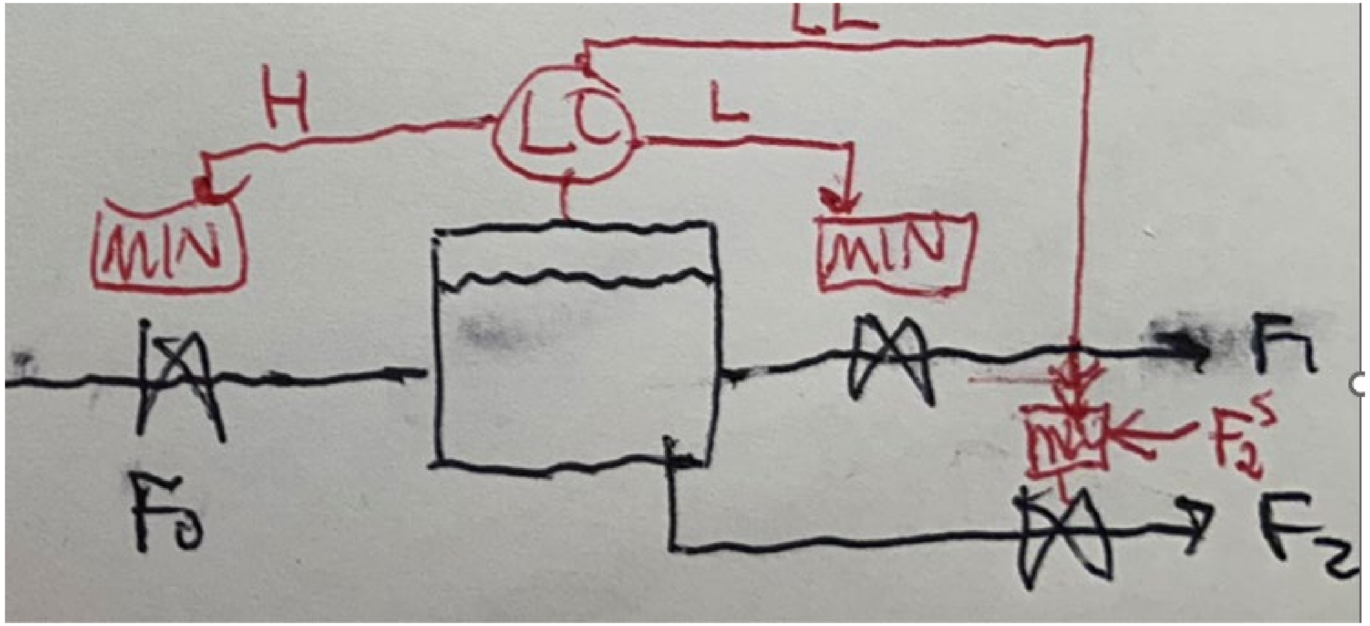
With two ratio controllers with different setpoints

Uses feedback so avoids problem

New slight problem: Must take ratio, problem if F01=0.

Adjustable split (same composition)

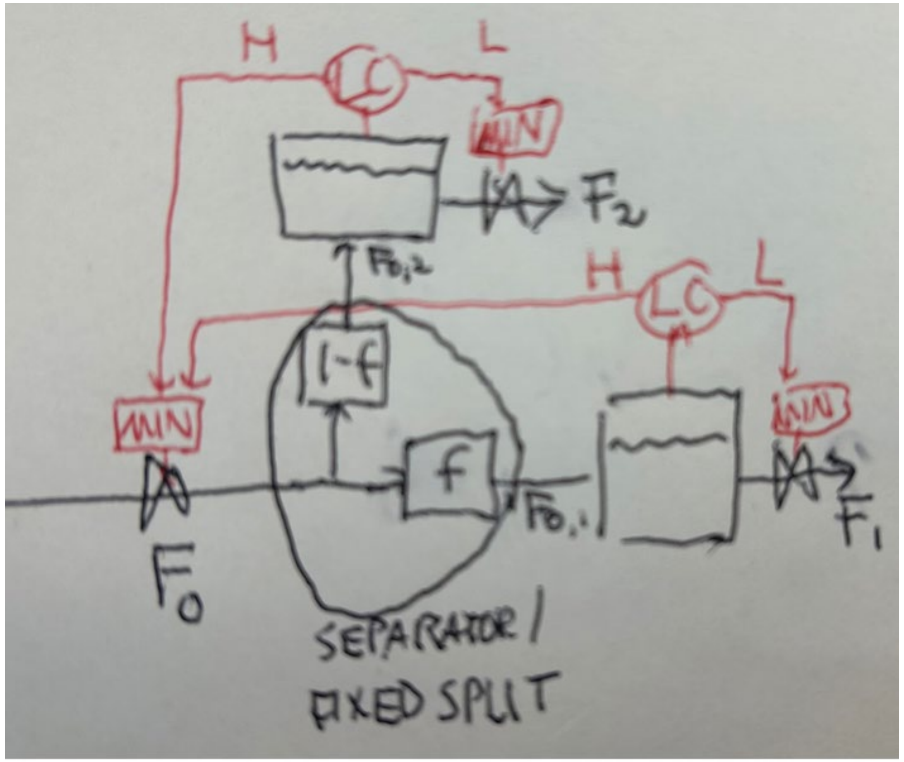
- For: Anti-surge, purge, parallell units



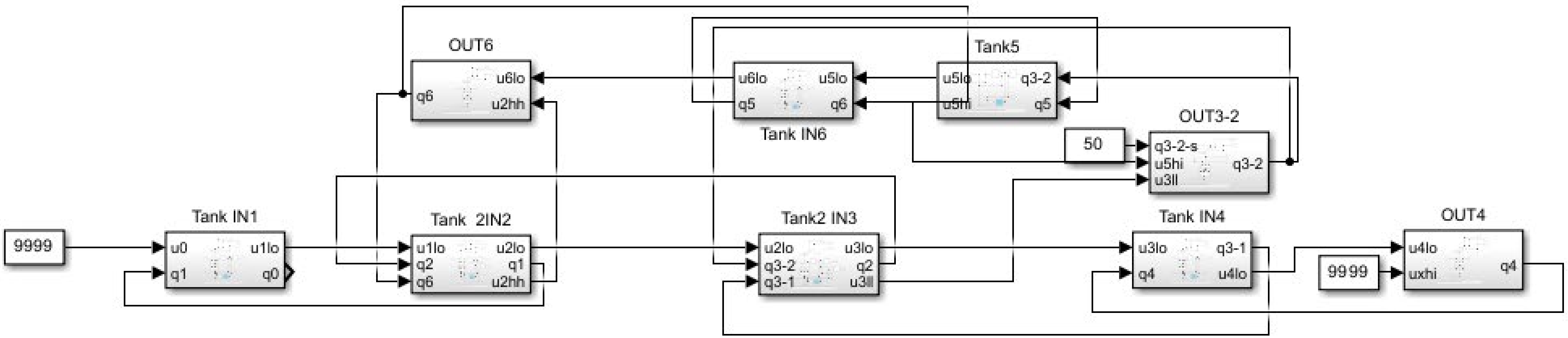
Bidirectional control with override for adjustable stream split. It is here assumed that F1 is used for inventory control (with a low setpoint L). The override level control for F2 (with an even lower setpoint LL) is used dynamically, e.g., to avoid emptying the tank.

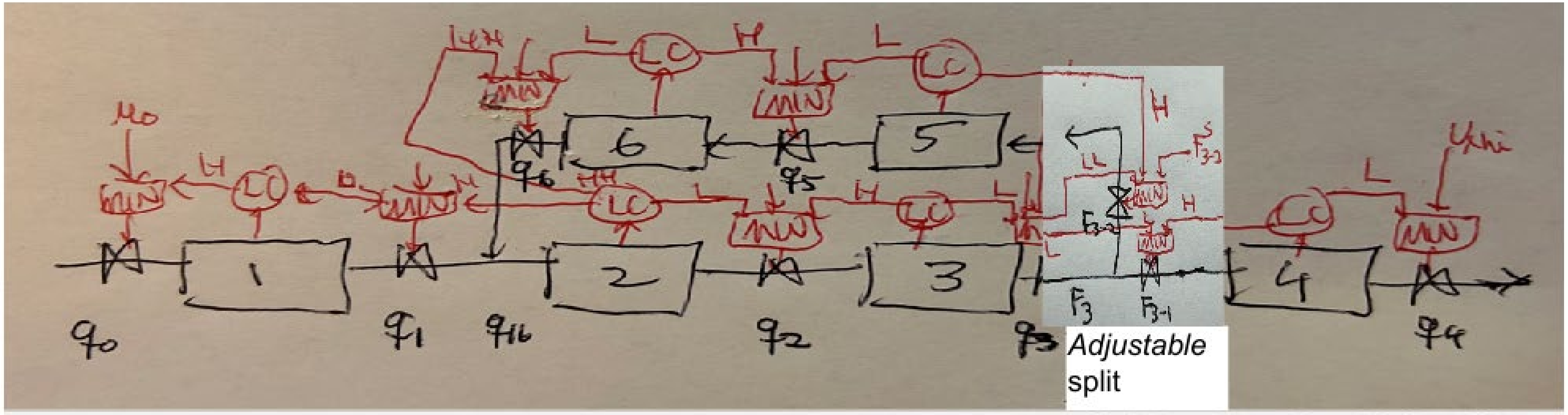
Separator = fixed split (different compositions)

- For: Distillation, cyclone, filter, crystallizer, phase separator,



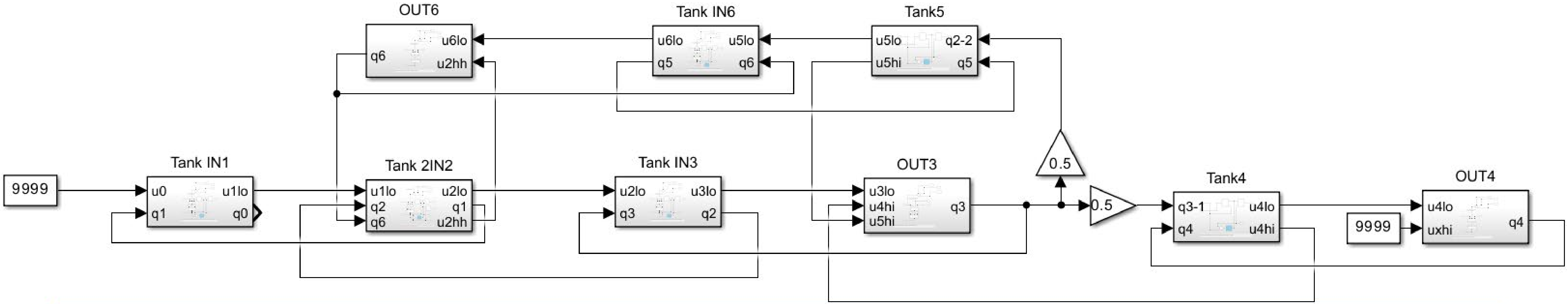
Recycle example with adjustable split (set at split point)

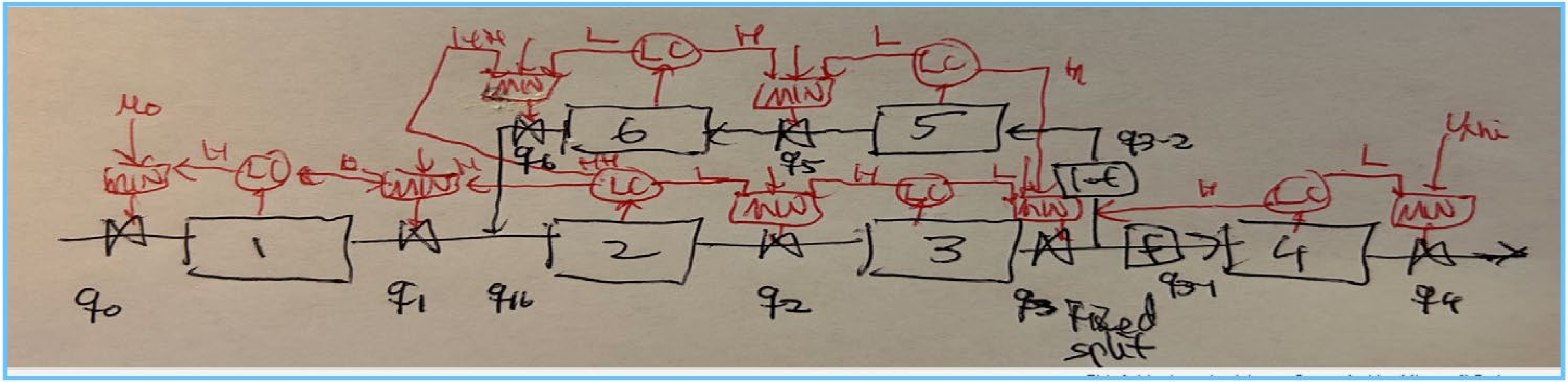




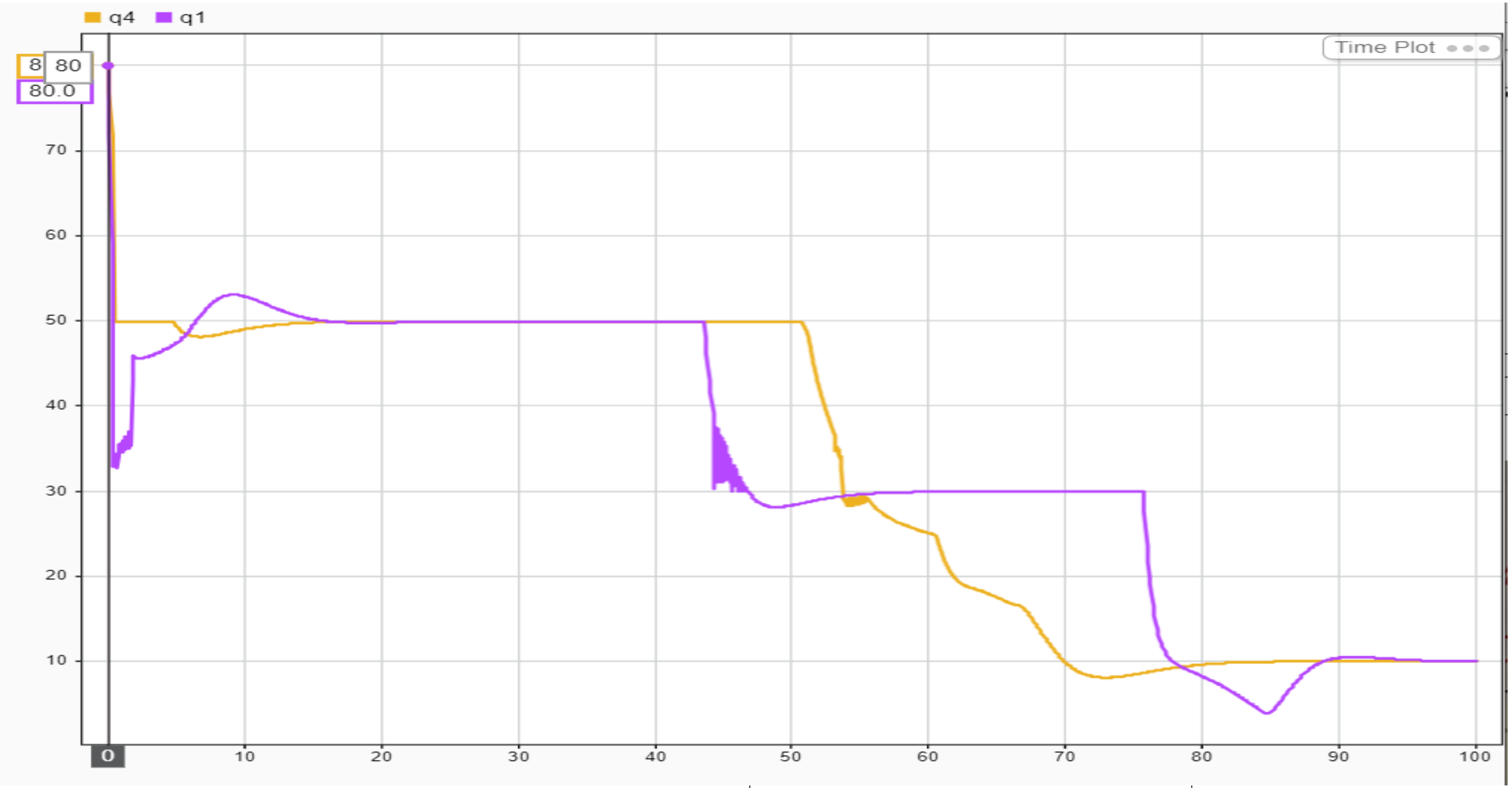
Adjustable split

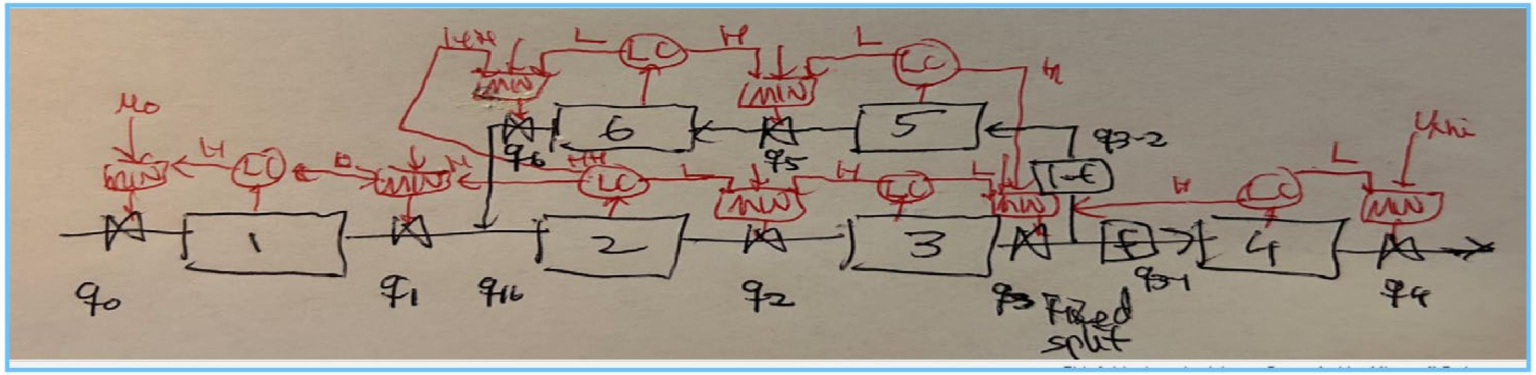
Recycle example with separator (fixed split)





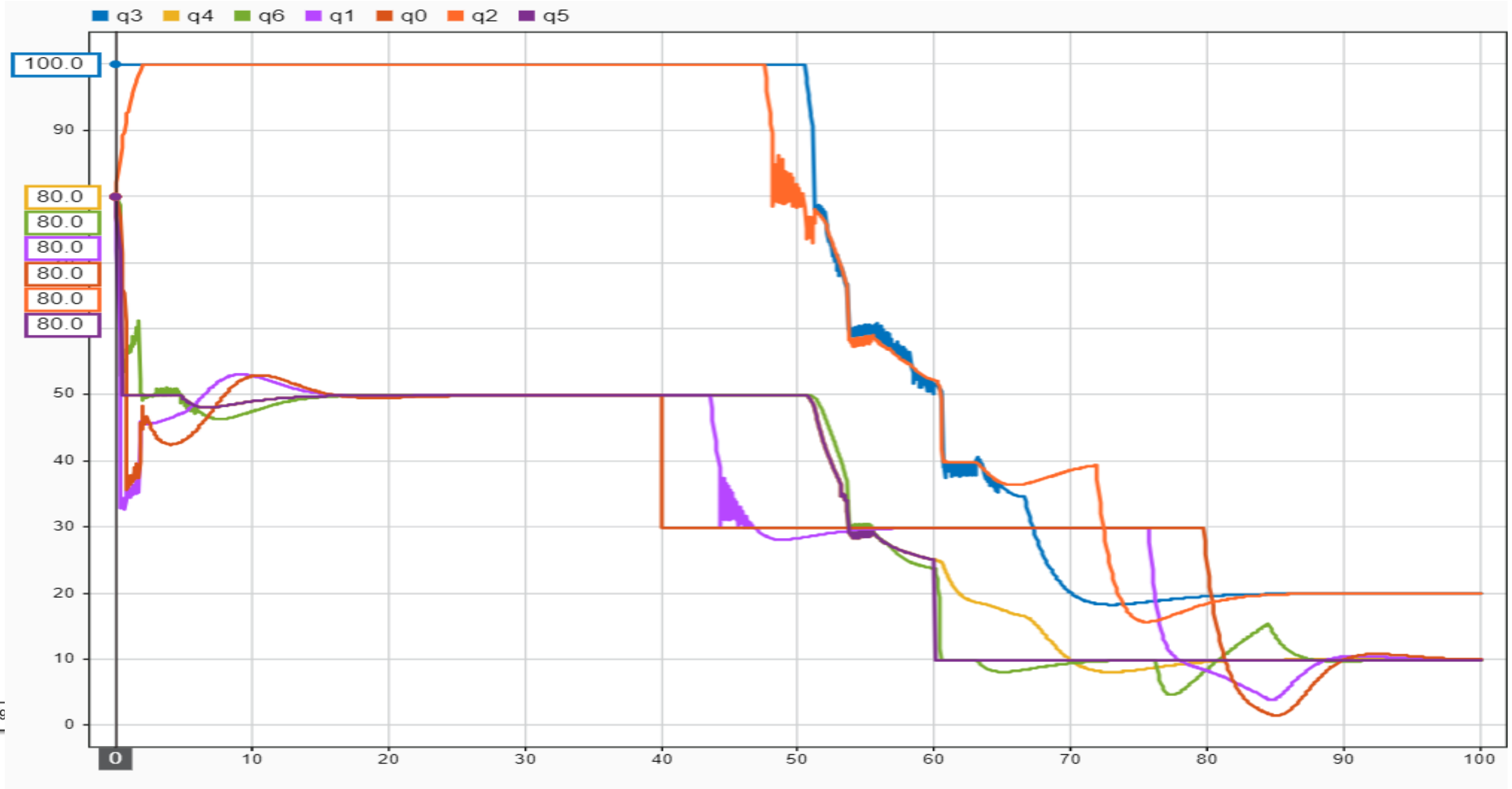
Simulation of Recycle example with separator (fixed split). It works great!



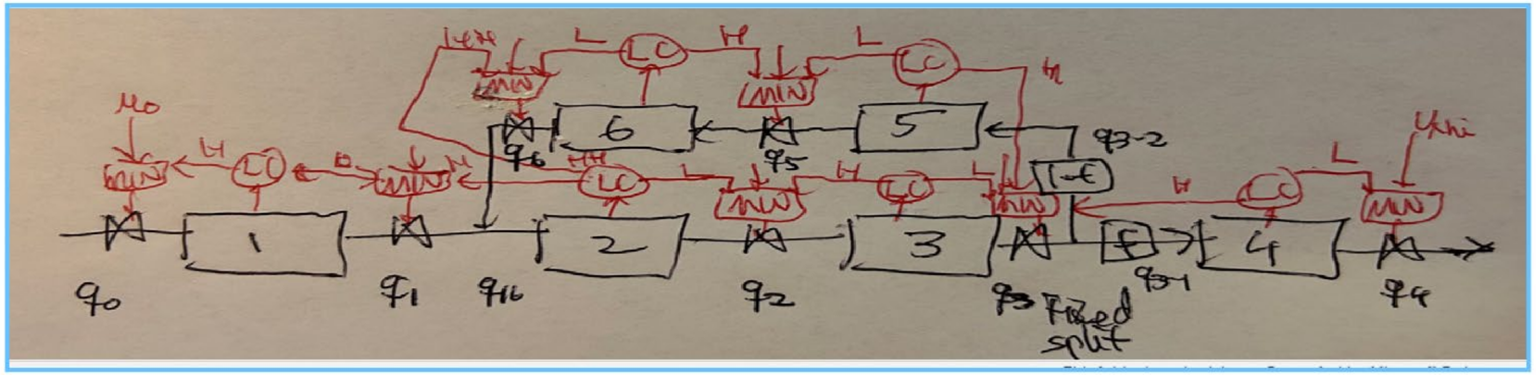


Flows in and out

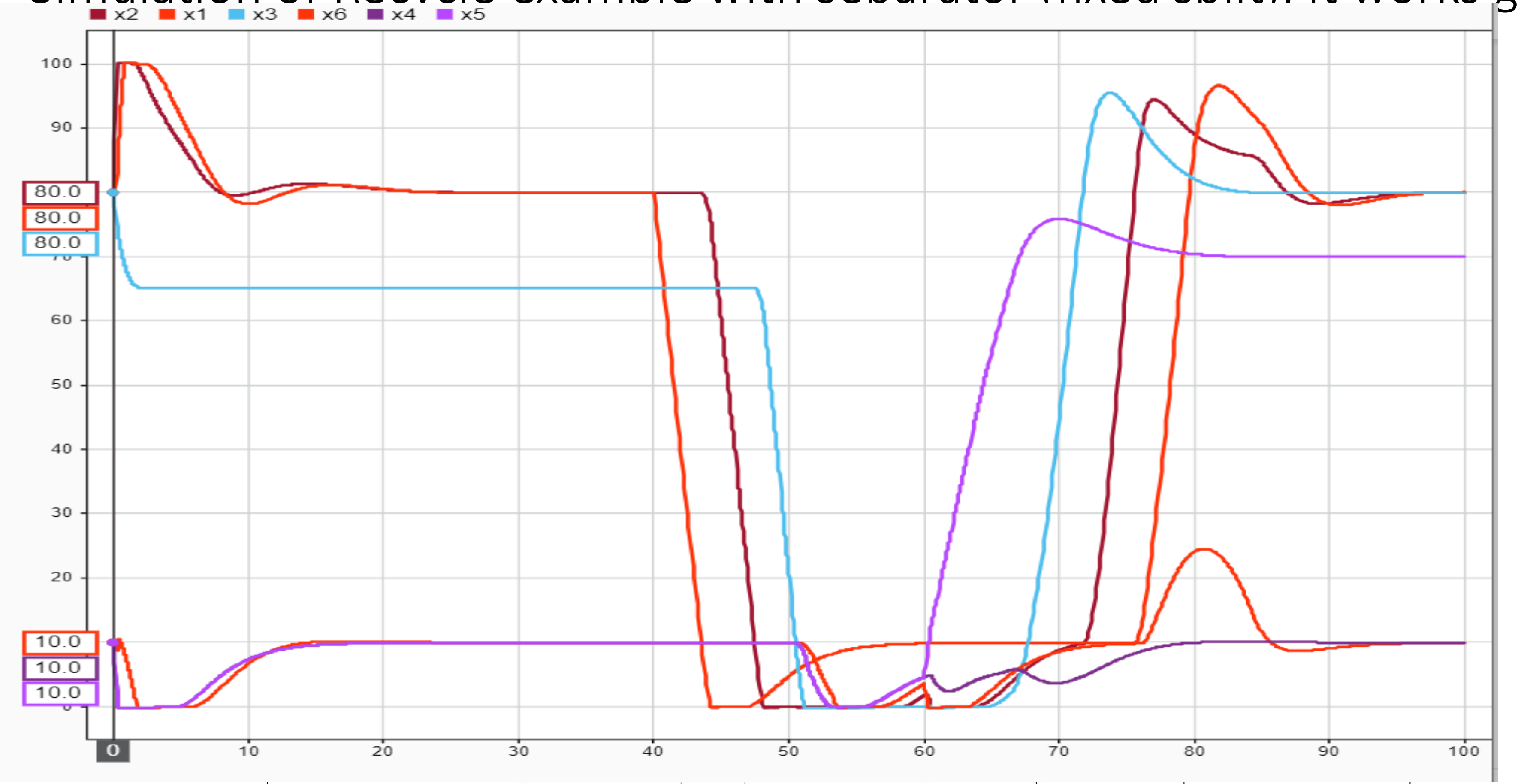
Simulation of Recycle example with separator (fixed split). It works great!



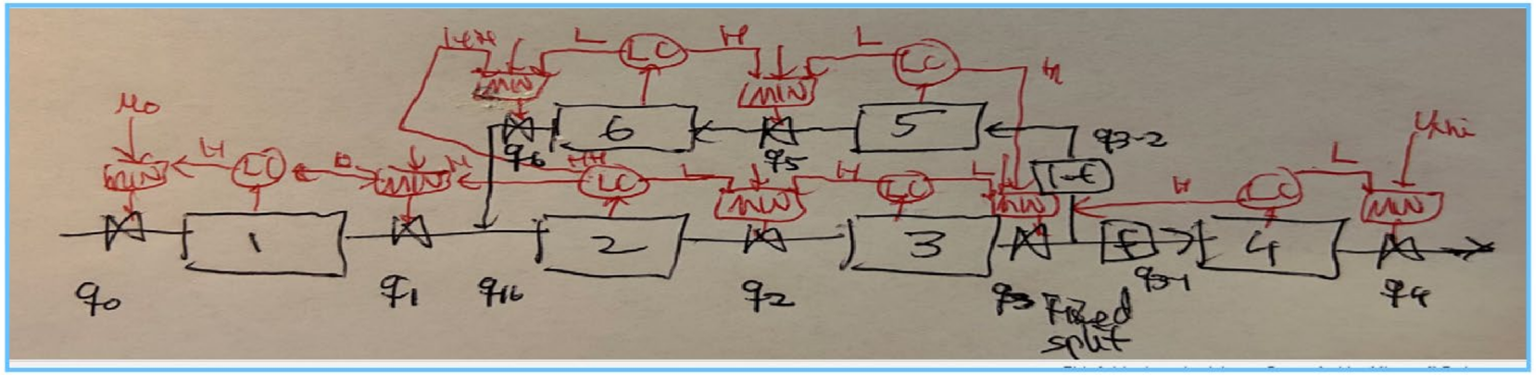
All flows



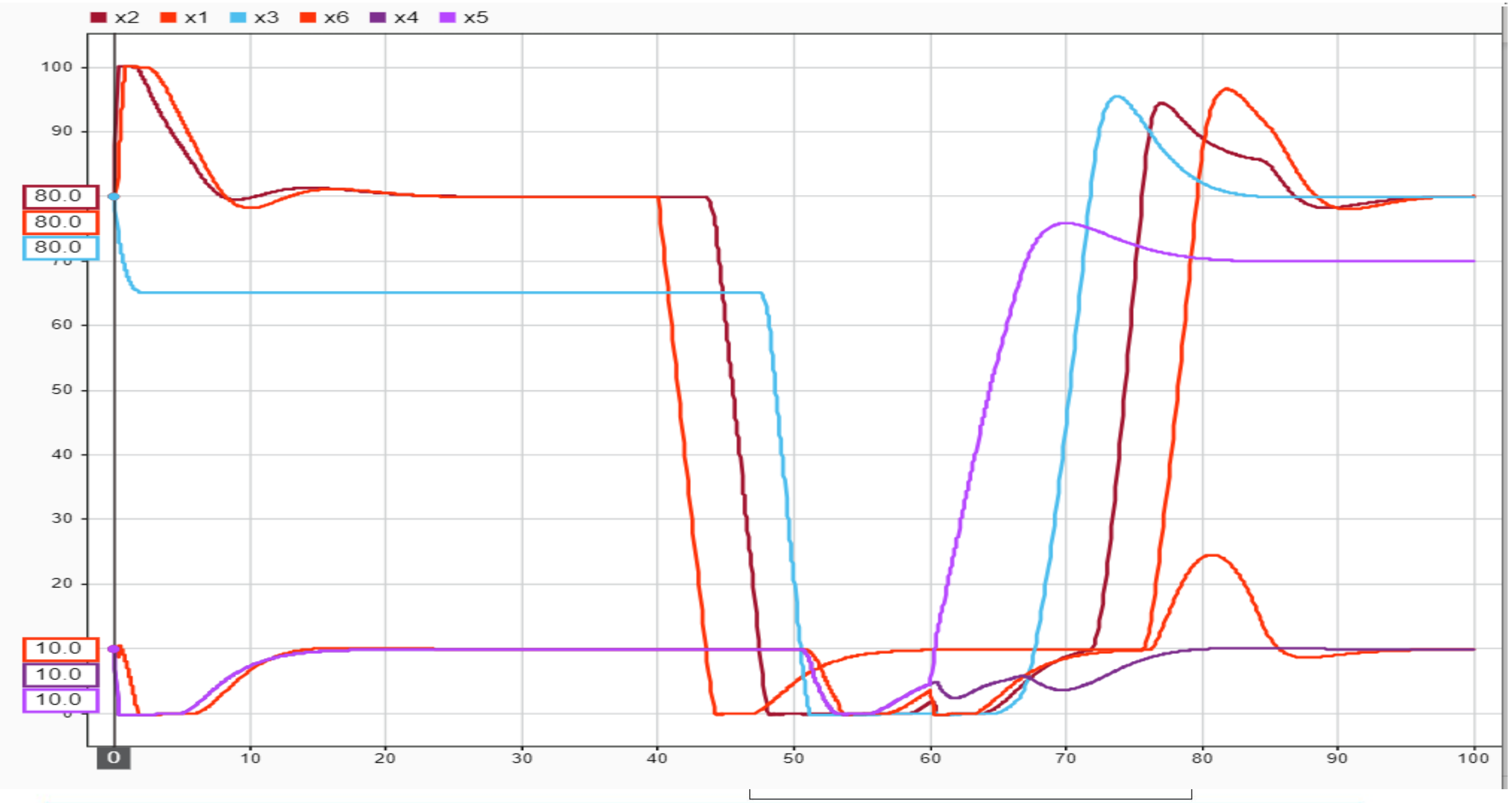
Simulation of Recycle example with separator (fixed split). It works great!

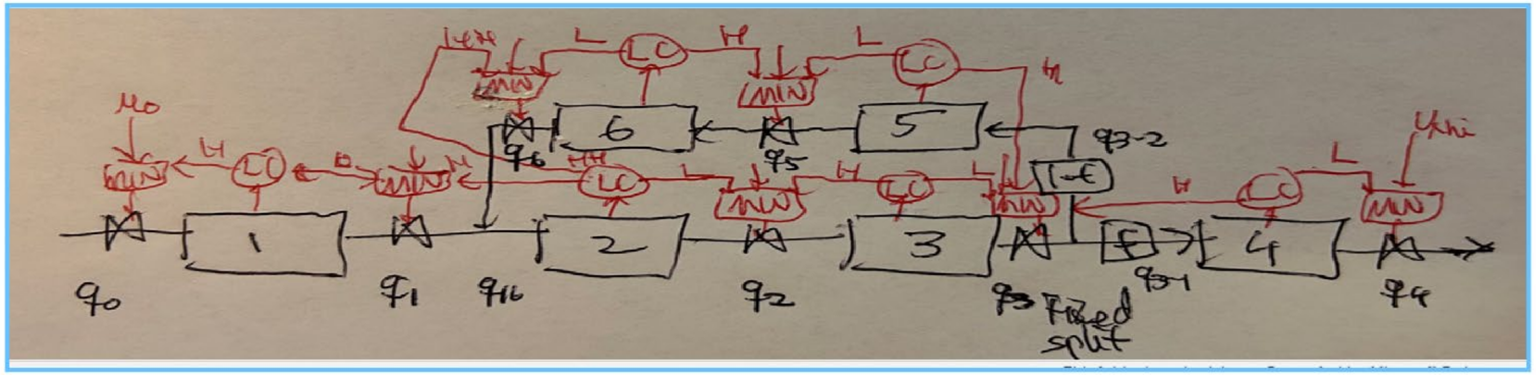


All six levels



Simulation of Recycle example with separator (fixed split). It works great!





Implementing optimal operation Summary

- Most people think
  - You need a detailed nonlinear model and an on-line optimizer (RTO) if you want to optimize the process
  - You need a dynamic model and model predictive control (MPC) if you want to handle constraints
  - The alternative is Machine Learning
- No! In many cases you just need to measure the constraints and use PID control
  - «Conventional advanced regulatory control (ARC)»
- How can this be possible?
  - Because optimal operation is usually at constraints
  - Feedback with PID-controllers can be used to identify and control the active constraints
  - For unconstrained degrees of freedom, one often have «self-optimizing» variables

- This fact is not well known, even to control professors
  - Because most ARC-applications are *ad hoc*
  - Few systematic design methods exists

- Today ARC and MPC are in parallel universes
  - Both are needed in the control engineer's toolbox

Academic process control community fish pond

Optimal centralized
Solution (**EMPC**)

Simple solutions that
work (**ARC** = PID++)

Please join us, we feel a little alone