more on switching

Change of active constraints. Four cases

CV-CV switching (because we may reach new CV constraint)

- Must select between CVs
- «Only» option: Many controllers with **selector**

MV-MV switching (because MV may saturate)

- Need many MVs to cover whole steady-state range
- Use only one MV at a time
- Three options:
  - A1. Split range control,
  - A2. Different setpoints,
  - A3. Valve position control (VPC)

Already covered

Now: MV-CV switching

Simple MV-CV switching: CV can be given up when reach MV saturation

- This means we followed «input saturation rule»
- Don't need to do anything

Complex MV-CV switching: CV cannot be given up (need to «repair loops»)

- Must combine MV-MV switching (three options) with CV-CV switching (selector)

Adriana Reyes-Lua and Sigurd Skogestad, Systematic Design of Active Constraint Switching Using Classical Advanced Control Structures, Ind.Eng.Chem.Res, 2020

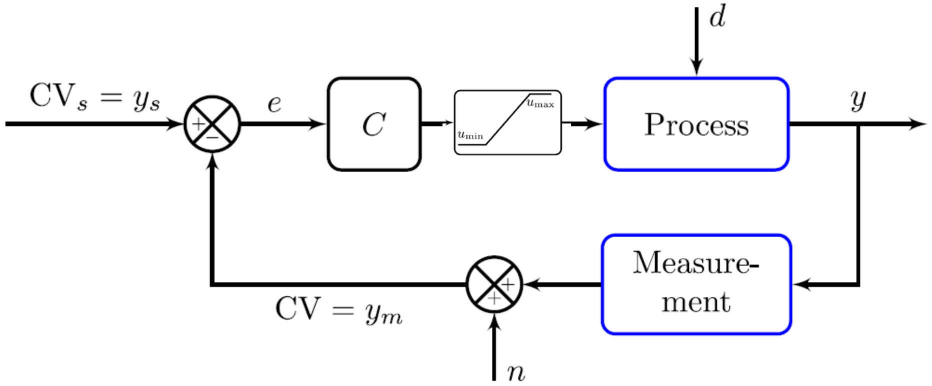
Note: we are here assuming that the constraints are not conflicting so that switching is possible

Simple MV-CV switching

- When MV (u) saturates, we can give up the CV (y).
  - Don't need to do anything, except having anti-windup in the controller
- This is because we have followed the

Input saturation rule: "Pair a MV that may saturate with a CV that can be given up (when the MV saturates)"

- Many examples (that it works is not always so obvious!)
  - 1. Driving as fast as possible to the airport
    - u=power $\leq u_{max}$
    - y = speed $\leq y_{max}$
    - $y_s = y_{max}$ = 90 km/h
    - "If we reach max power (u=umax), we must give up controlling y"
  - 2. Heating of cabin in the winter
    - u=power ≥ 0
    - y = temperature $\geq$ 8C
    - $y_s = y_{min}$ = 8C
    - "If we reach min. power (u=0), then it is hot outside - and there is no need to control y"
  - 3. Anti-surge control
    - u =bypass ≥ 0,
    - y = flowrate $\geq y_{min}$
    - $y_s = y_{min}$
    - "If we reach min. bypass (u=0), then the feedrate is larger than y_{min} - and there is no need to control y"

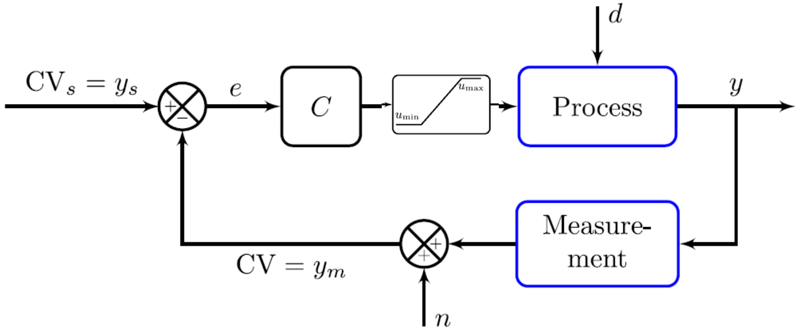


Optimization with PI-controller

max *y*

s.t. $y \le y^{max}$

$u \le u^{max}$



Example: Drive as fast as possible to airport (u=power, y=speed, y^{max} = 110 km/h)

- **Optimal solution has two active constraint regions:**
  1. $y = y^{max}$ → **speed limit**
  2. $u = u^{max}$ → **max power**

- **Solved with PI-controller**
  - $y^{sp} = y^{max}$
  - Anti-windup: I-action is off when $u=u^{max}$

s.t. = subject to
y = CV = controlled variable

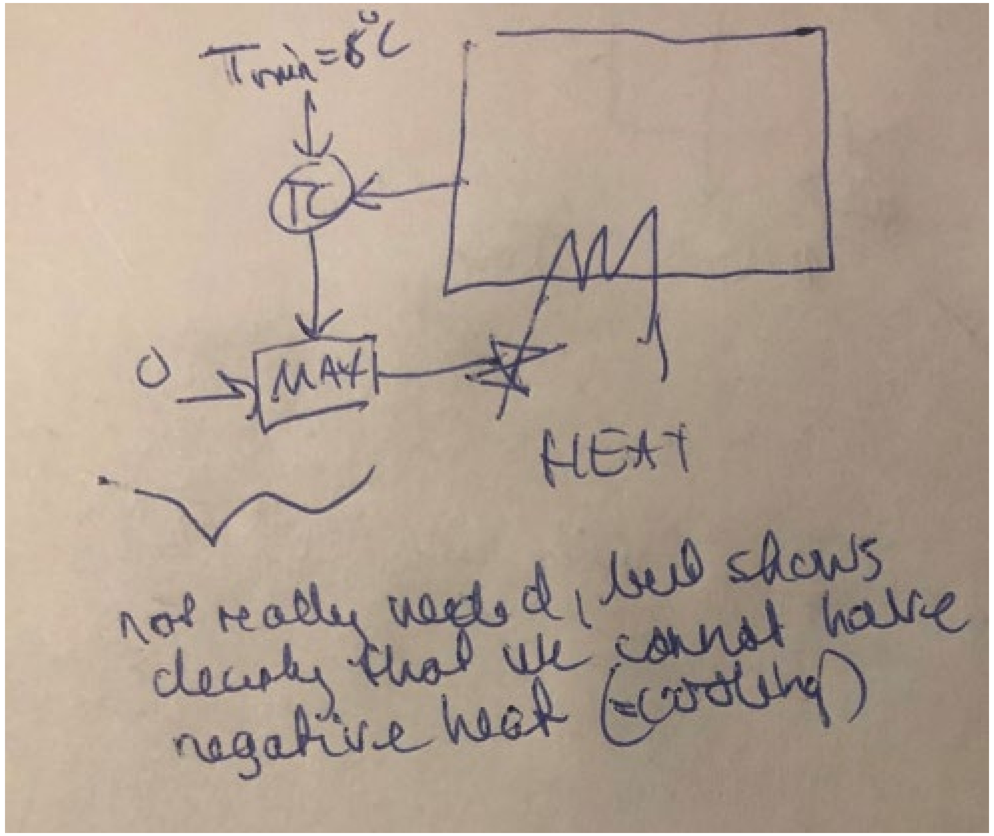
Simple MV-CV switching, Example 2

Avoid freezing in cabin

$$\text{Minimize } u \text{ (heating), subject to}$$
$$T \geq T_{min}$$
$$u \geq 0$$

Keep CV=T>T_{min} = 8C in cabin in winter by using MV=heating

If it’s hot outside (>8C), then the heat will go to zero (MV=Q=0), but this does not matter as the constraint is over-satisfied.



not really needed, but shows clearly that we cannot have negative heat (=cooling)

Example 3, «simple» MV-CV switching (no selector)

Anti-surge control (= min-constraint on F)

$$\textit{Minimize } u \textit{ (recycle), subject to}$$
$$F \geq F_{min}$$
$$u = z \geq 0$$

Keep minimum flow F_{min} for pump or compressor using recycle valve.

If the flow F_0 (and thus F) becomes large then the recycle valve will close (MV=0), but this does not matter as the constraint on F is over-satisfied.

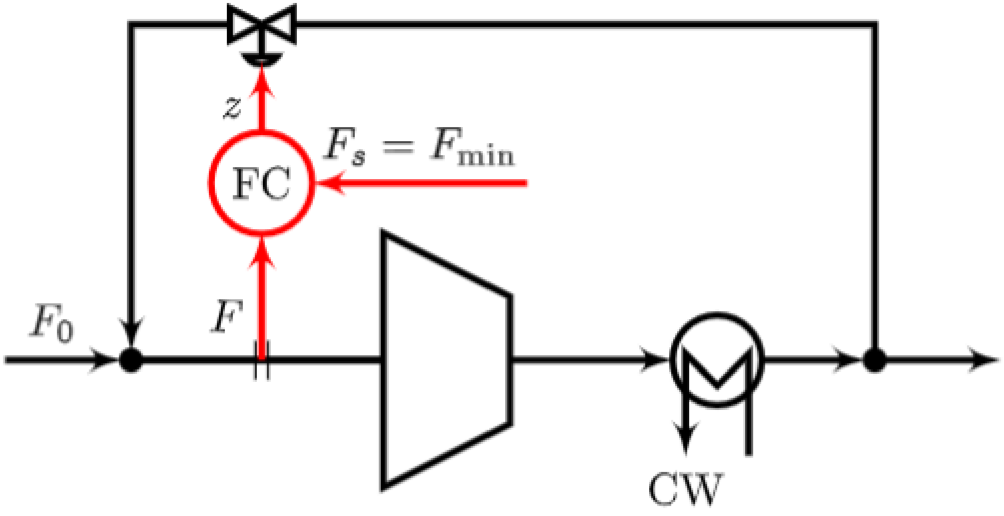
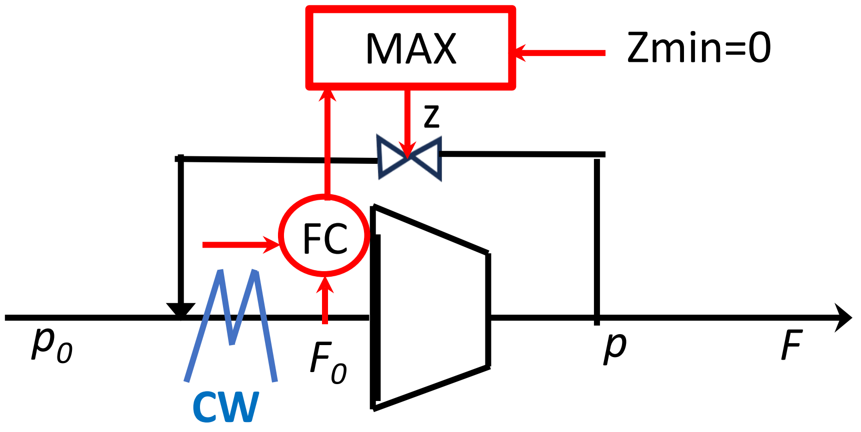


Fig. 32. Flowsheet of anti-surge control of compressor or pump (CW = cooling water). This is an example of simple MV-CV switching: When MV=z (valve position) reaches its minimum constraint ($z = 0$) we can stop controlling CV=F at $F_s = F_{min}$, that is, we do not need to do anything except for adding anti-windup to the controller. Note that the valve has a "built in" max selector.

- No selector required, because MV=z has a «built-in» max-selector at z=0.
- Generally: «Simple» MV-CV switching (with no selector) can be used if we satisfy the input saturation rule: «*Pair a MV =z that may saturate with a CV =F that can be given up (when the MV saturates at z=0)"*

QUIZ Compressor control

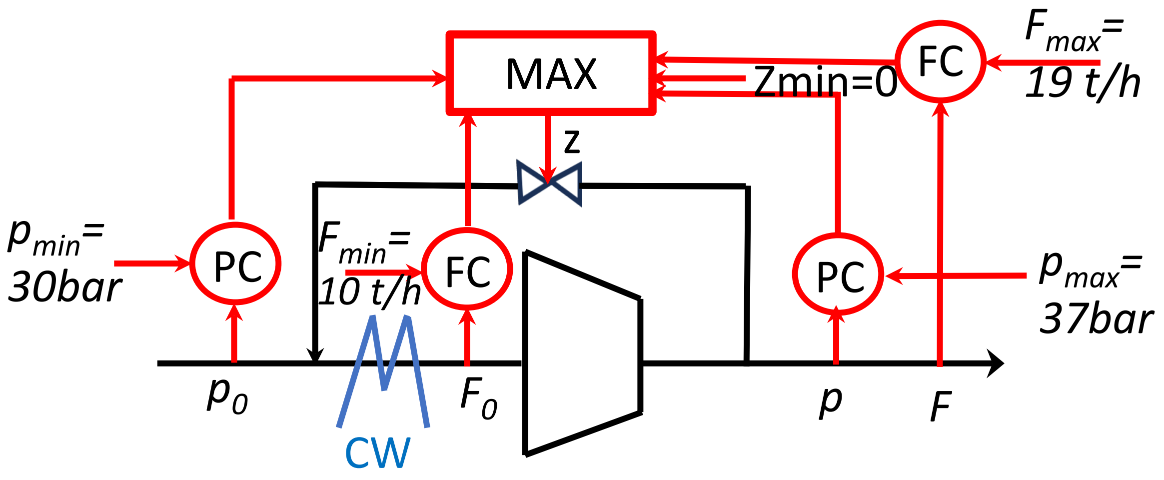


Suggest a solution which achieves

- $p < p_{max} = 37$ bar *(max delivery pressure)*
- $P_0 > p_{min} = 30$ bar *(min. suction pressure)*
- $F < F_{max} = 19$ t/h *(max. production rate)*
- $F_0 > F_{min} = 10$ t/h *(min. through compressor to avoid surge)*

All these 4 constraints are satisfied by a large z
-> MAX-selector

SOLUTION



Complex MV-CV switching

  - Didn’t follow input saturation rule
  - This is a repairing of loops
  - Need to combine MV-MV switching with CV-CV-switching
- The CV-CV switching always uses a selector
- As usual, there are three alternatives for the MV-MV switching:
  1. Split range control (block /\): Has problems because limits may change
  2. Several controllers with different setpoints (often the best for MV-CV switching)
  3. Valve position control (Gives «long loop» but avoids repairing).

  +4. Shinskey alternative (not covered here)

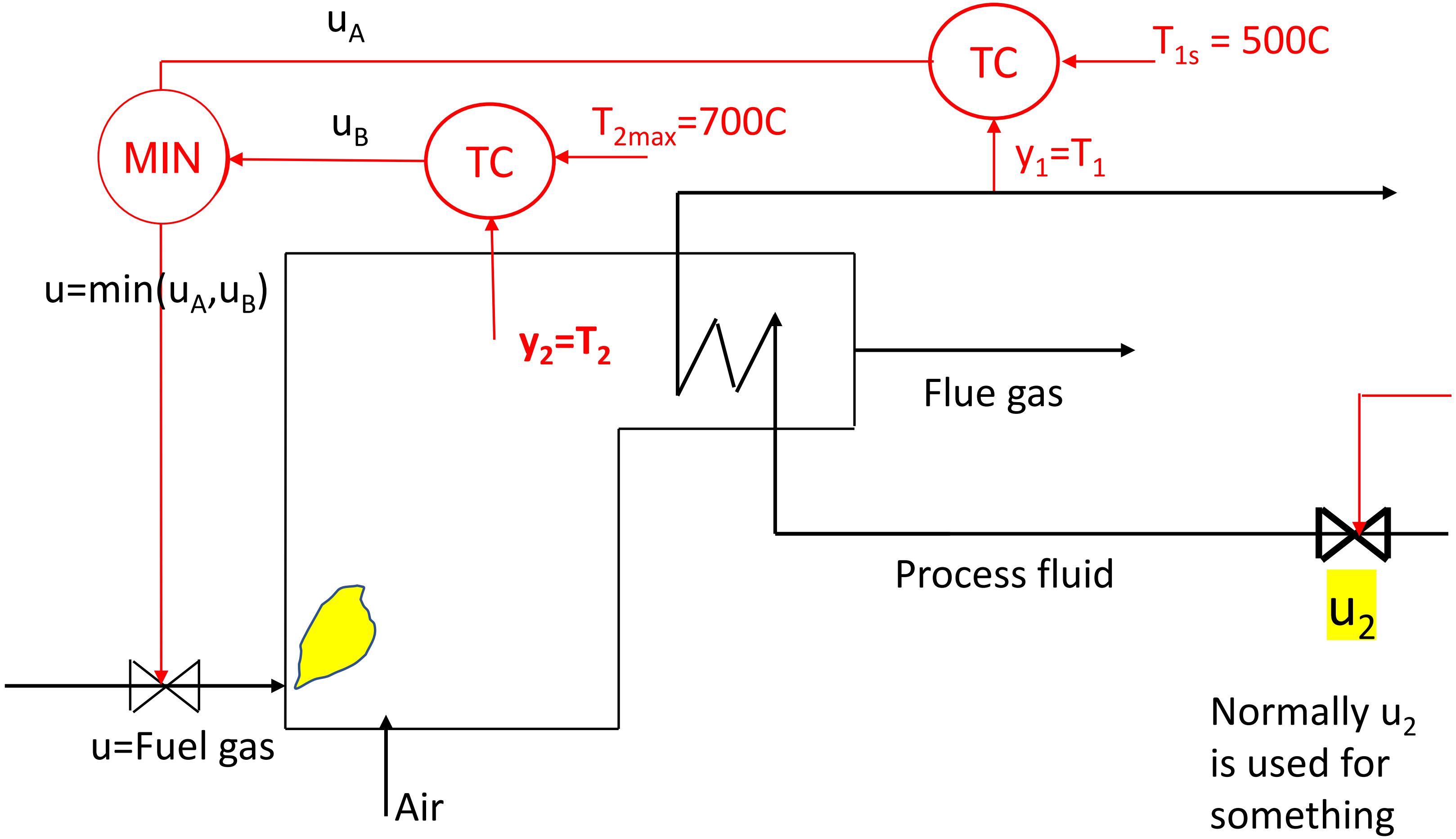
Furnace control : Cannot give up control of y_1=T_1. What to do?

Inputs (MV)

- u = Fuel gas flowrate
- u_2 = Process flowrate

Output (CV)

- y_1 = process temperature T_1 (with desired setpoint)



Normally u_2 is used for something else

Complex MV-CV switching

Cannot give up controlling T_1

Solution: Cut back on process feed (u_2) when T_1 drops too low

Inputs (MV)

- u = Fuel gas flowrate
- u_2 = Process flowrate

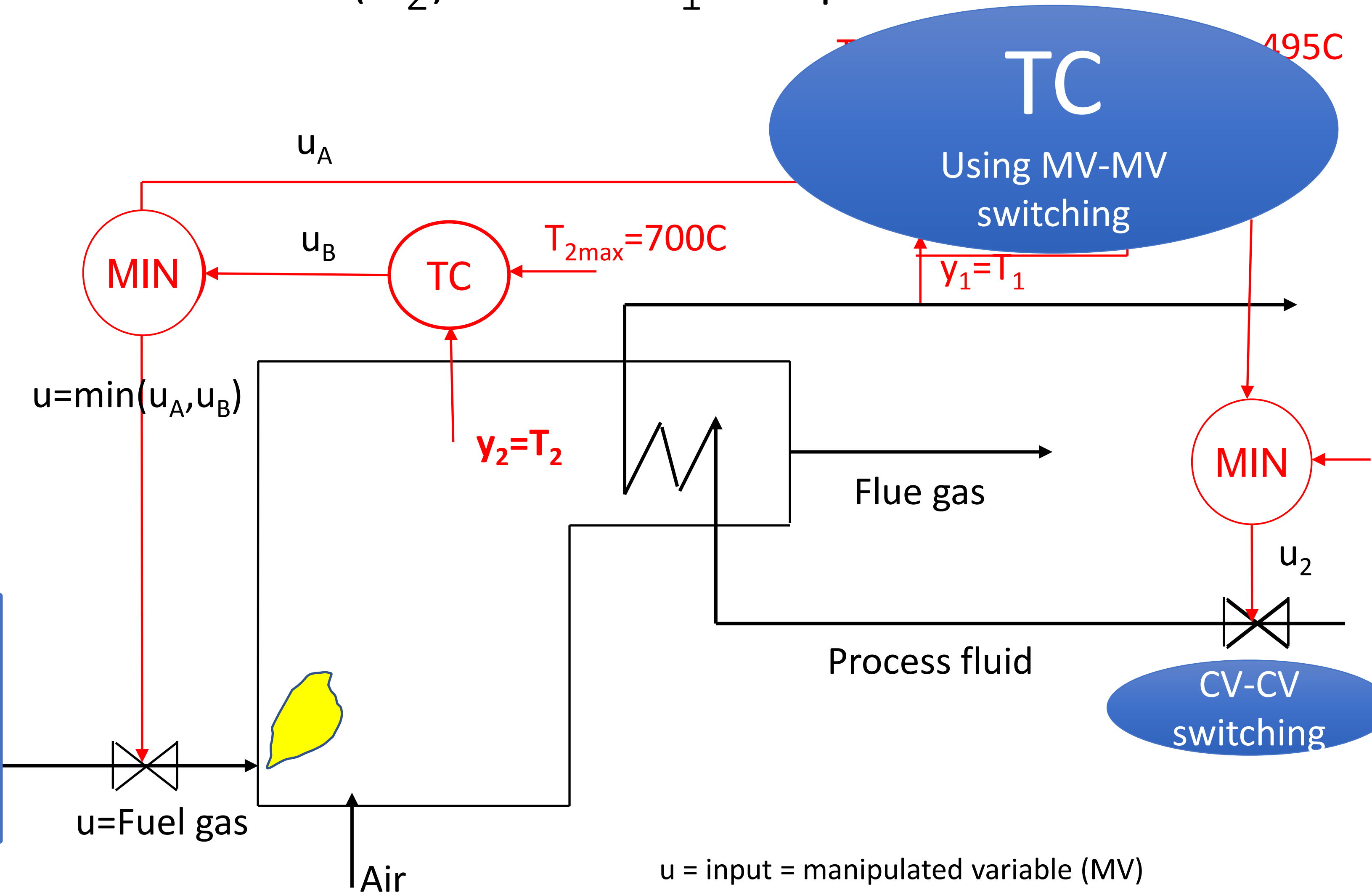
Output (CV)

- y_1 = process temperature (with desired setpoint)

Note: Standard Split Range Control (Alt. 1) is not good here for MV-MV switching.
Could be two reasons for too little fuel

- Fuel is cut back by override (safety)
- Fuel at max,

So don't know limit for MV1 to use in SRC-block.

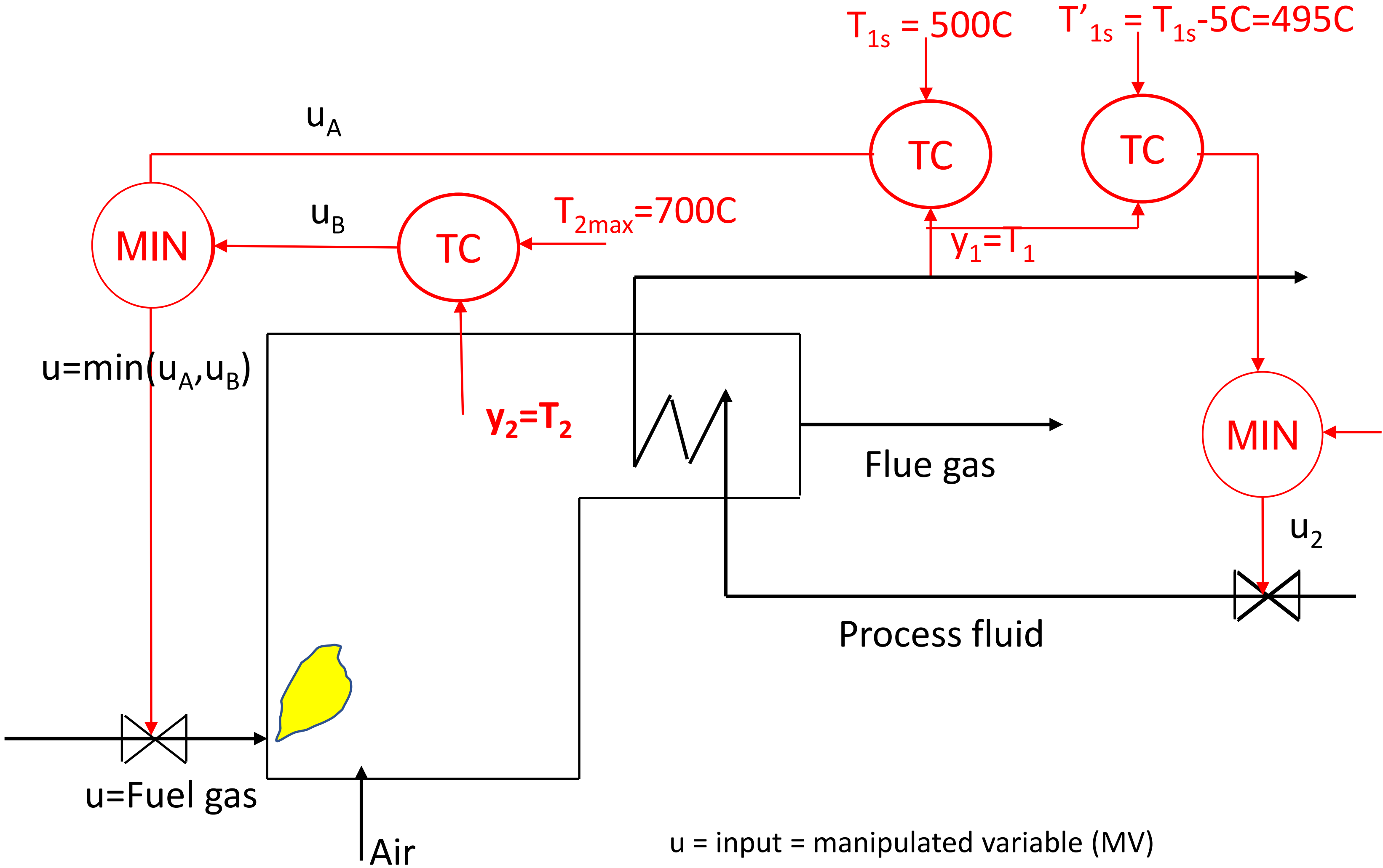


u = input = manipulated variable (MV)
y = output = controlled variable (CV)

Use Alt. 2: Two controllers

Inputs (MV)
- u = Fuel gas flowrate
- u2 = Process flowrate

Output (CV)
- y_1 = process temperature (with desired setpoint)



u = input = manipulated variable (MV)
y = output = controlled variable (CV)

Implementing optimal operation by switching

- 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

More on inventory control

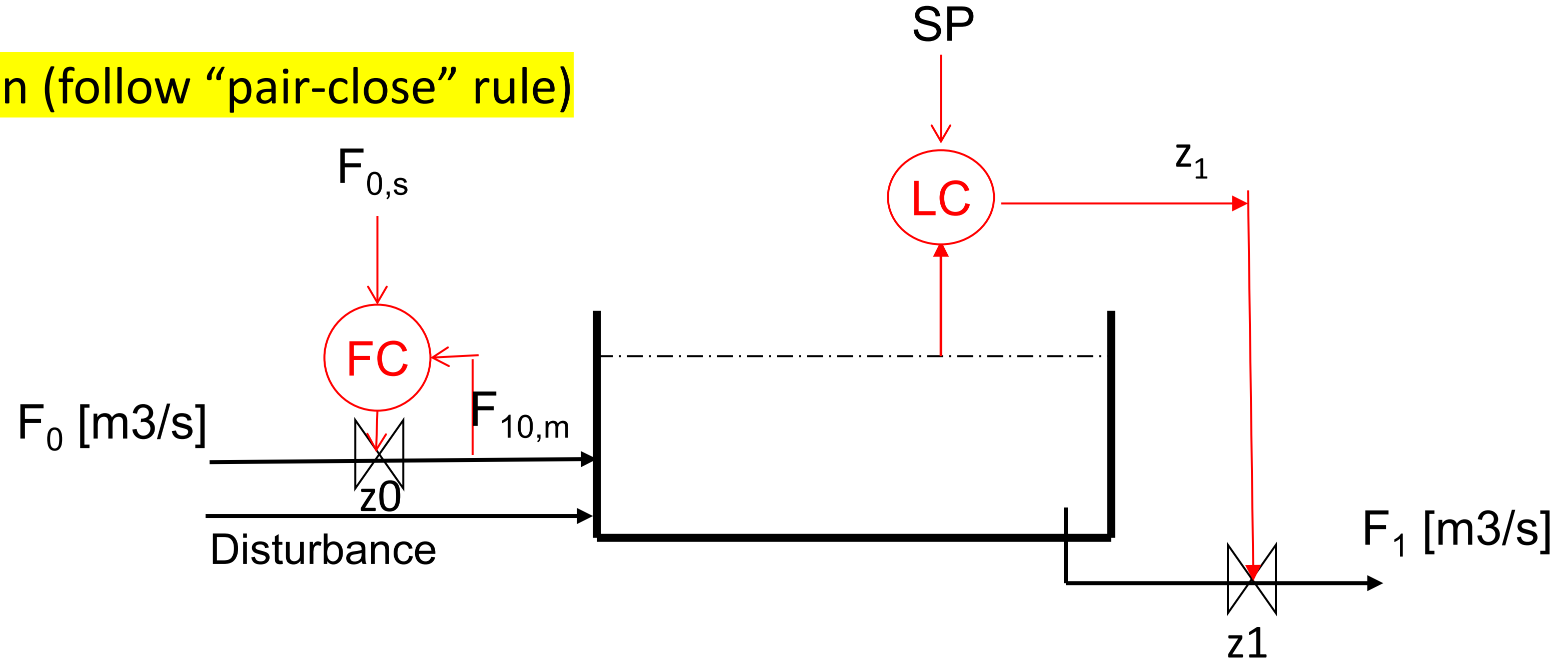
Level control

1. Pairing: Use in- or outflow
   - Radiation rule
   - Don’t cross TPM
2. Tuning: Tight or slow («averaging») level control
   - Averaging is good to dampen flow disturbances
   - «Floating» (uncontrolled level) is good for isolating process parts
     - But requires tight control when we reach max- or min level

Example : Level control

MV1 = z0 (inflow valve position)
MV2 = z1 (outflow valve position) (likely to saturate)
CV1 = F0 (inflow): Should be controlled at setpoint $F_{0,s}$ (if possible)
CV2 = level: must always be controlled (at some SP)

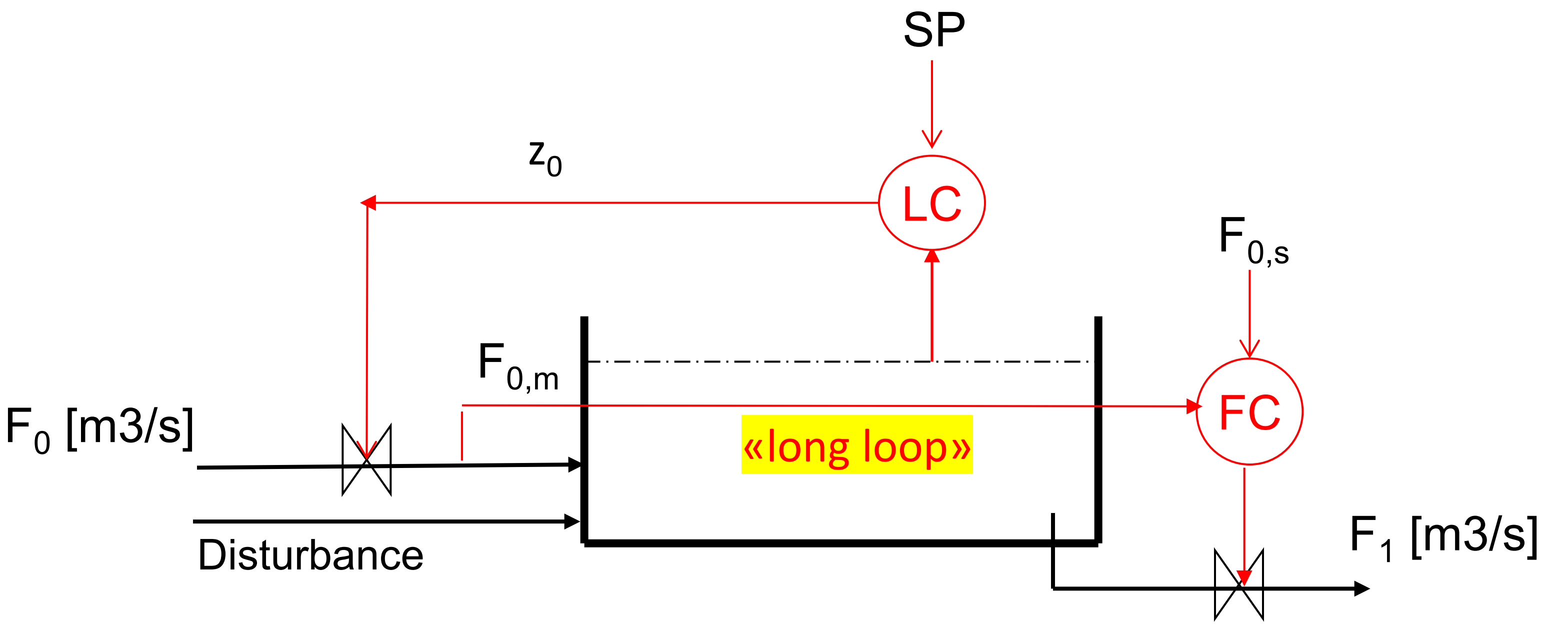
Nominal design (follow “pair-close” rule)



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)

This gives simple MV-CV switching (if z1 saturates at fully open)

Reverse pairing (follows “input saturation rule”):



BUT with Reverse pairing: Get “long loop” for F0
In addition: loose control of y2= level if z0 (F0-valve) saturates

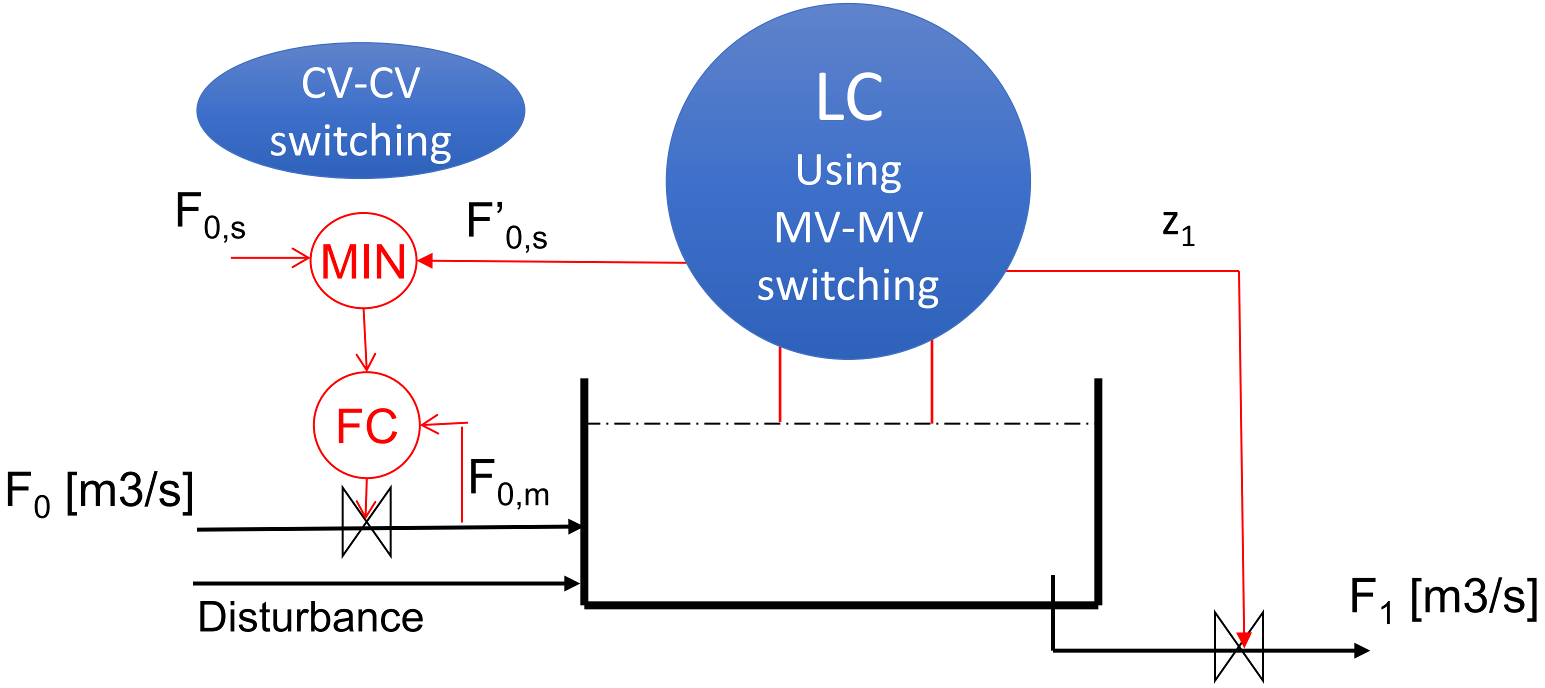
«Long loop» = Works through other loops

This is complex MV-CV switching

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

When z1 saturates at max, use the other MV (z0) for level control and give up controlling F0

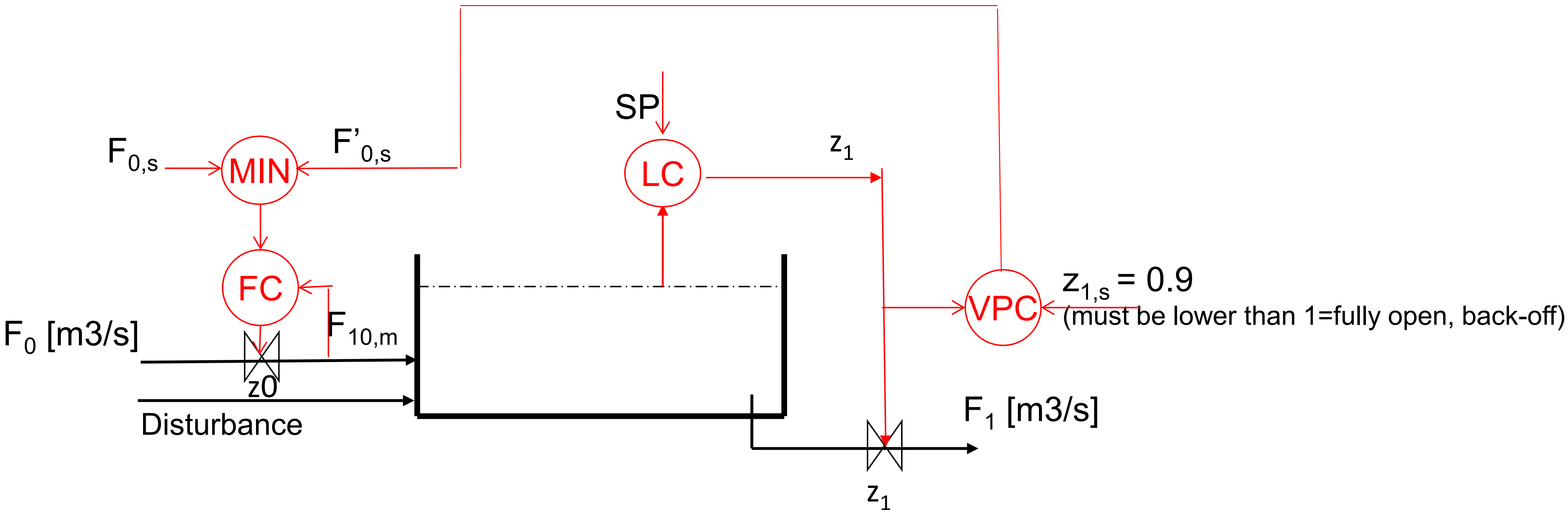
Get: “Bidirectional inventory control”



Three alternsatives for MV-MV switching

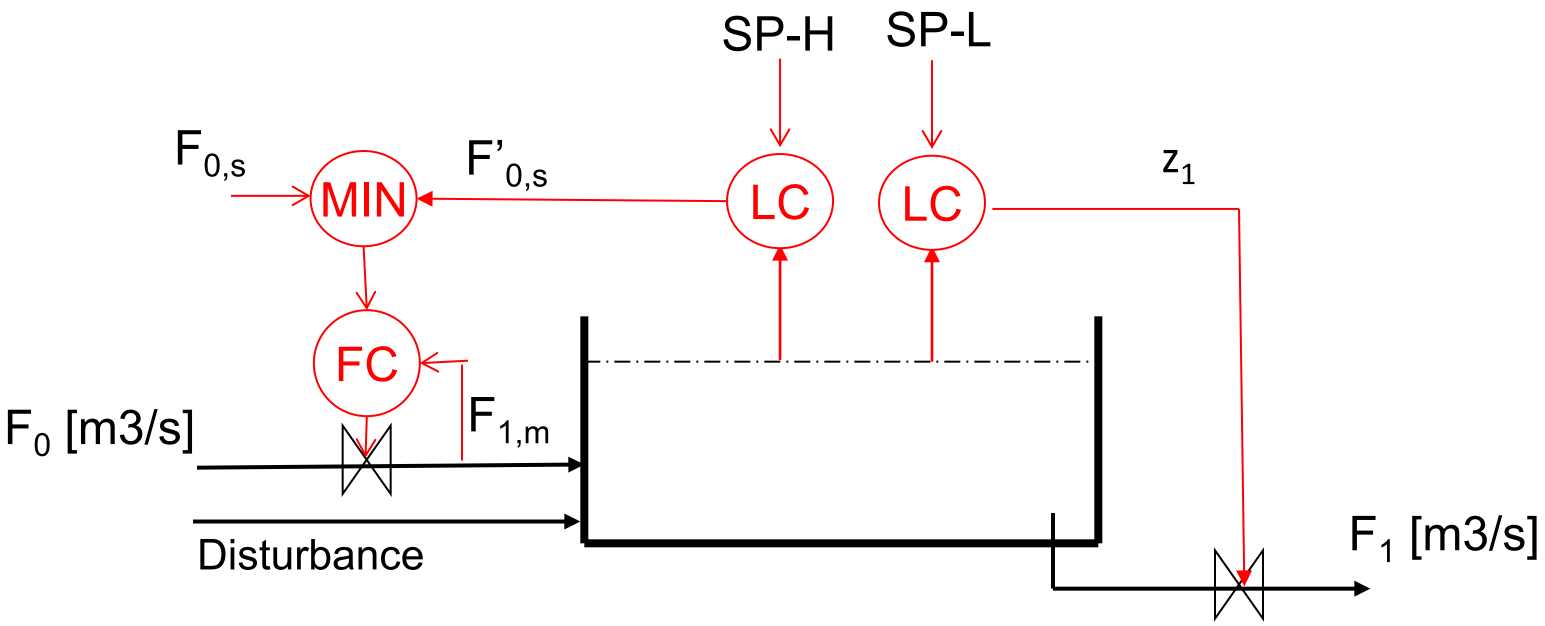
1. SRC (problem since F_{0s} varies)
2. Two controllers
3. VPC (“Long loop” for z1, backoff)

Alt. 3 MV-MV switching: VPC



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

Alt. 2 MV-MV switching: Two controllers (recommended)



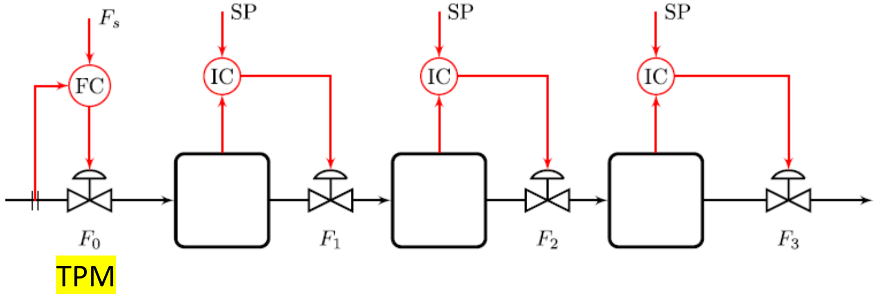
SP-L = low level setpoint
SP-H = high level setpoint

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

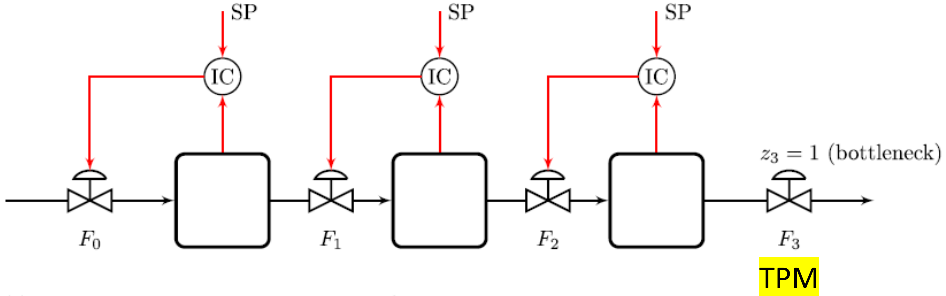
- Use low setpoint when level is controlled by product (outflow): Have room for feed if outflow stops temporarily.
- Use high setpoint when level is controlled by feed (inflow): Can keep producing if inflow stops temporarily.

Inventory control for units in series

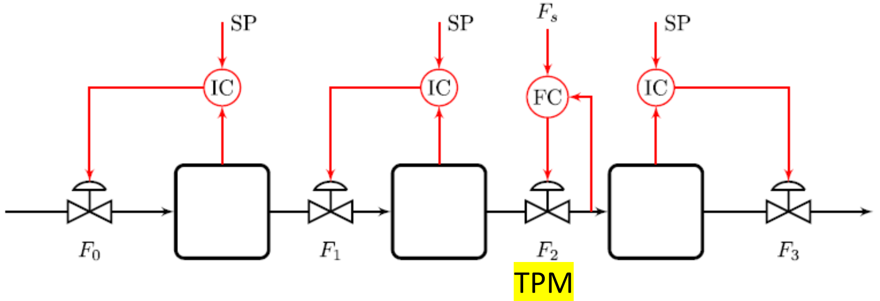
Radiating rule:
Inventory control should be "radiating" around a given flow (TPM).



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

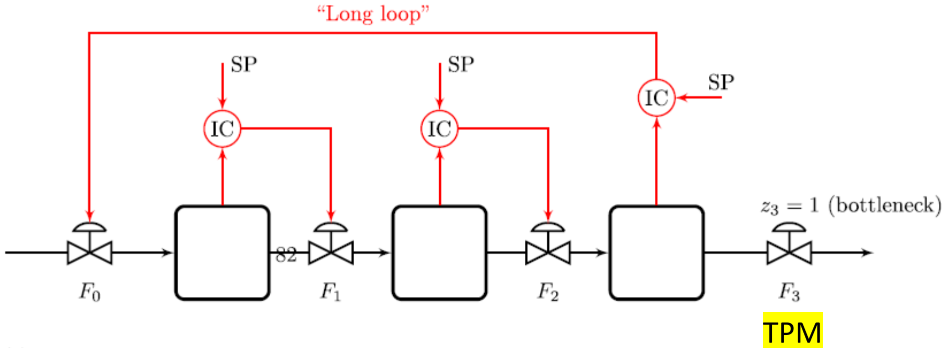


(b) Inventory control in opposite direction of flow (for given product flow, TPM= F_3)



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

Follows radiation rule



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

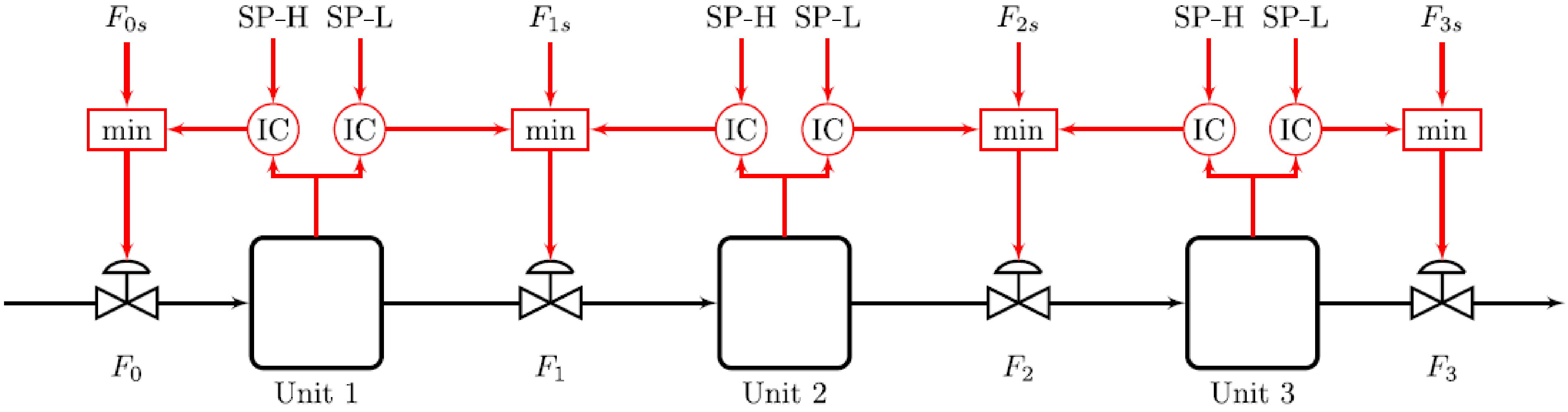
Does NOT follow radiation rule

Generalization of bidirectional inventory control

Reconfigures automatically with optimal buffer management!!

Maximize throughput:

$F_s = \infty$



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

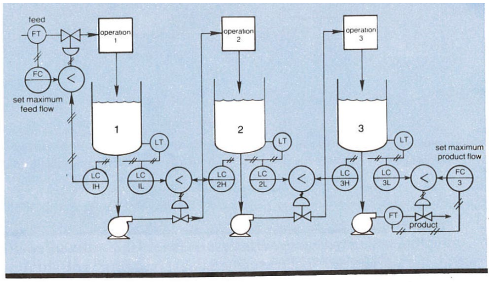
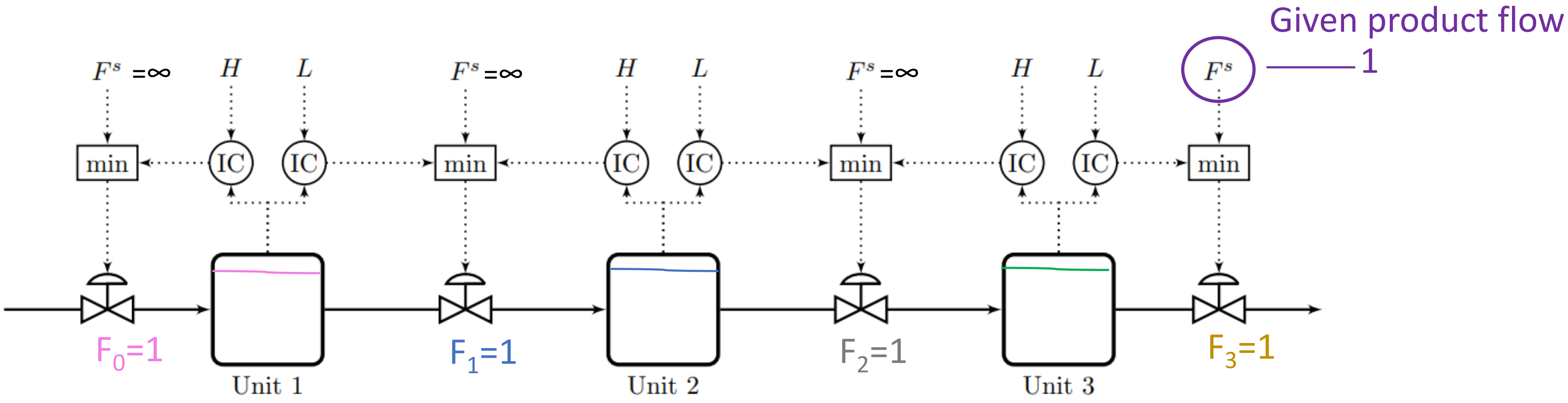
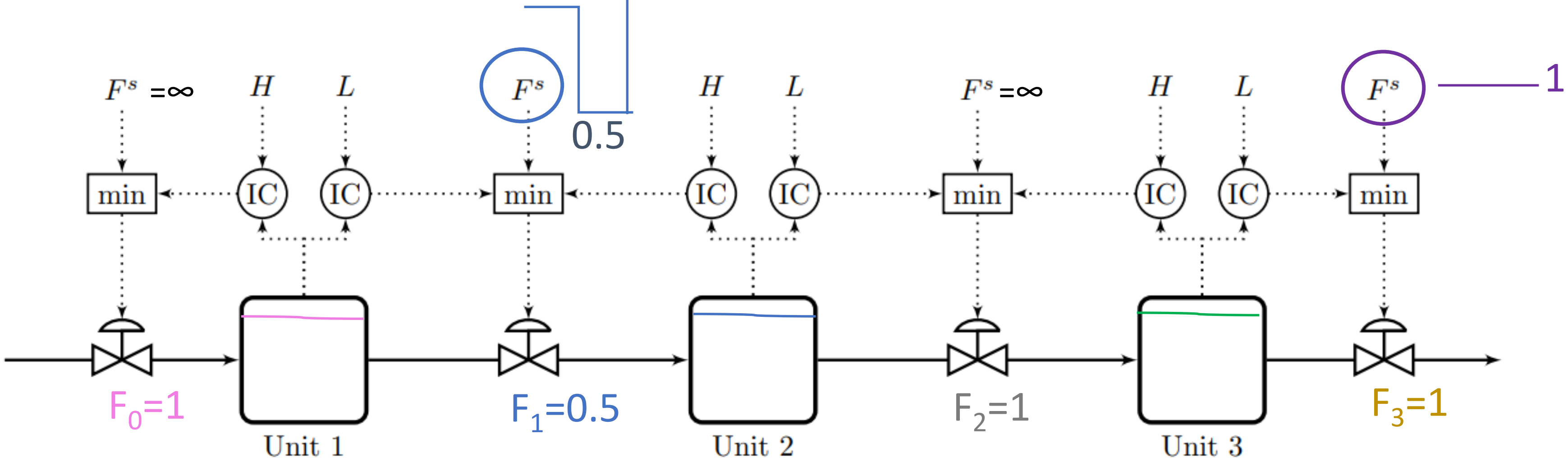


Fig. 3-7. Production rate can be set at either end of the process or constrained at any intermediate point without loss of inventory control.

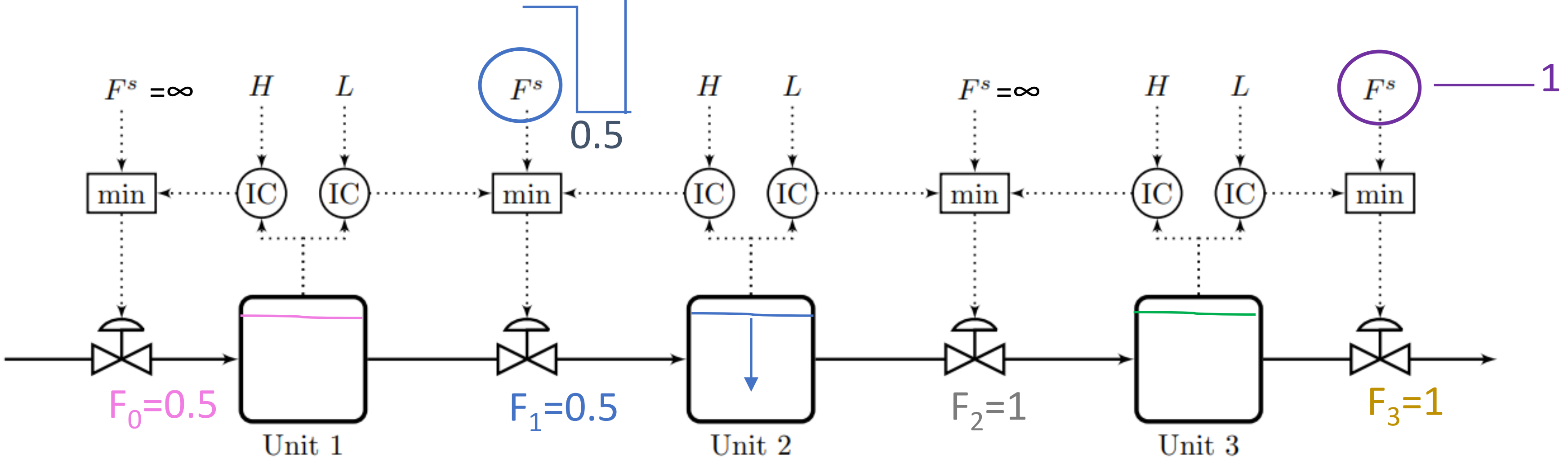
Cristina Zotica, Krister Forsman, Sigurd Skogestad ,»Bidirectional inventory control with optimal use of intermediate storage», Computers and chemical engineering, 2022



All levels are high (SP-H)

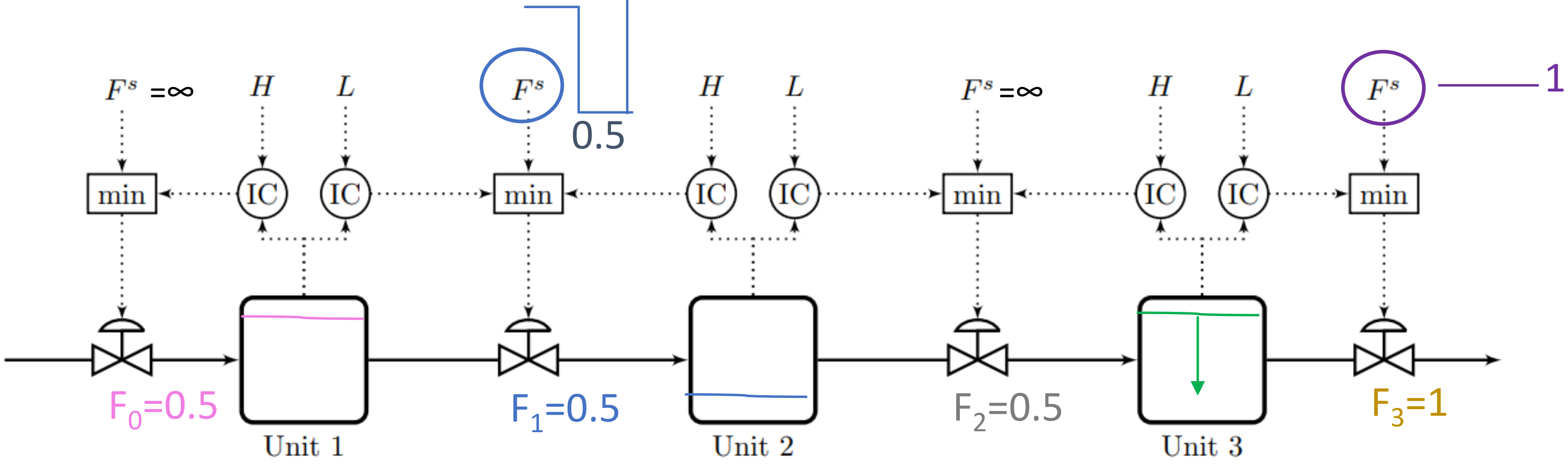


Temporary reduction in flow F1 (feed to unit 2)

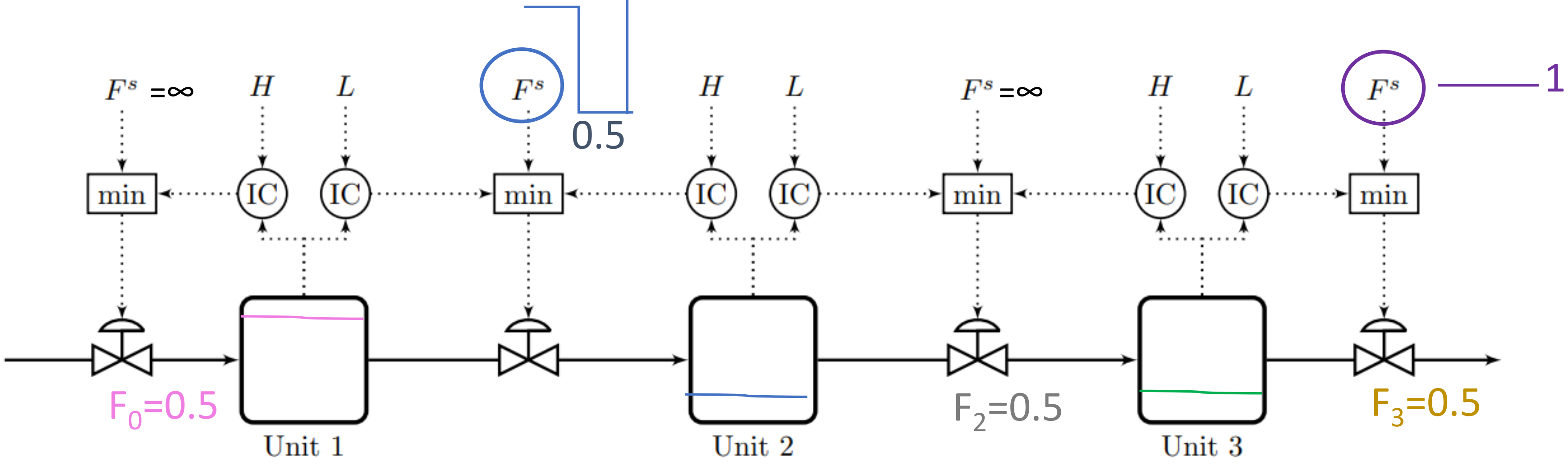


Level 1 constant:
Reduction in feed to unit 1

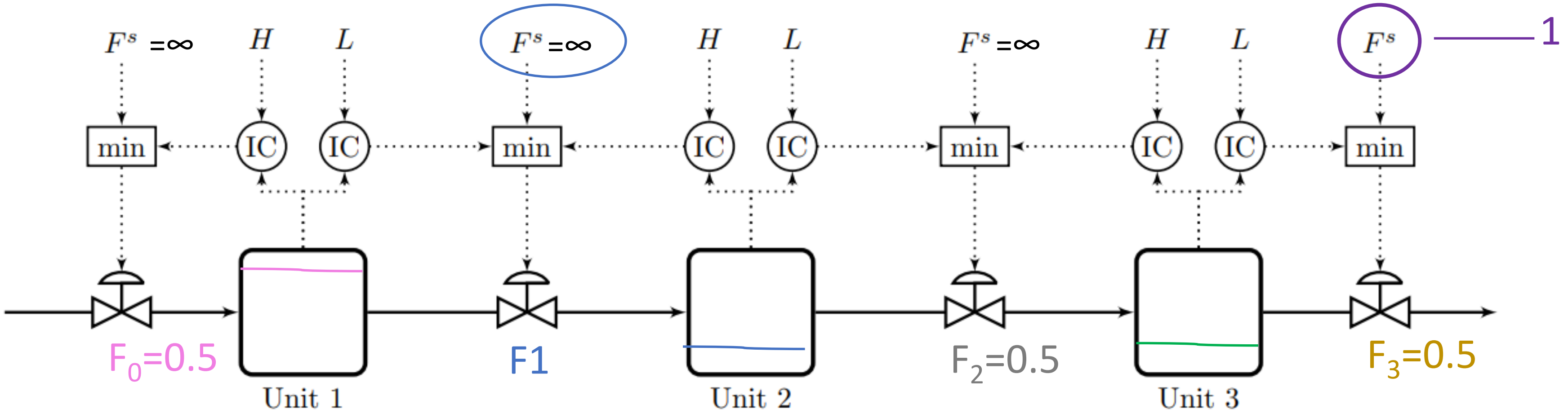
Level in unit 2 drops



Level 2 reaches SP-L:
Flow reduction
moves to unit 3

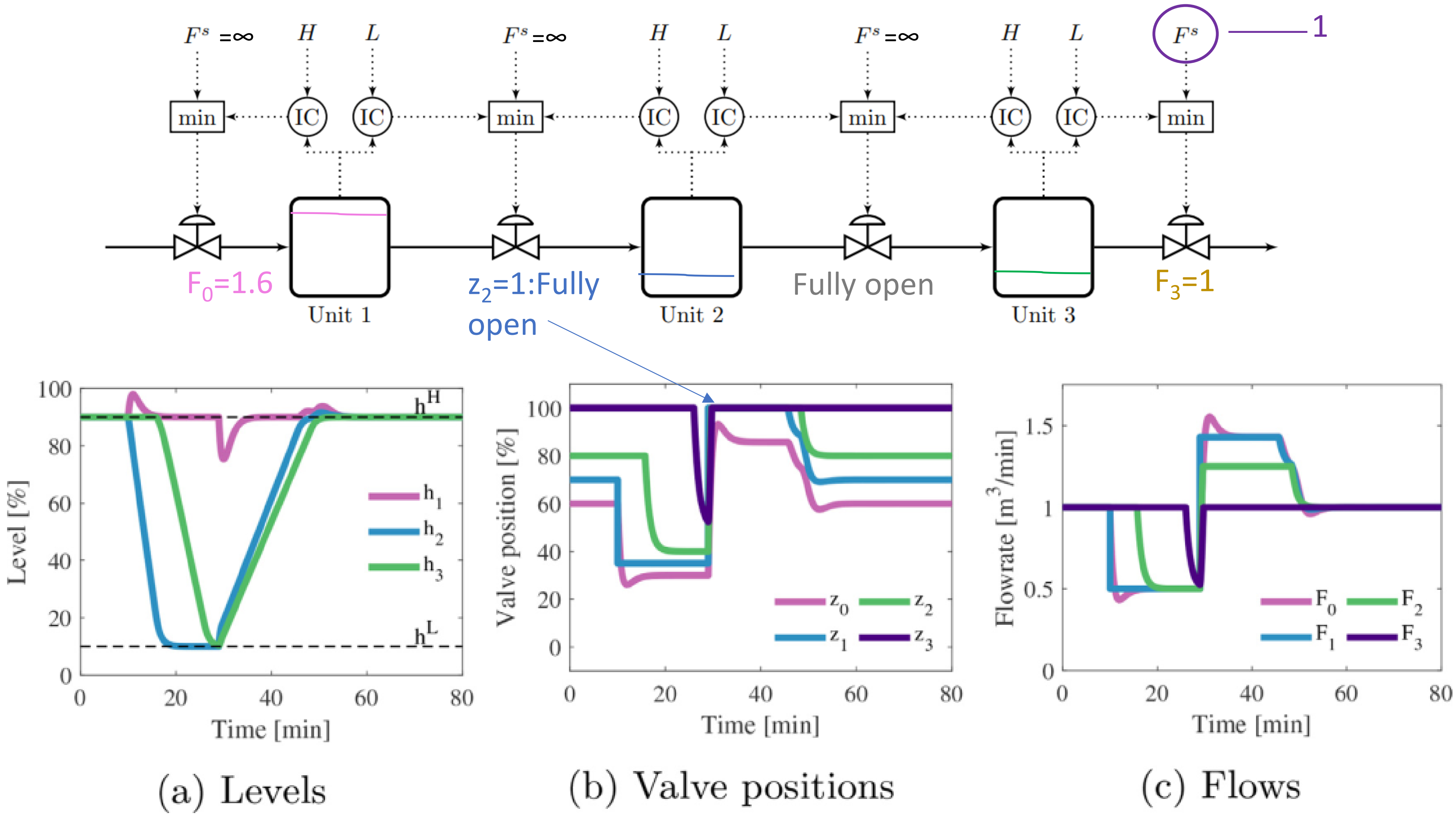


Flow reduction reaches product after some time



Temporary flow
reduction in F1 is over.
Get z_1=1 (fully open).

System recovers:
Temporary need F_0 > 1



1

F_0=1.6

z_2=1:Fully open

Fully open

F_3=1

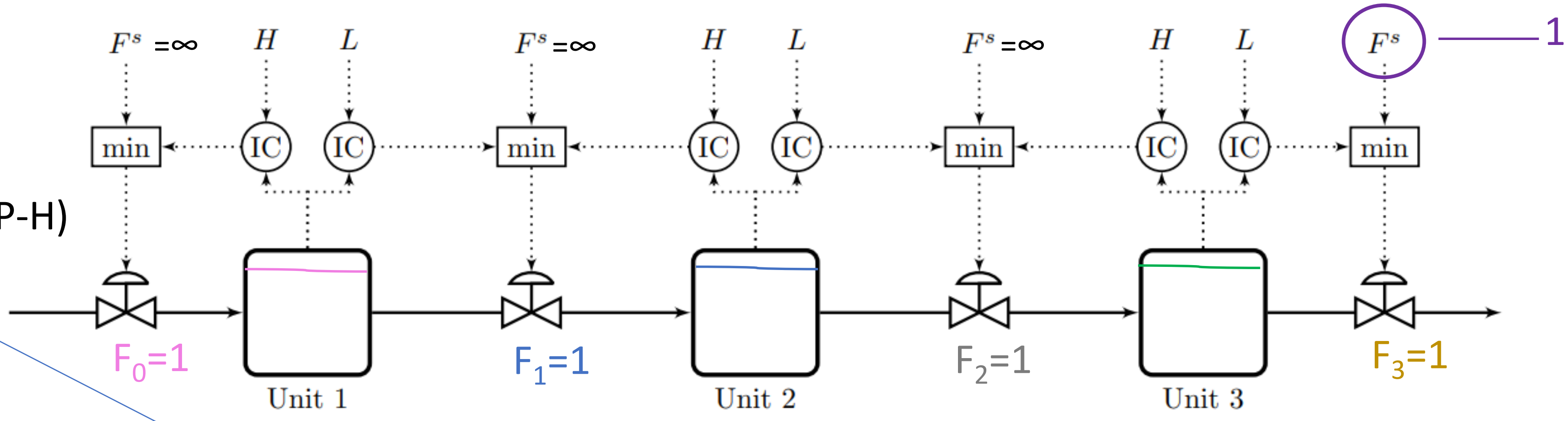
(a) Levels

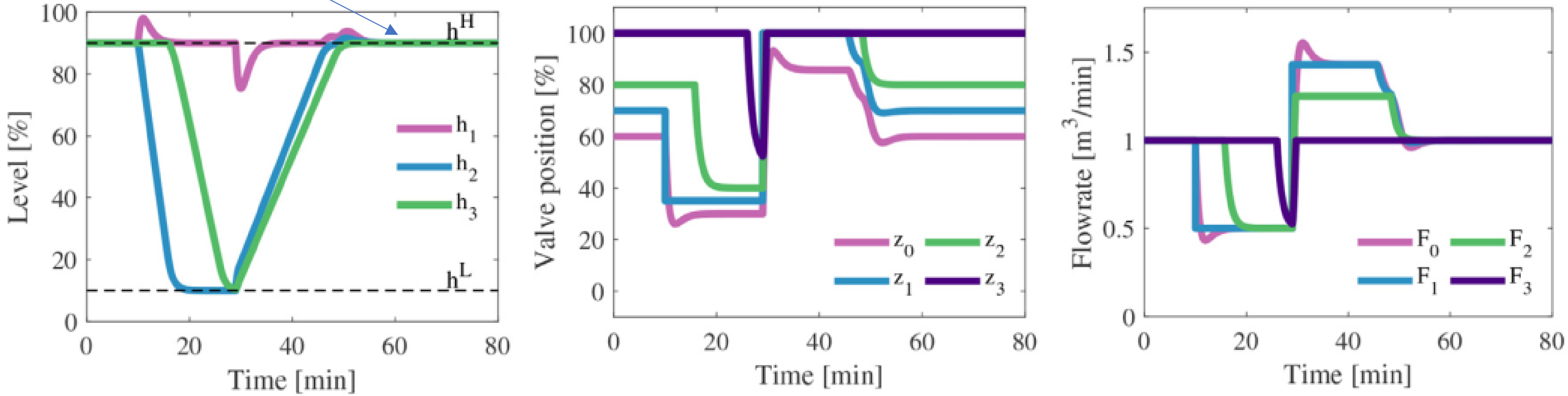
(b) Valve positions

(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).

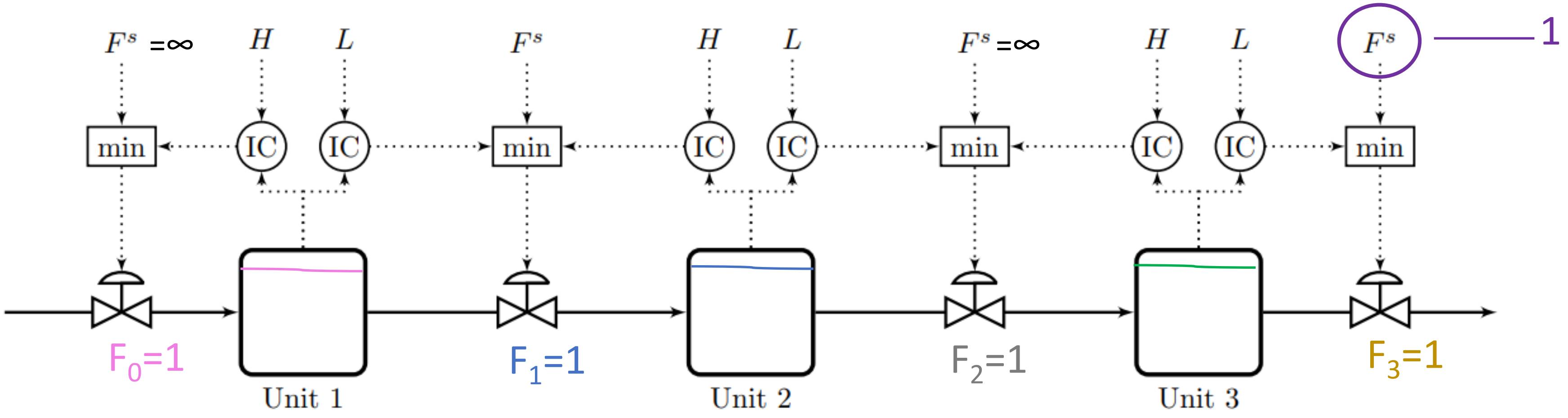
Final steady state
All levels are high (SP-H)





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

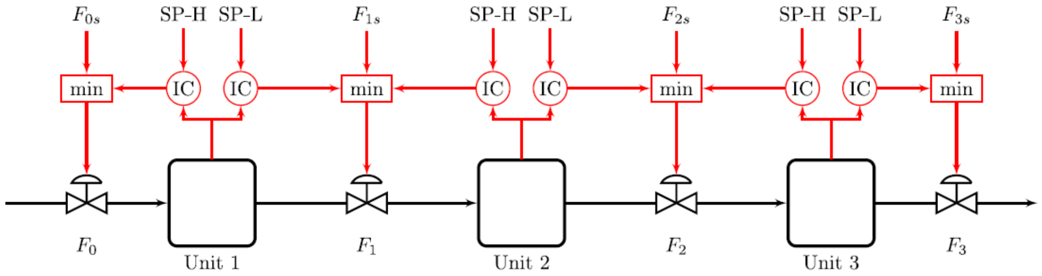
Fig. 13. Simulation of a temporary (19 min) bottleneck in flowrate F_1 for the proposed control structure in Fig. 10. The TPM is initially at the product (F_3).



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

Comments on Bidirectional inventory control



- It’s almost like magic (meaning that it’s difficult to understand what is actually happening)
- It both moves the TPM optimally and gives optimal levels.
- It is more like an invention.
- One cannot generally except to be able to solve complex problems without coordination, but this is a special case.

Extension . **Bidirectional inventory control** with minimum flow for F_2

Max flow: $F_s = \infty$

L = 10%,

M_L = 40%,

M_H = 60%

H = 90%.

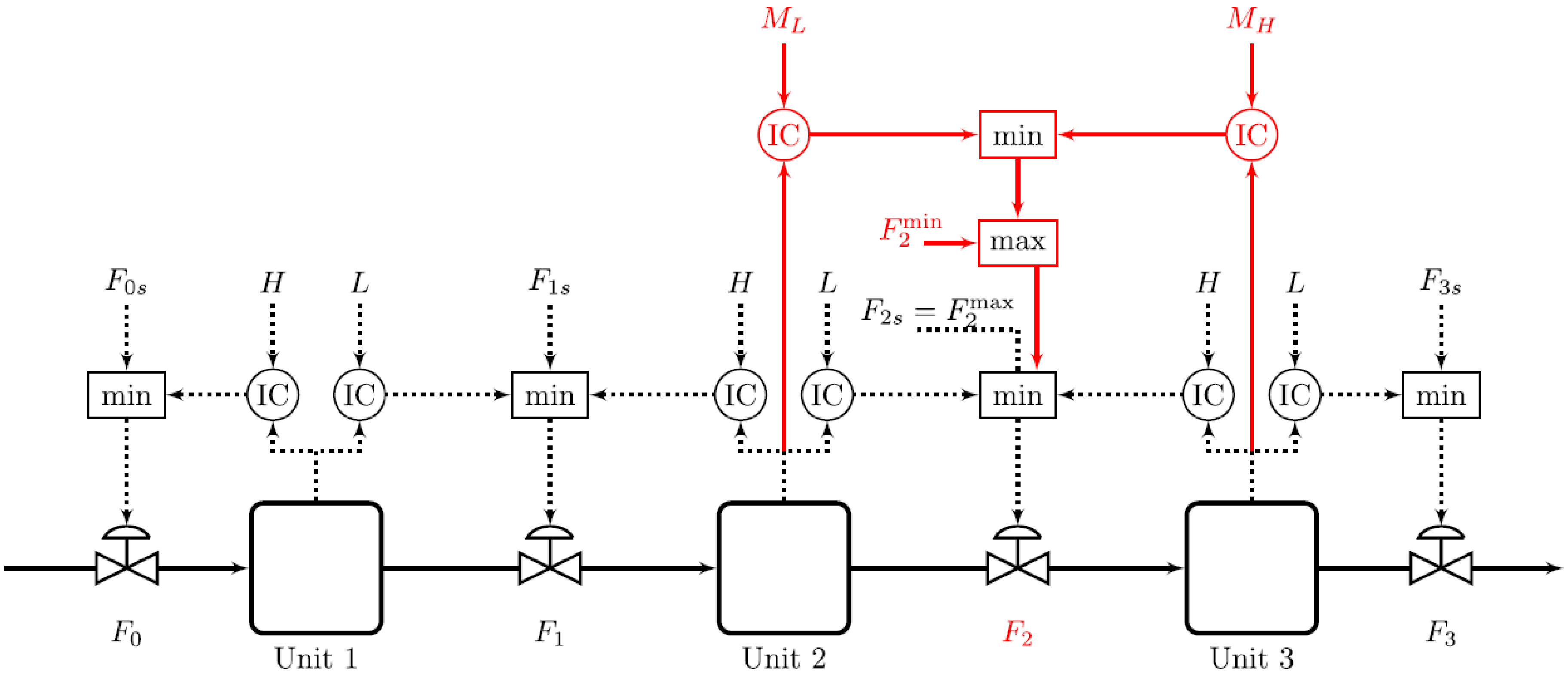
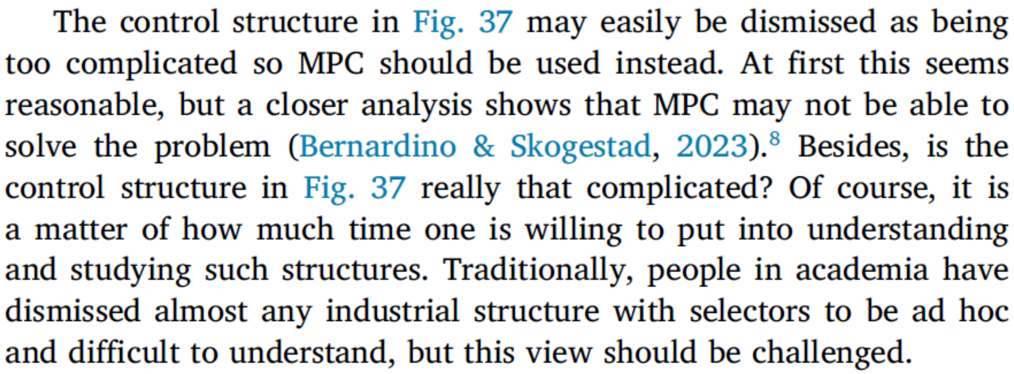


Fig. 37. Bidirectional inventory control scheme for maximizing throughput (dashed black lines) while attempting to satisfy minimum flow constraint on F_2 (red lines). H, L, M_L and M_H are inventory setpoints.


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.

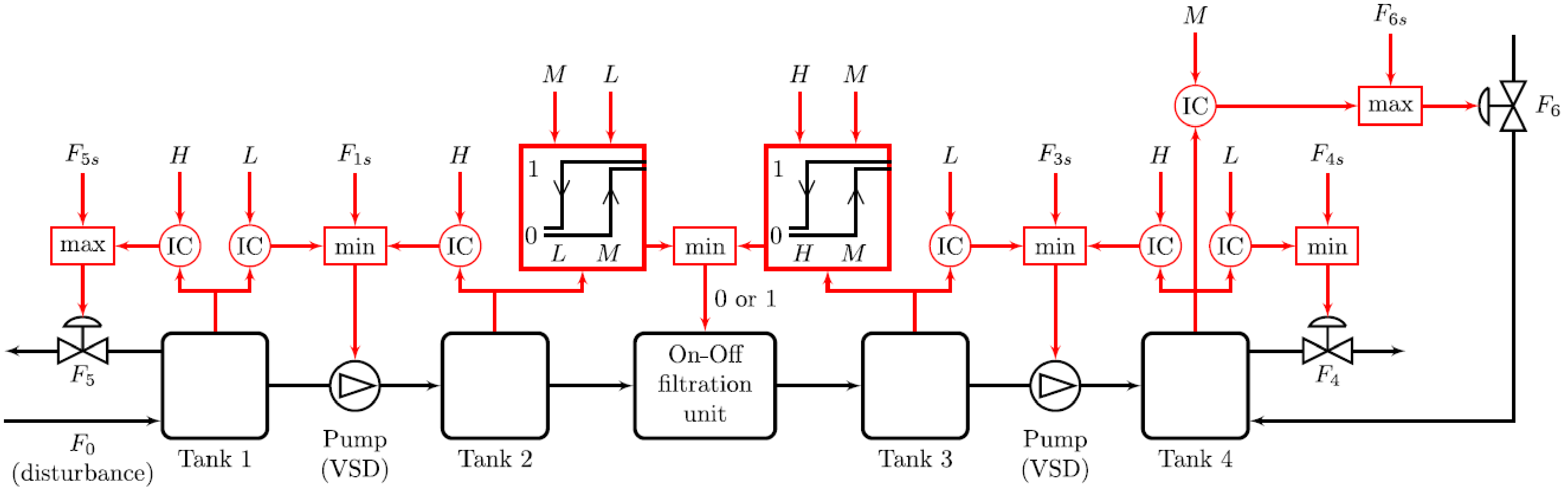
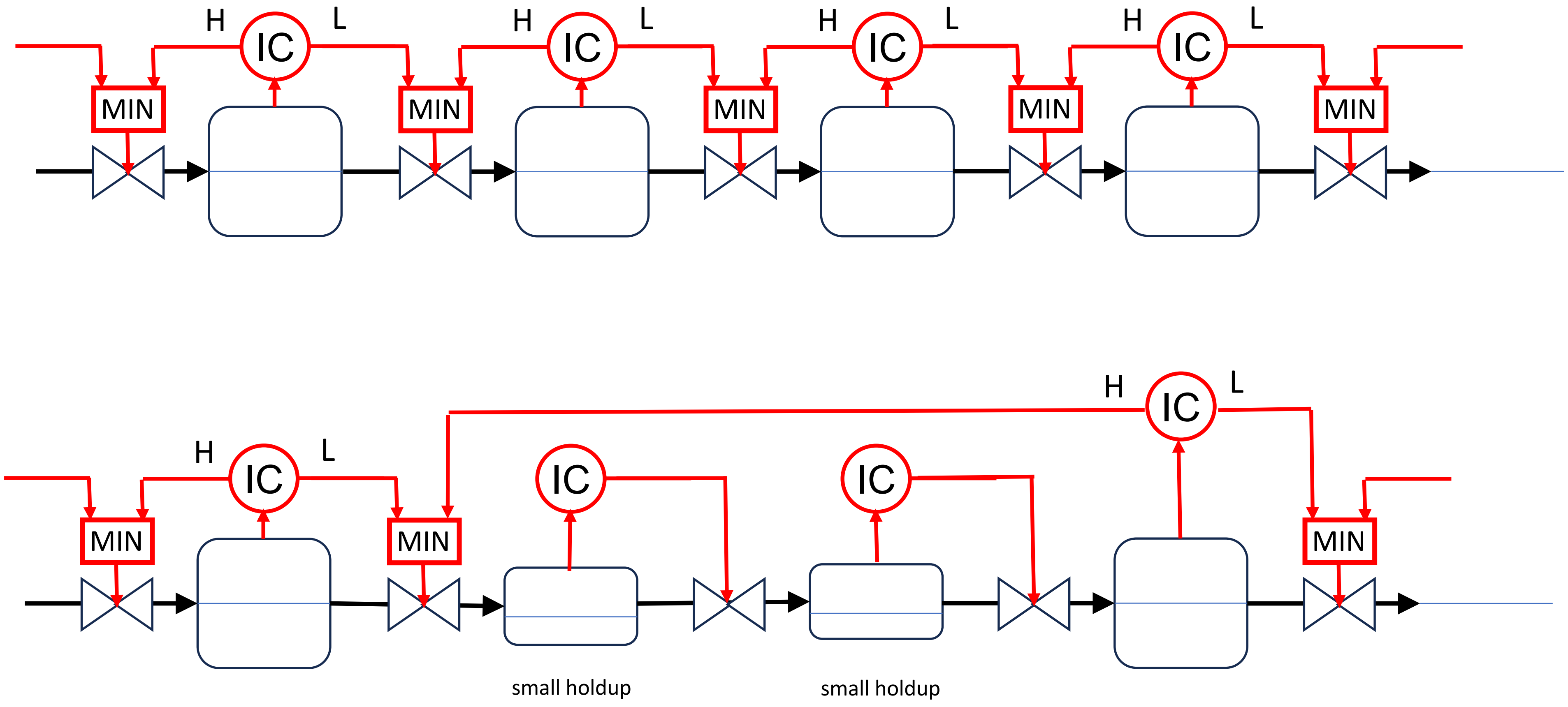


Fig. 38. Bidirectional inventory control structure for industrial plant with on/off (1/0) control of filtration unit.
H, L and M are inventory setpoints with typical values 90%, 10% and 50%.
If it is desirable to set a flowrate (F_s) somewhere in the system, then flow controllers must be added at this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

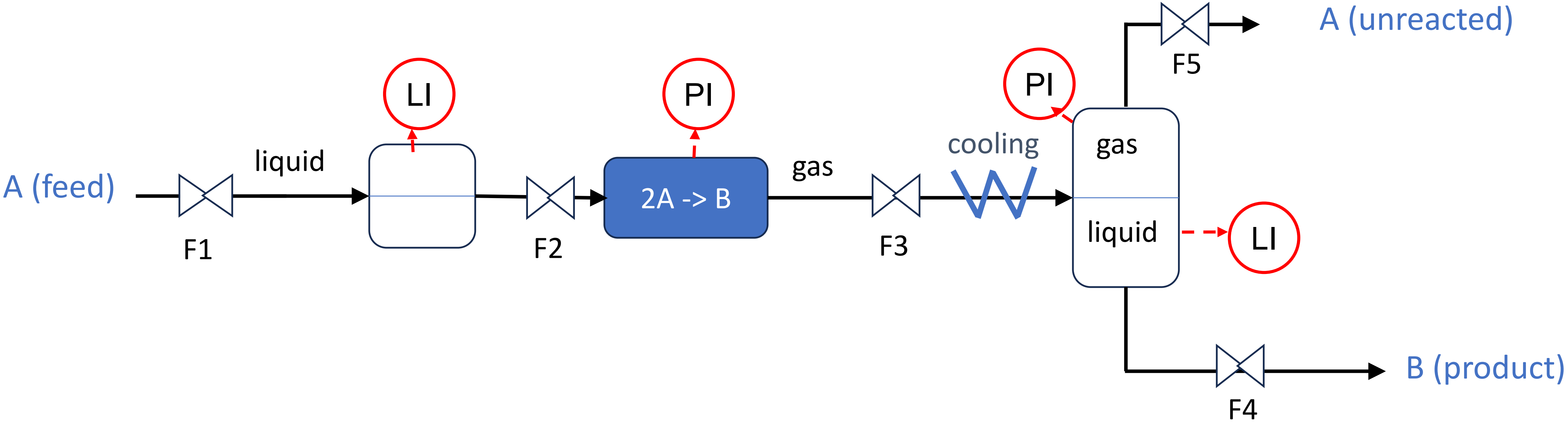
Don’t need bidirectional control on all units



Bidirectional control for recycle processes

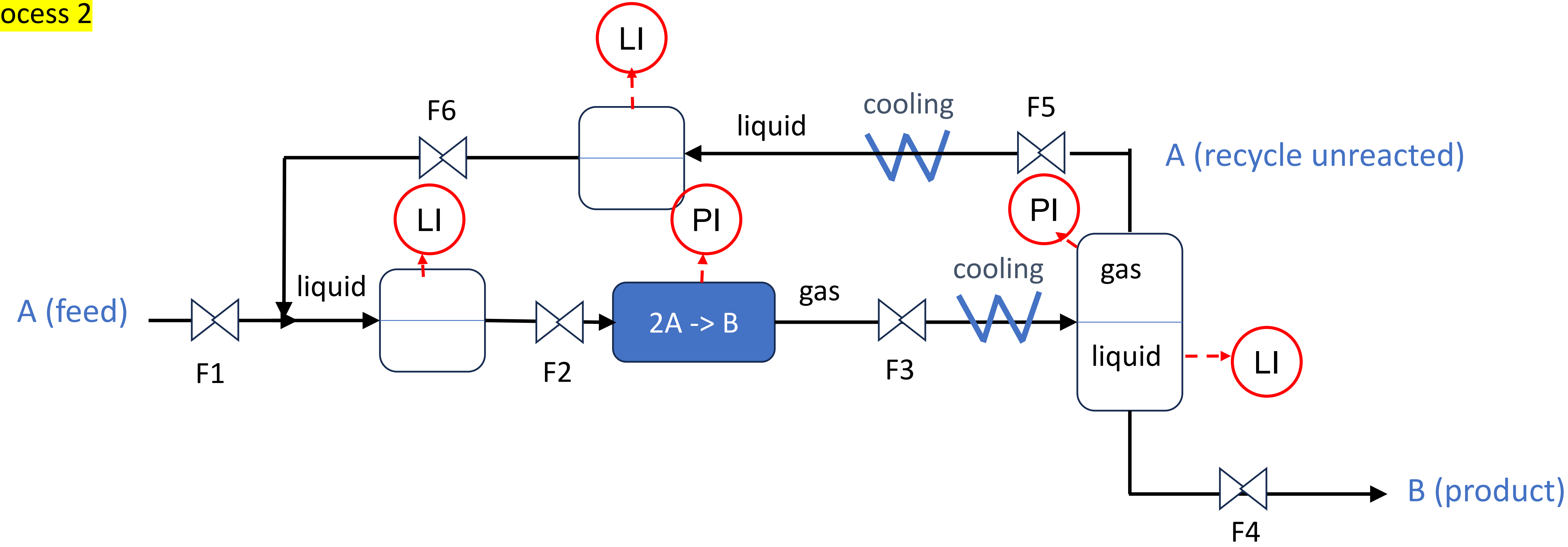
Examples (see exam)

Process 1



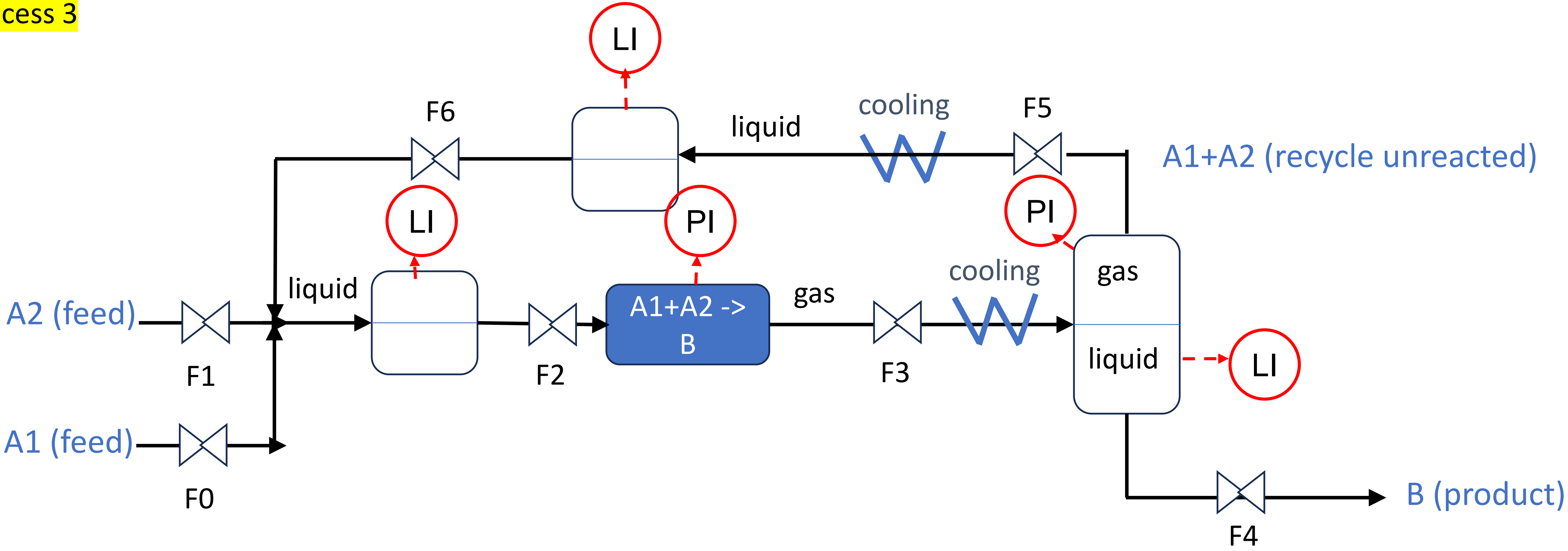
Exothermic reaction

Process 2

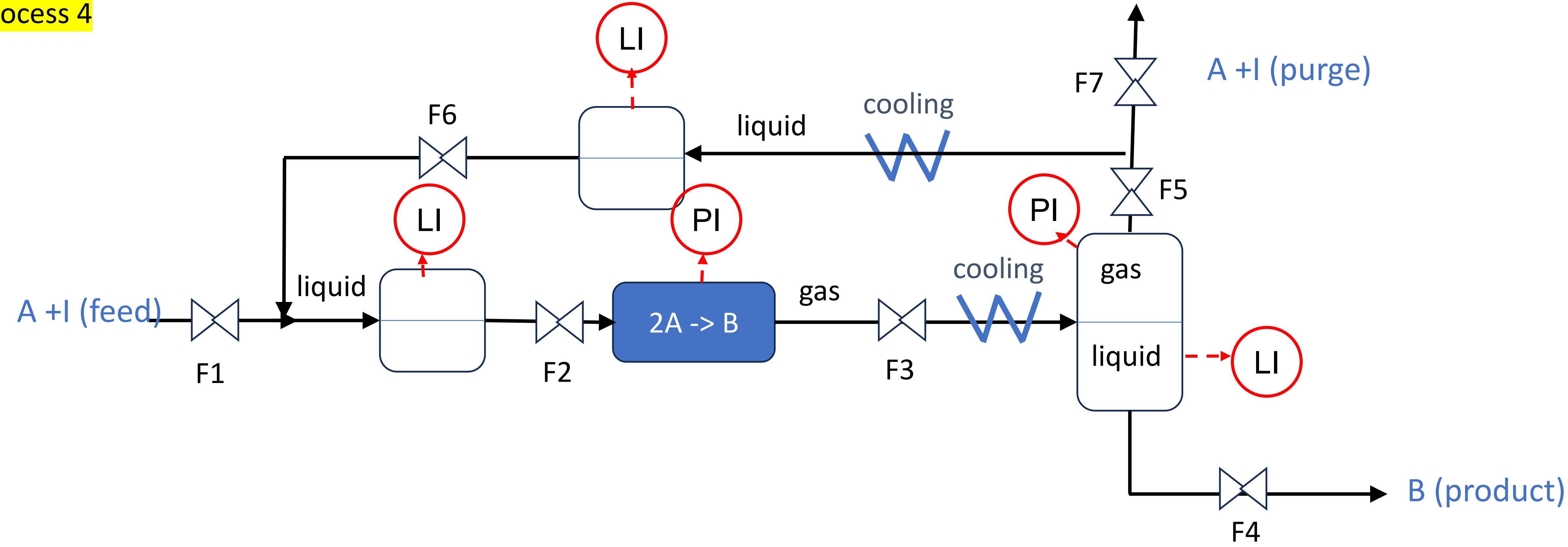


Comment: Valve F5 may not be necessary. Could use valve on cooling instead

Process 3

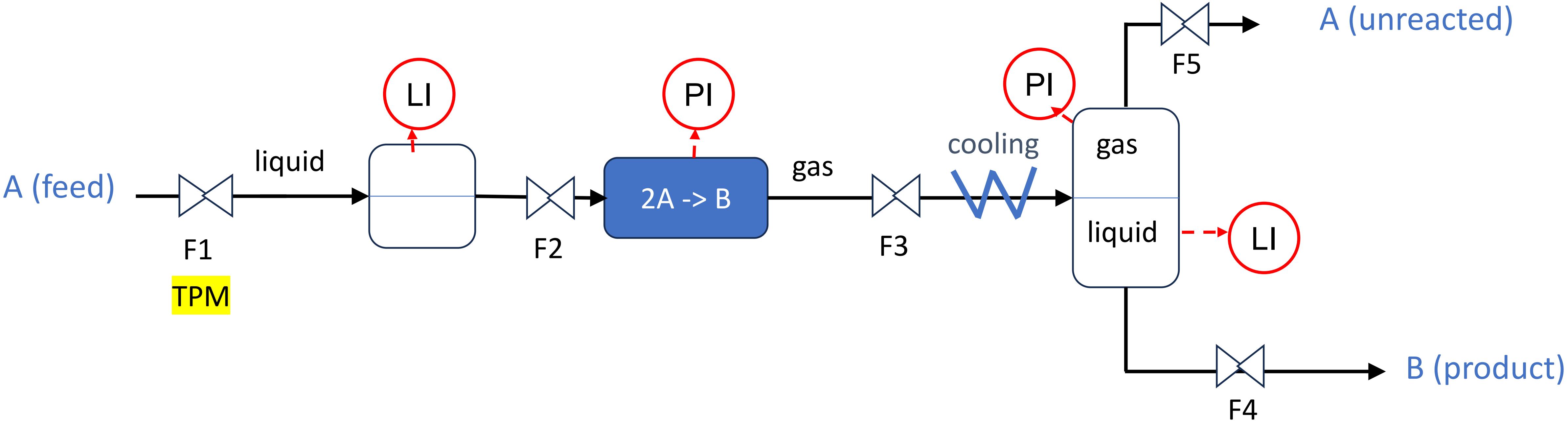

LI
F6
cooling
F5
liquid
A1+A2 (recycle unreacted)
LI
PI
PI
liquid
A2 (feed)
A1+A2 -> B
gas
cooling
gas
liquid
LI
F1
F2
F3
A1 (feed)
F0
B (product)
F4

Process 4


LI
F7
A +I (purge)
cooling
F6
liquid
LI
PI
PI
F5
liquid
cooling
gas
A +I (feed)
gas
2A -> B
liquid
LI
F1
F2
F3
B (product)
F4

Process 1

Control

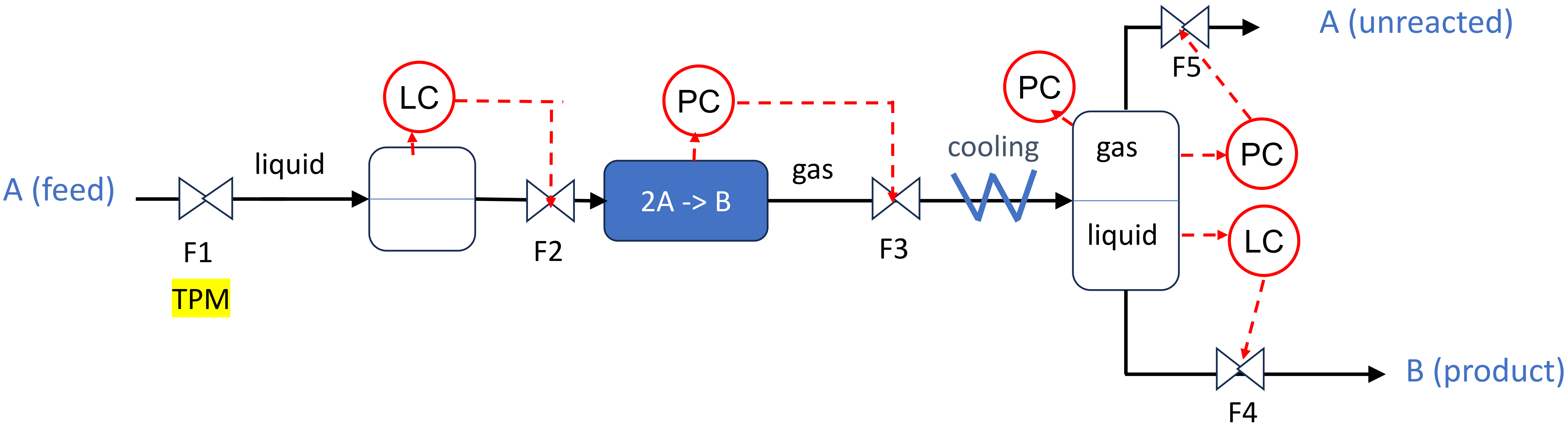


TPM

Exothermic reaction

Process 1

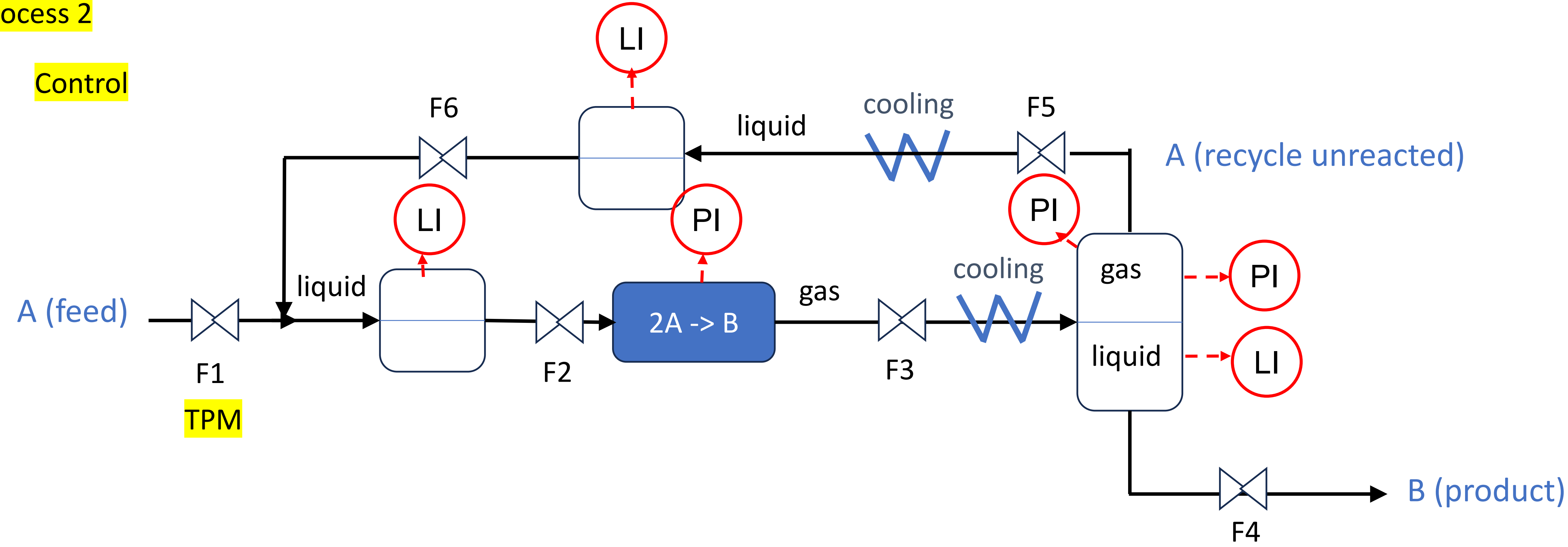
Control



Exothermic reaction

Process 2

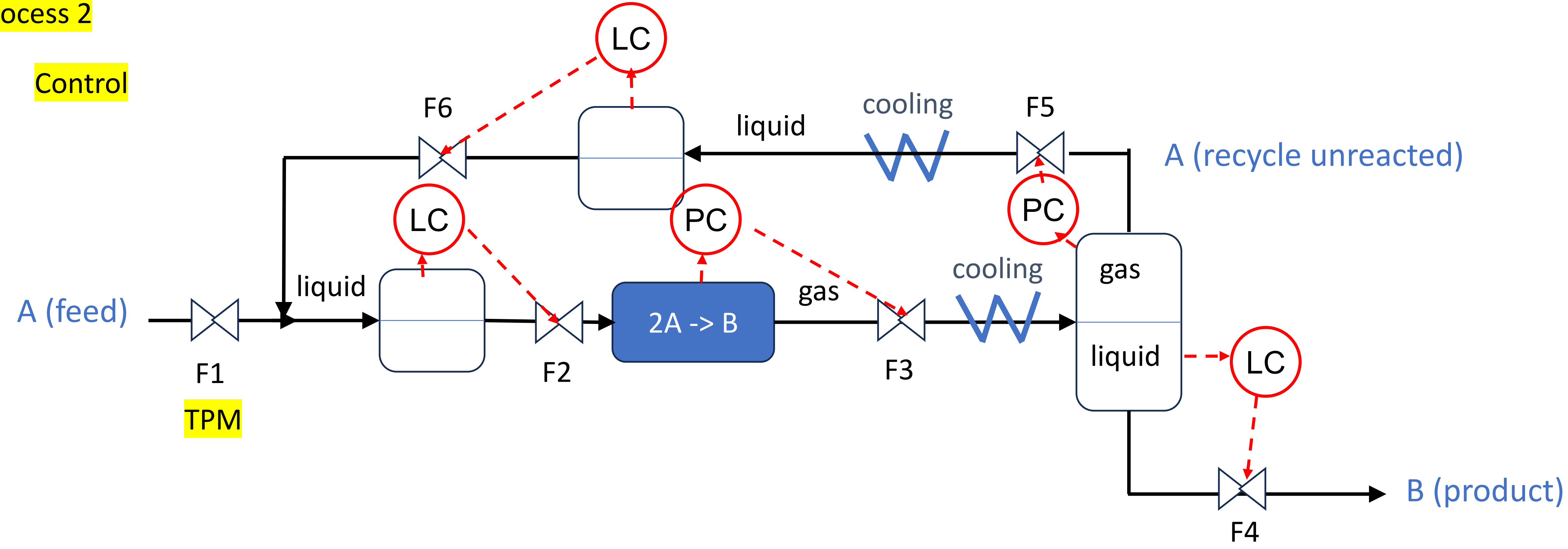
Control



TPM

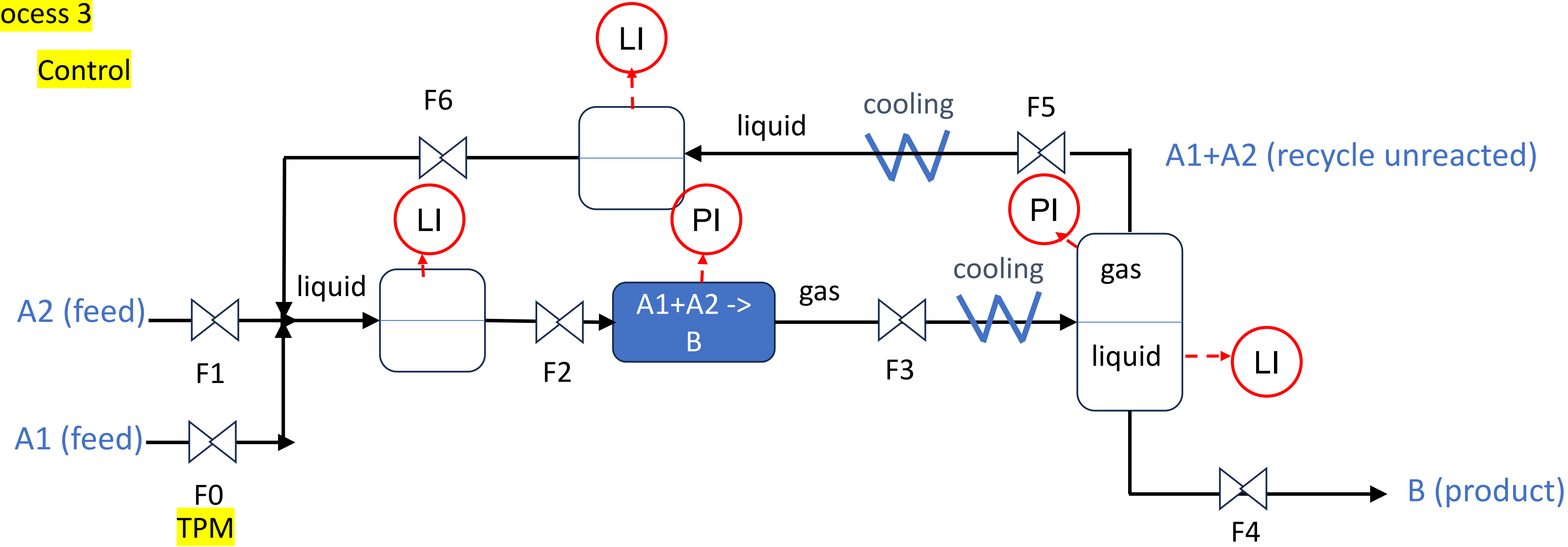
Process 2

Control



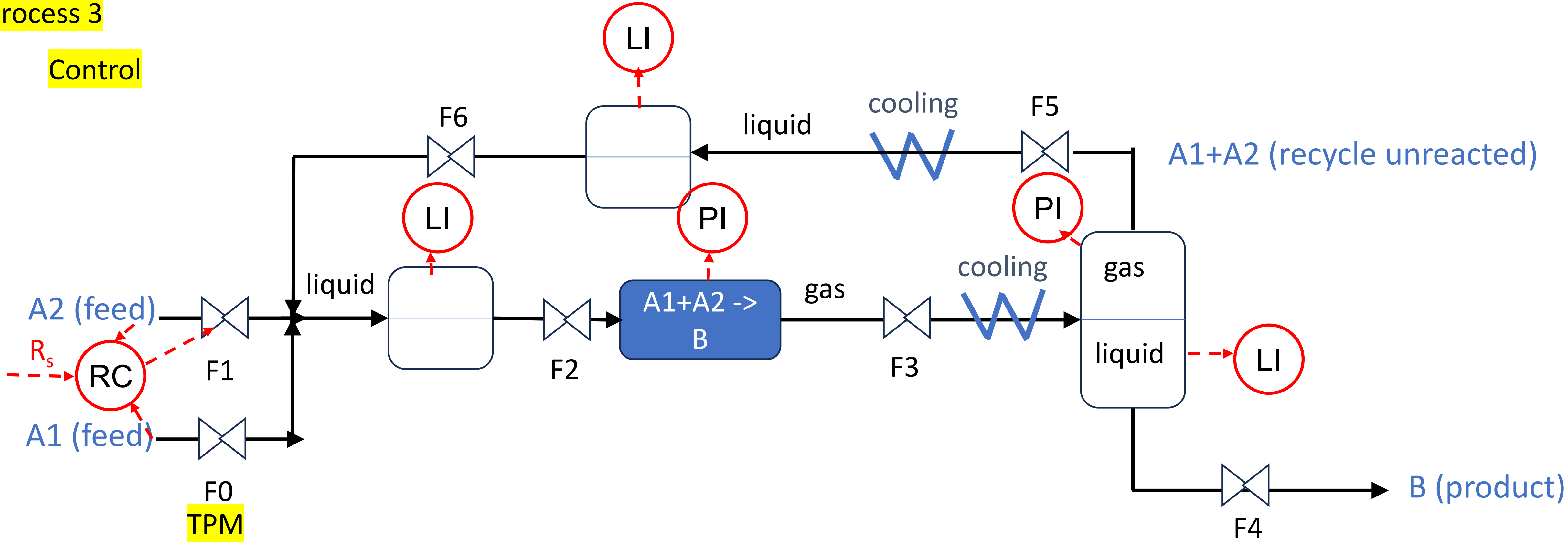
Process 3

Control



Process 3

Control



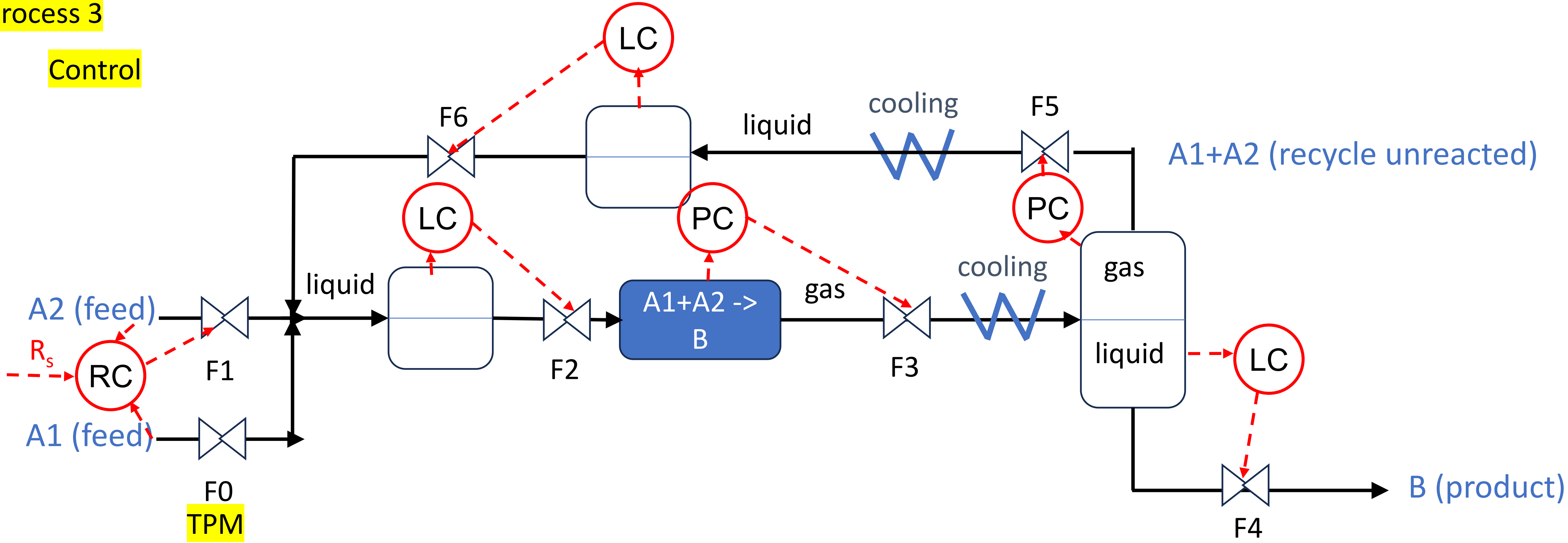
The ratio control can be done in different ways.

It requires two flow measurements (F0, F1)

One of the flows is the TPM

Process 3

Control

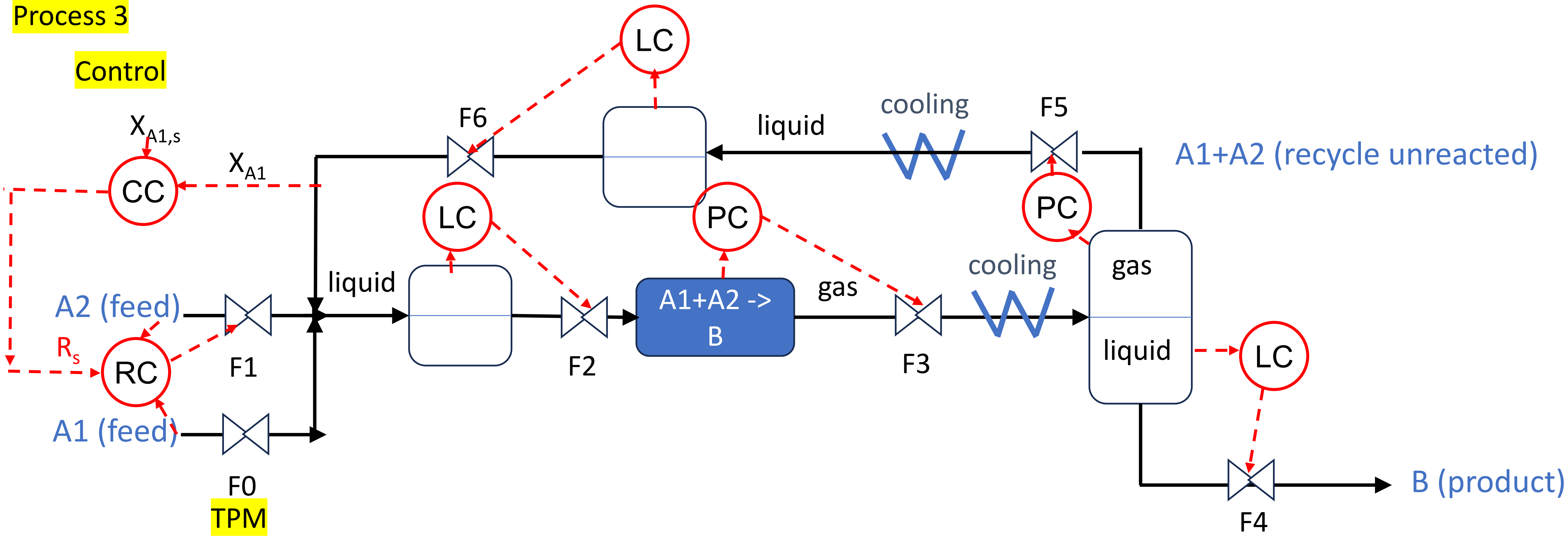


Will this work?

No, it’s not possible to feed exactly the same amount of A1 and A2 without feedback correction

Process 3

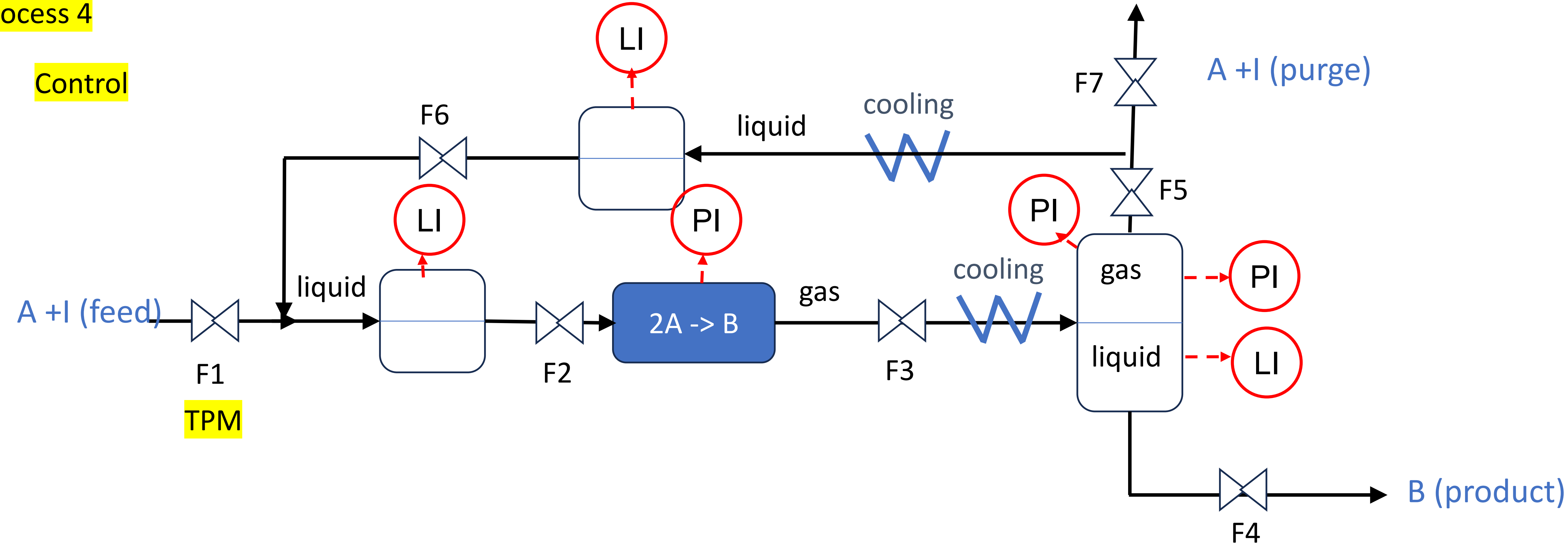
Control



With composition control of A1 (or A2).
This works!

Process 4

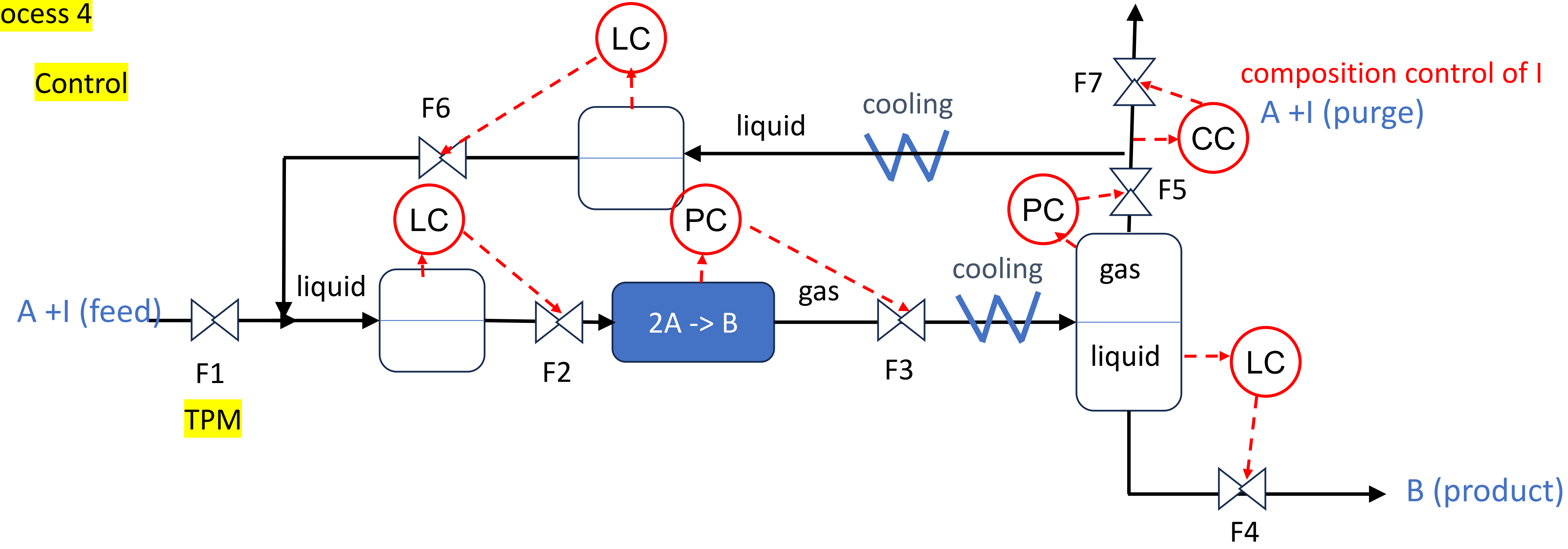
Control



TPM

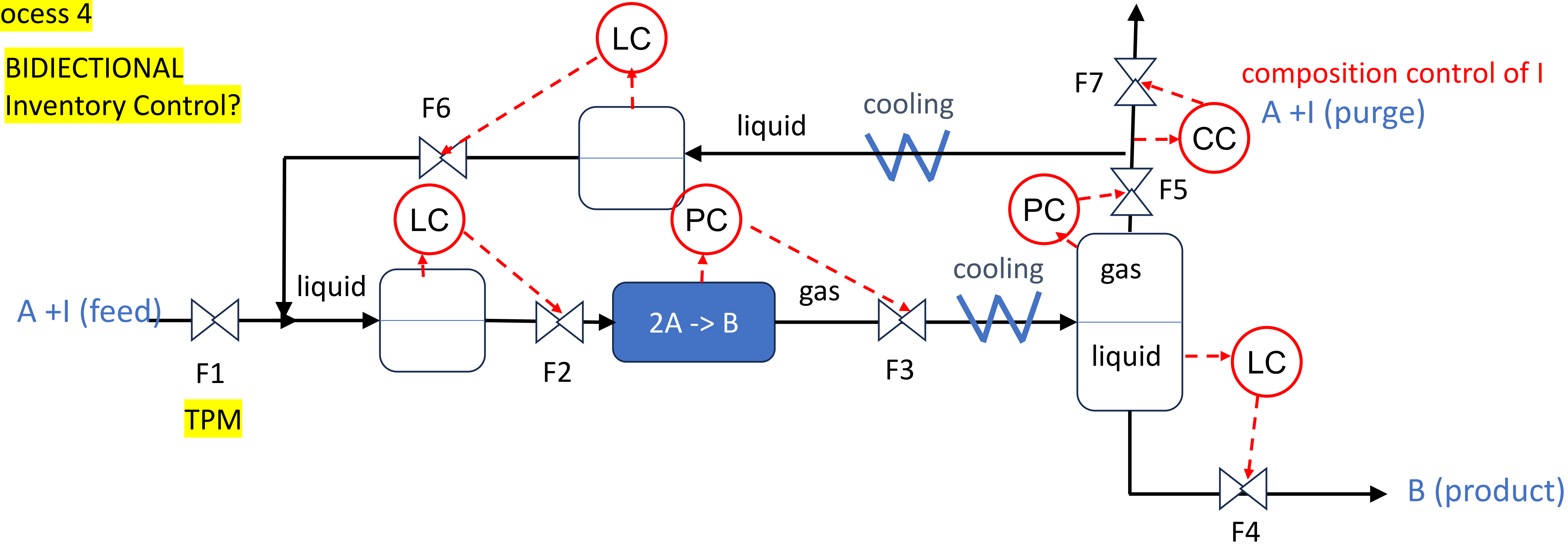
Process 4

Control



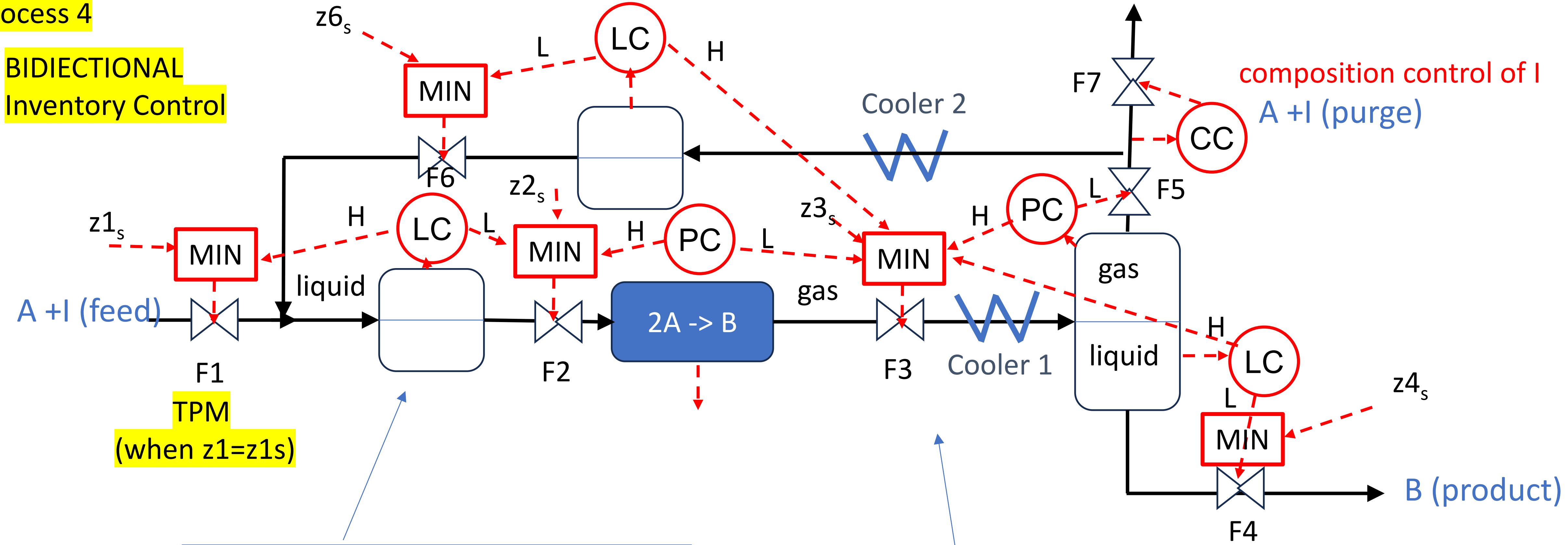
Process 4

BIDIECTIONAL
Inventory Control?



Process 4

BIDIECTIONAL
Inventory Control



This LC is two controllers which both control level.

- The one with outflow F2 as the MV has a Low level setpoint
- The one with inflow F1 as the MV has a High level setpoint

3 H-setpoints go to this MIN-selector:
Reduce F3 if

1. too high pressure (cooler 2 max),
2. too much gas (high level) (F6 limiting)
3. too much liquid (high level) (F4 limiting)

z1$_s$

Comments on 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

- 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 (that is, we don’t use bidirectional inventory control): Locate TPM at expected bottleneck
  - Otherwise you will need a “long loop” and you get loss in production because of backoff from constraint

Summary: Systematic design of advanced regulatory control (ARC) system

- First design simple control system for nominal operation
  - With single-loop PID control we need to make pairing between inputs (MVs) and outputs (CVs):
  - Should try to follow two rules
    1. «Pair close rule» (for dynamics).
    2. «Input saturation rule»:

Then: design of switching schemes

- Make a list of possible new contraints that may be encountered (because of disturbances, parameter changes, price changes)
- Reach constraint on new CV
  - Simplest: Find an unused input (simple MV-CV switching)
  - Otherwise: CV-CV switching using selector (may involve giving up a CV-constraint or a self-optimizing CV)
- Reach constraint on MV (which is used to control a CV)
  - Simplest (If we followed input saturation rule):
    - Can give ip controlling the CV (Simple MV-CV switching)
    - Don't ned to do anything
  - Otherwise (if we cannot give up controlling CV)
    - Simplest: Find an unused input
      - MV-MV switching
    - Otherwise: Pair with a MV that already controls another CV
      - Complex MV-CV switching
      - Must combine MV-MV and CV-CV switching
- Is this always possible? No, pairing inputs and outputs may be impossible with many constraints.
- May then instead use RTO or feedback-RTO
- Maybe MPC?

Here is a summary of some additional insights from this paper:

- If the industrial solution has a selector (sometimes realized using a saturation element, especially for the cascade implementation) then generally there is a CV constraint involved. Most likely, the selector is performing a steady-state CV-CV switch (E4), although there may be exceptions as seen in the cross-limiting example below.
  - A CV-CV switch can be realized in two ways, either with two (or more) independent controllers with a selector on the MV (Fig. 17), or as a cascade implementation with a selector on the CV setpoint (Fig. 19).
  - If there are several selectors (max and min) in series then we know that the constraints are potentially conflicting and that the highest priority constraint should be at the end (Fig. 18).

- If the industrial solution has a valve position controller (VPC) then there may be two quite different problems that it is addressing (see E3 and E7 in Table 1), and it may not be immediately clear which.
  1. If we have an extra MV for dynamic reasons (E3; Fig. 12) then the two controllers (and MVs) are used all the time. The MV manipulated by the VPC (MV_1 in Fig. 12) is then used on the longer time scale, whereas the MV linked to the CV (MV_2 in Fig. 12) is used for dynamic reasons (fast control). Here, an alternative is to use parallel control (Fig. 13).
  2. There is also another possibility, namely, when the VPC makes use of an extra MV to avoid that the primary MV saturates at steady-state (E7; Fig. 24). This is then a case where the VPC is used for MV-MV switching and the VPC is only active part of the time.

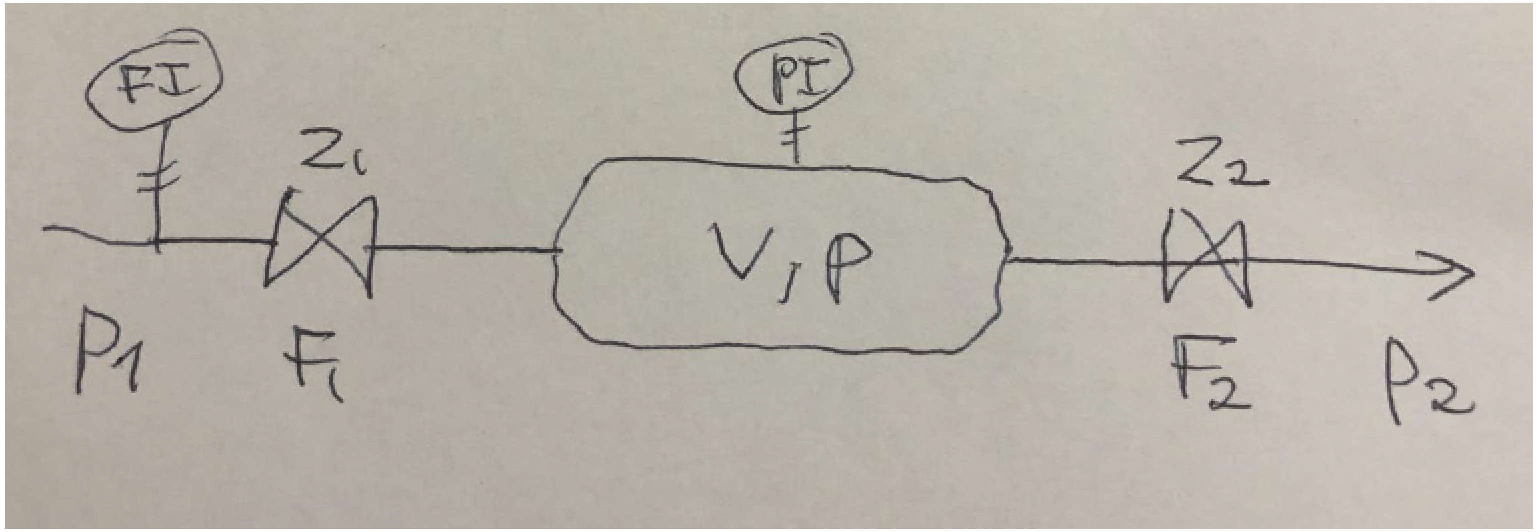
- For MV-MV switching there are three alternatives.
  1. A common solution is split range control (E5; Fig. 21) which is usually easy to identify.
  2. Another common solution is multiple controllers with different setpoints (E6; Fig. 23). It may be a bit more difficult to identify.
  3. Finally, there is VPC (E7), as just discussed, which is probably the least common solution for MV-MV switching

  One should have all these three alternatives in mind when choosing the best solution for MV-MV switching, as there is not one alternative which is best for all problems (see Section 5.1 for details).

QUIZ

What happens if we do not follow radiation rule (5b)?

Problem 5 (25%). Modelling and control of flow and pressure



Consider a gas pipeline with two valves. We have measurements of the inflow F_1 and the intermediate pressure p and these should be controlled. The volume of the pipeline can be represented as a tank with volume V as shown in the figure above.

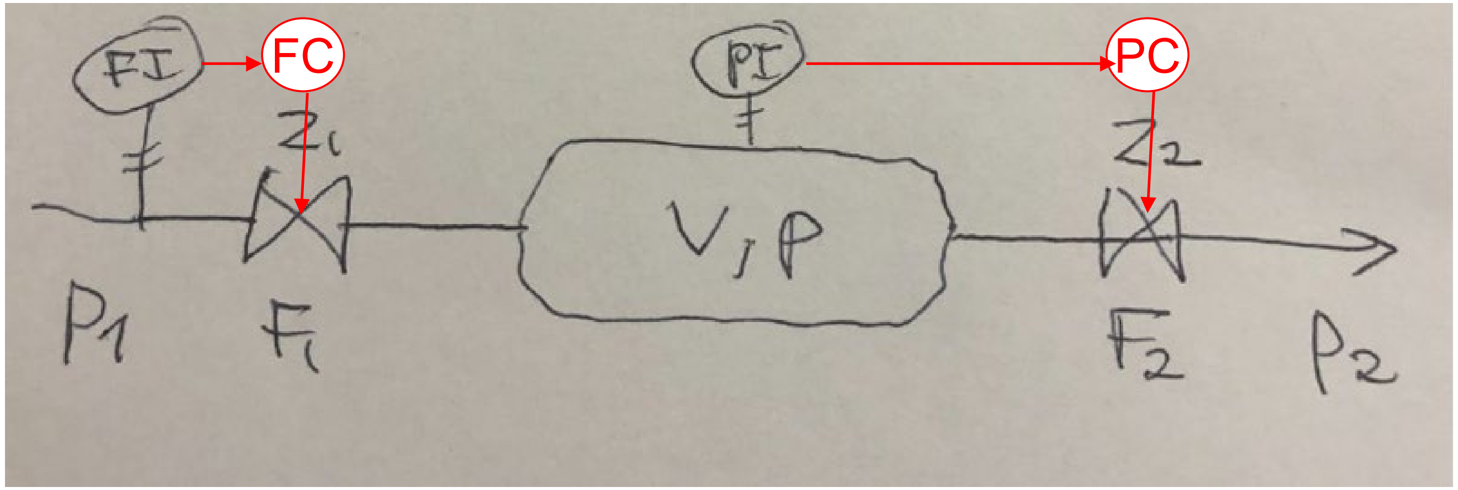
Steady-state data: $F_1=1$ kg/s, $z_1=z_2=0.5$, $p_1=2$ bar, $p=1.88$ bar, $p_2=1.8$ bar, $V=130$ m^3, $T=300$ K, Parameters: $R=8.31$ J/K.mol, $M_W=18e-3$ kg/mol (so the gas is steam).

The following model equations are suggested to describe the system.

(1) $dm/dt = F_1 - F_2$
(2) $m = k_p p$ where $k_p = VM_w/(RT)$
(3) $F_1 = C_1 z_1 \sqrt{p_1 - p}$
(4) $F_2 = C_2 z_2 \sqrt{p - p_2}$

(a) Suggest a control structure
(b) What if we want to control p2 instead of p?

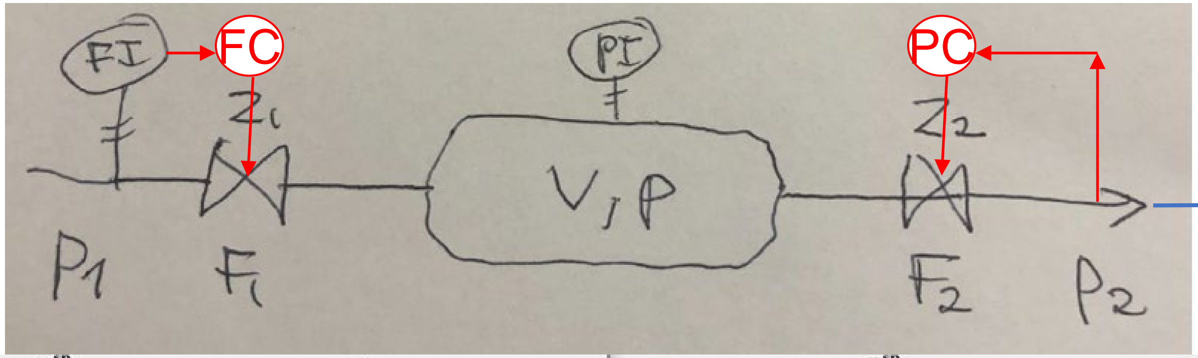
(a) The «obvious» pair-close pairing os OK. However, interactions between loops may be severe. Suggest tuning the FC first, and the PC about 5 times slower.



(b)

NO!

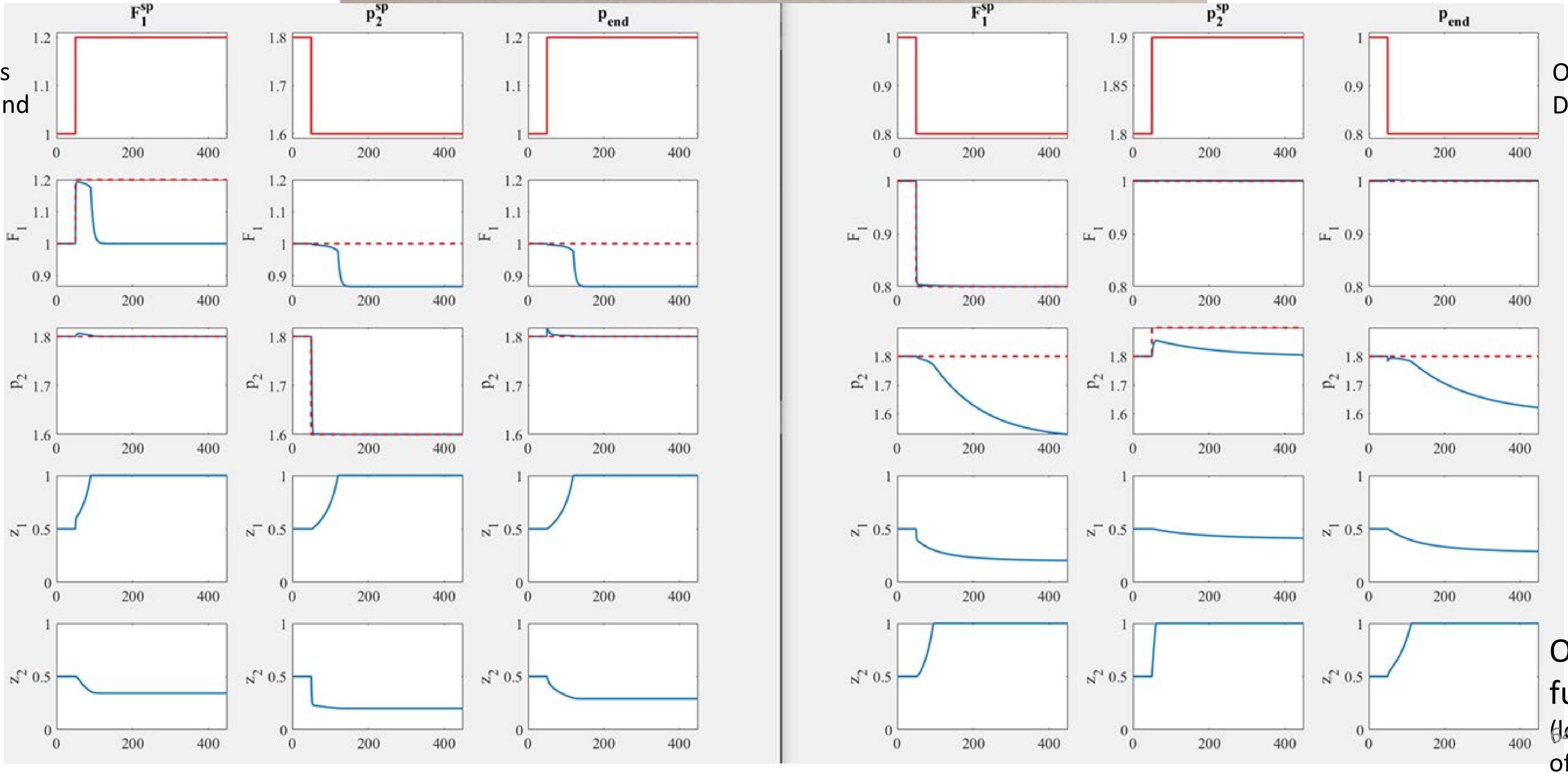
Not consistent



$F_3 = c_3(p_2 - p_{end})^{1/2}$

Disturbances in F1, p2, pend

Opposite Disturbances

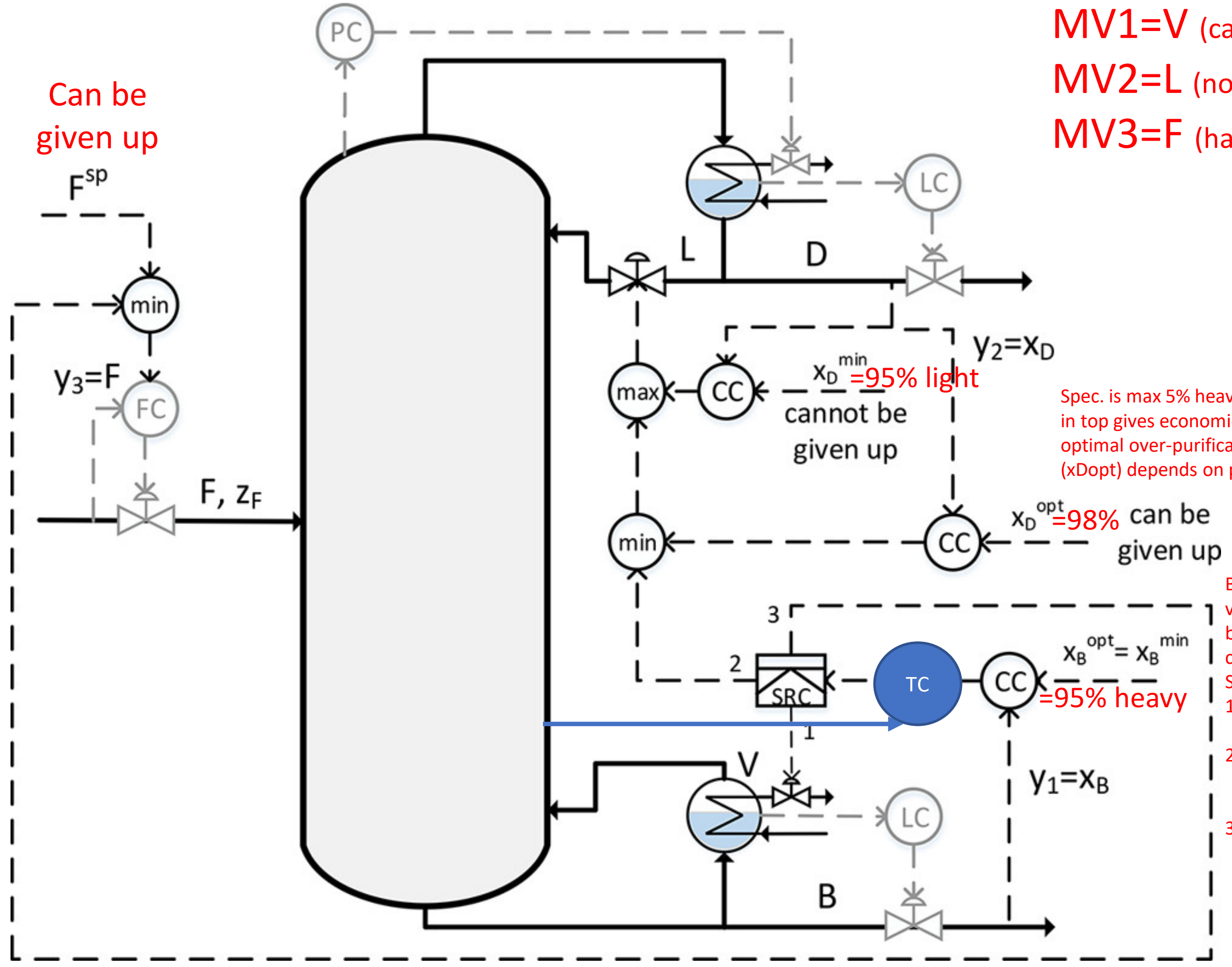


z1 to fully open (lose control of F1)

Or: z2 to fully open (lose control of p2)

Distillation example.

CV1=xB (cannot be given up)
MV1=V (can reach max)
MV2=L (normally used for xD)
MV3=F (has setpoint)



Spec. is max 5% heavy in top, but heavy in top gives economic loss. Economic optimal over-purification of top product (xDopt) depends on prices p

Bottom product is the most valuable and should always be kept at its purity constrant (xBmin).
Split range control*:

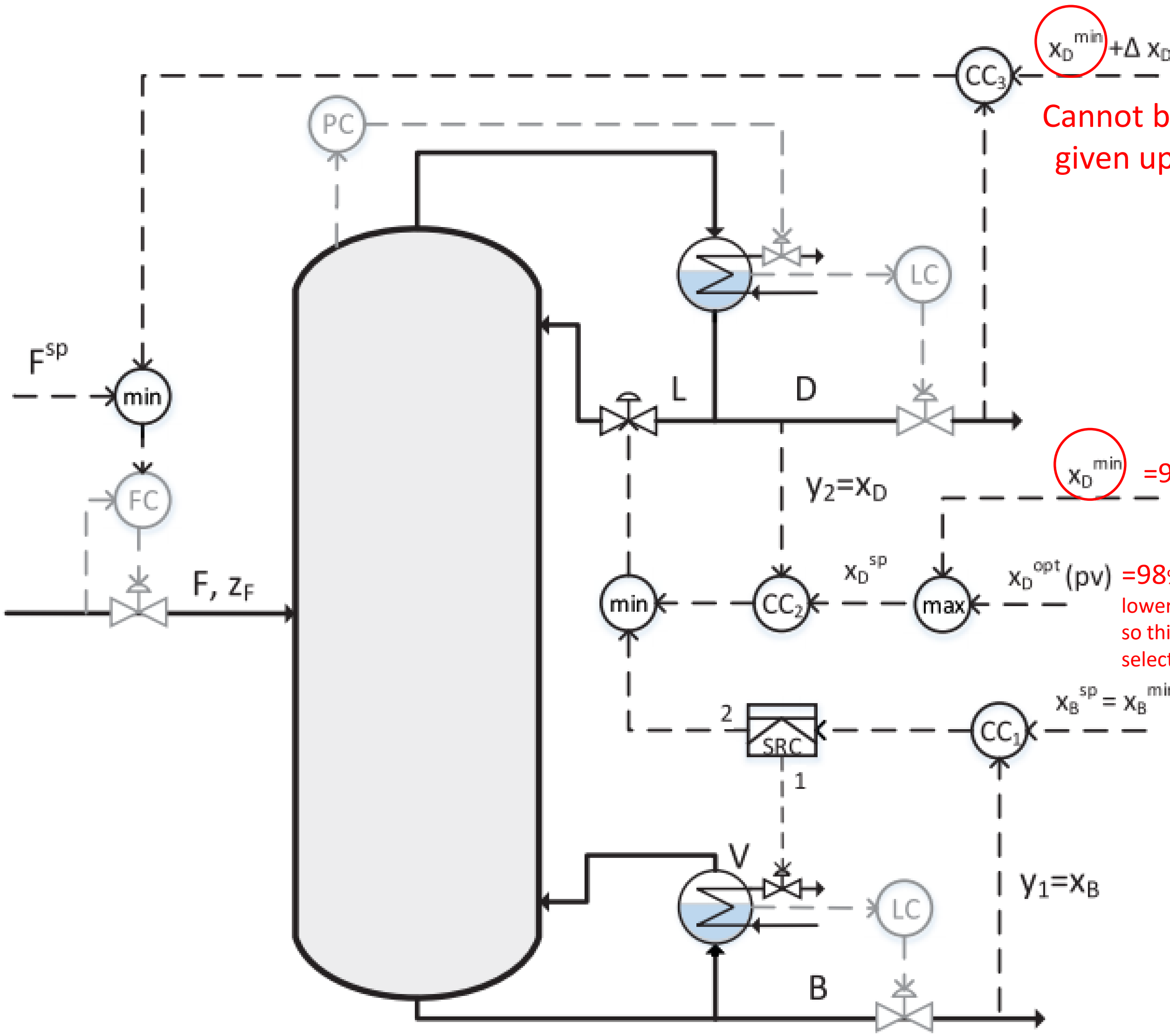
1. Normally we control xB with V
2. If V reaches Vmax then we instead use reflux L (and give up xDopt)
3. If L is not availabe (beacuse it's used to control sDmin) then we instead use the feedrate F to control xB

*Split range control can be replaced by three controllers with different setpoints for xB

"Systematic Design of Active Constraint Switching Using Classical Advanced Control Structures"
Adriana Reyes-Lúa and Sigurd Skogestad
Industrial & Engineering Chemistry Research **2020** *59* (19), 9342-9342

This is an example where MPC may be preferred

Alternative solution with different setpoints



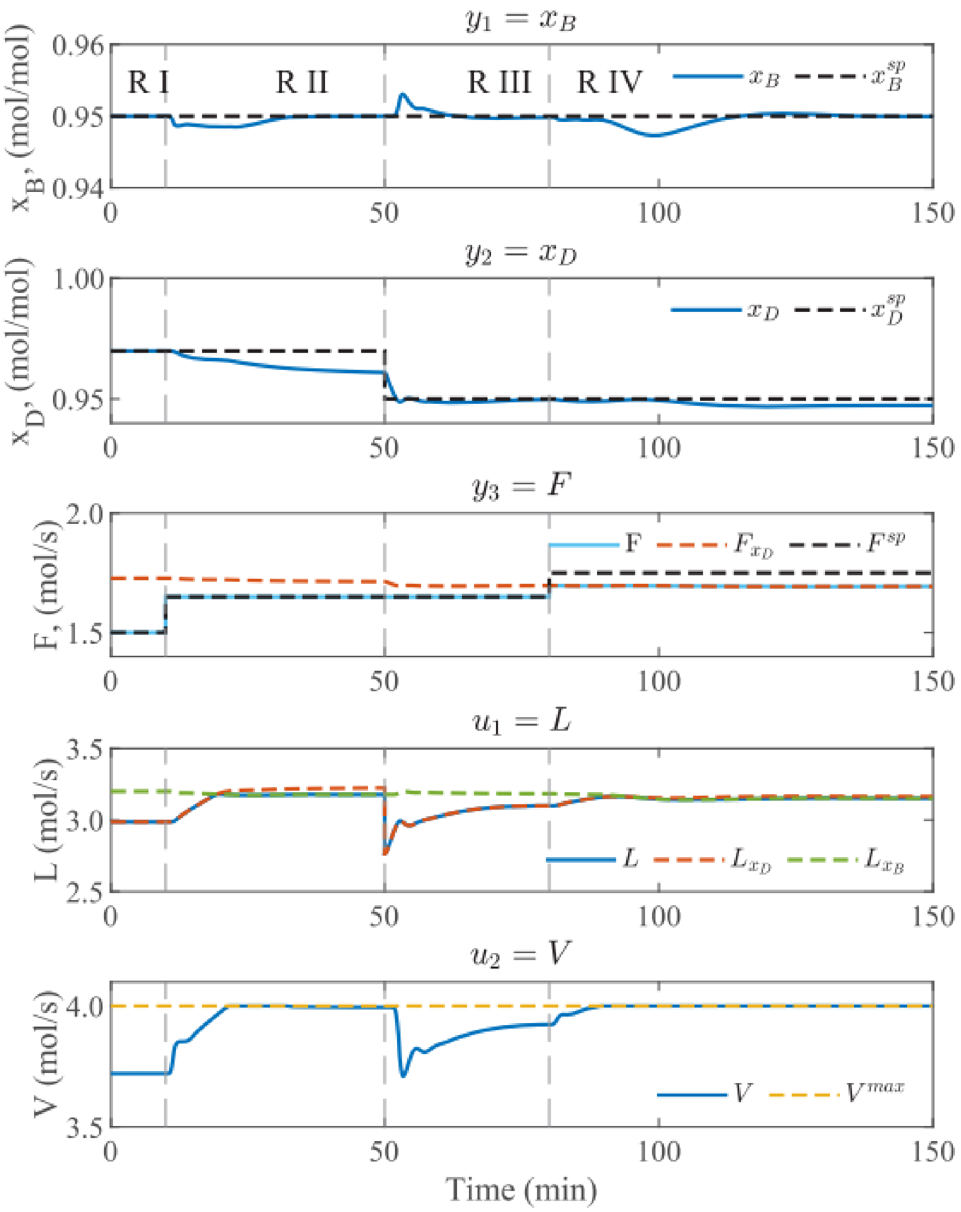
$x_D^{min} + \Delta x_D$ = 94% light

Cannot be given up

x_D^{min} =95% light

x_D^{opt}(pv) =98% (but can change and be lower if energy (V) is expensive, so this is the reason for the max-selector)

This solution looks simpler, but it is not as good dynamically in cases where we need to limit feed F to the column.
We then use F to control top composition, and L to control bottom compoistion.
The reverse pairing is better (which is what we get with the other solution)



Simulation of alternative solution. The problematic pairing is used toward the end (t>80), but it’s not really tested because there are no disturbances

Example adaptive cruise control: CV-CV switch followed by MV-MV switch

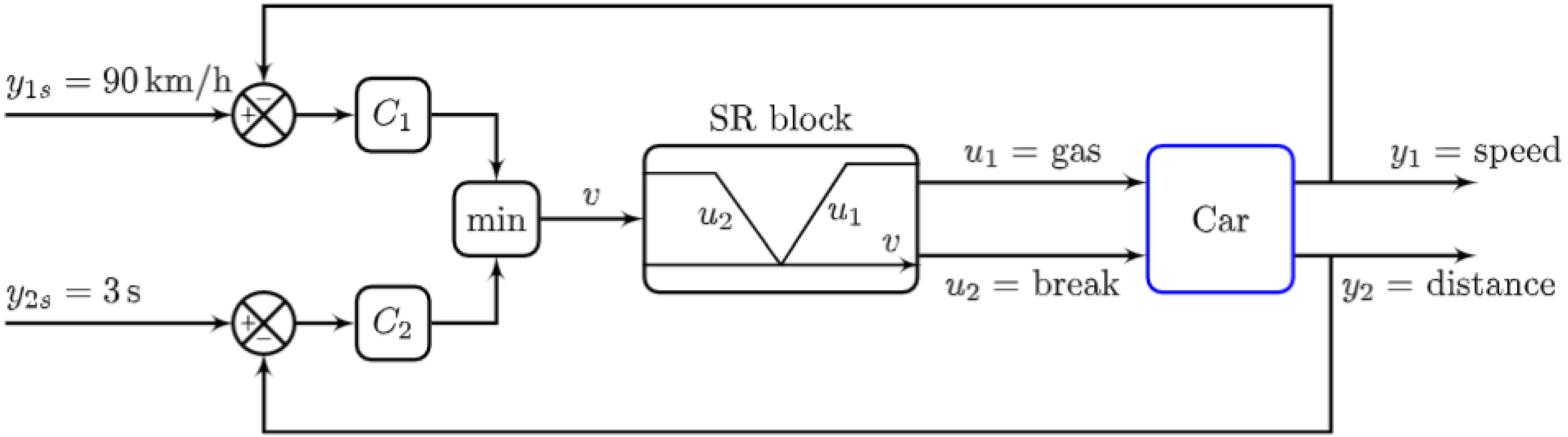


Fig. 31. Adaptive cruise control with selector and split range control.

Note: This is not Complex MV-CV switching, because then the order would be opposite.