Procedure .

- Skogestad procedure for control structure design

  I Top Down

  - Step S1: Define operational objective (cost) and constraints
  - Step S2: Identify degrees of freedom and optimize operation for disturbances
  - Step S3: Implementation of optimal operation
    - What to control ? (primary CV's)
    - Active constraints
    - Self-optimizing variables for unconstrained, c=Hy
  - Step S4: Where set the production rate? (Inventory control)

  II Bottom Up

  - Step S5: Regulatory control: What more to control (secondary CV's) ?
  - Step S6: Supervisory control
  - Step S7: Real-time optimization

Step S4. Where set production rate?

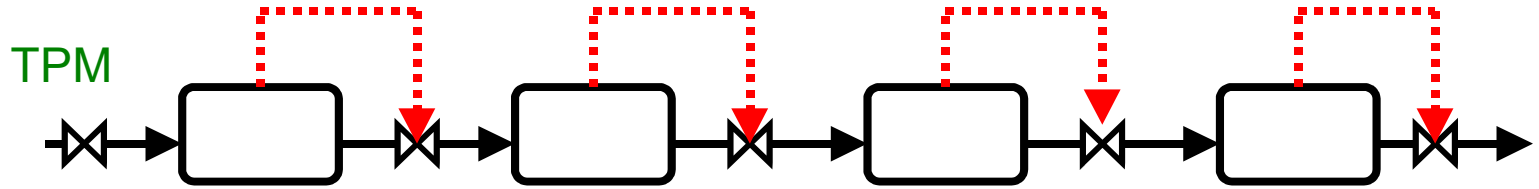
- Very important decision that determines the structure of the rest of the inventory control system!
- May also have important economic implications
- Link between **Top-down** (economics) and **Bottom-up** (stabilization) parts
  - Inventory control is the most important part of stabilizing control

- "Throughput manipulator" (TPM)
  = MV for controlling throughput (production rate, network flow)
- Where set the production rate = Where locate the TPM?
  - Traditionally: At the feed
  - For maximum production (with small backoff): At the bottleneck

TPM and link to inventory control

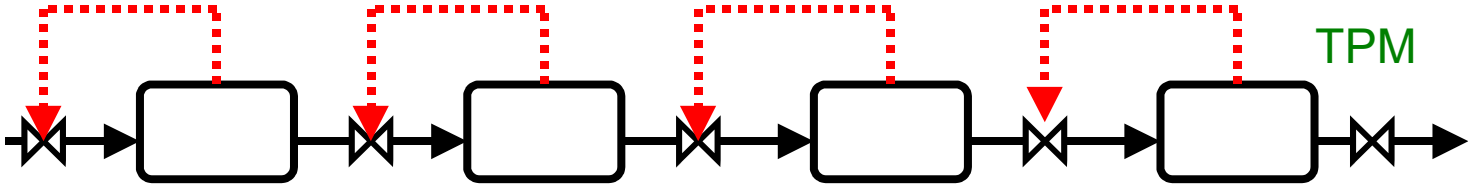
- Liquid inventory: Level control (LC)
  - Sometimes pressure control (PC)
- Gas inventory: Pressure control (PC)
- Component inventory: Composition control (CC, XC, AC)

Production rate set at inlet :
Inventory control in direction of flow*



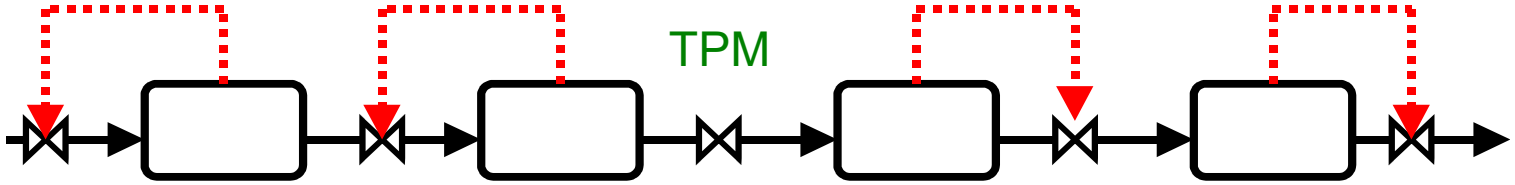
* Required to get “local-consistent” inventory control

Production rate set at outlet: Inventory control opposite flow*



* Required to get “local-consistent” inventory control

Production rate set inside process*



General Radiating Rule: “Need radiating inventory control around TPM” (Georgakis)

Consistency of inventory control

- **Consistency** (required property):

  An inventory control system is said to be **consistent** *if the steady-state mass balances (total, components and phases) are satisfied for any part of the process, including the individual units and the overall plant.*

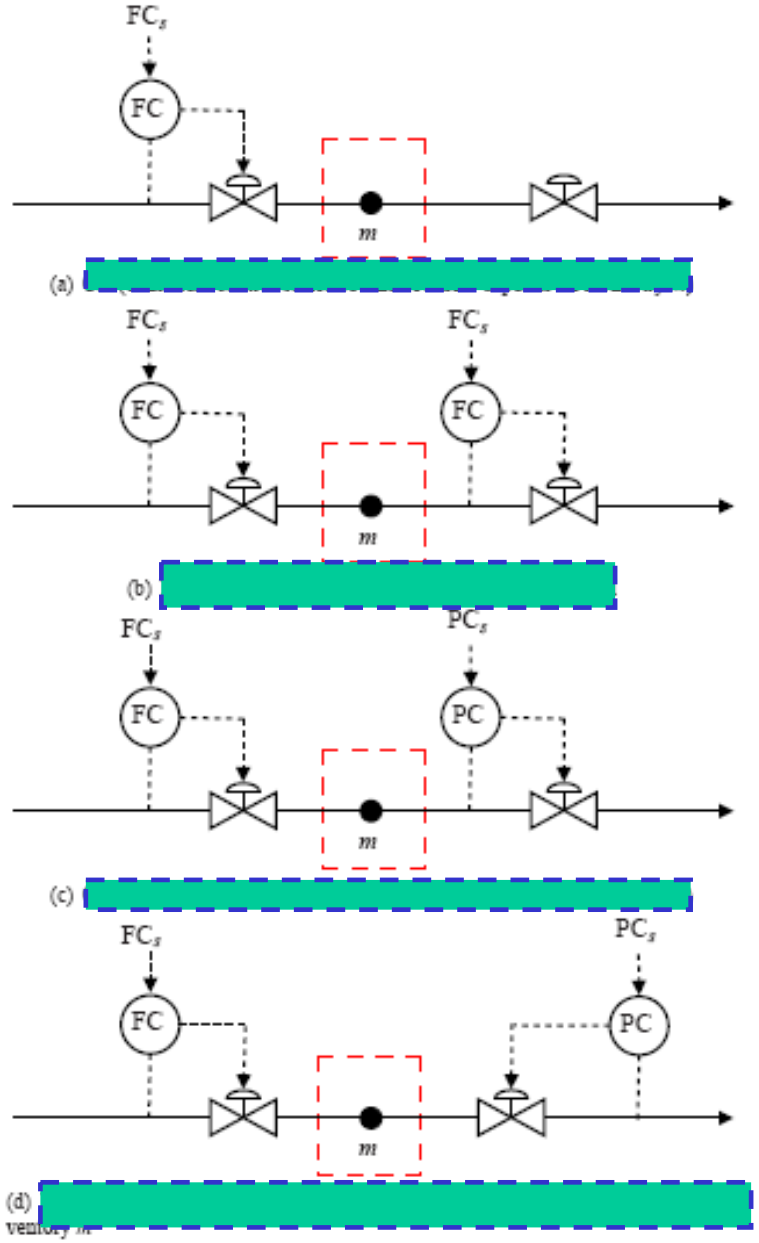
- **Local Consistency** (desired property):

  … is when the inventory control system follows the "pair-close" rule.

  This implies that it must follow the "Radiating Rule".

QUIZ 1

CONSISTENT?



Flow rate: $q = C_v f(z)\sqrt{\frac{p_1 - p_2}{\rho}}$ $[\mathrm{m}^3/\mathrm{s}]$

Rule: Controlling pressure at inlet or outlet gives indirect flow control
(because of pressure boundary condition)

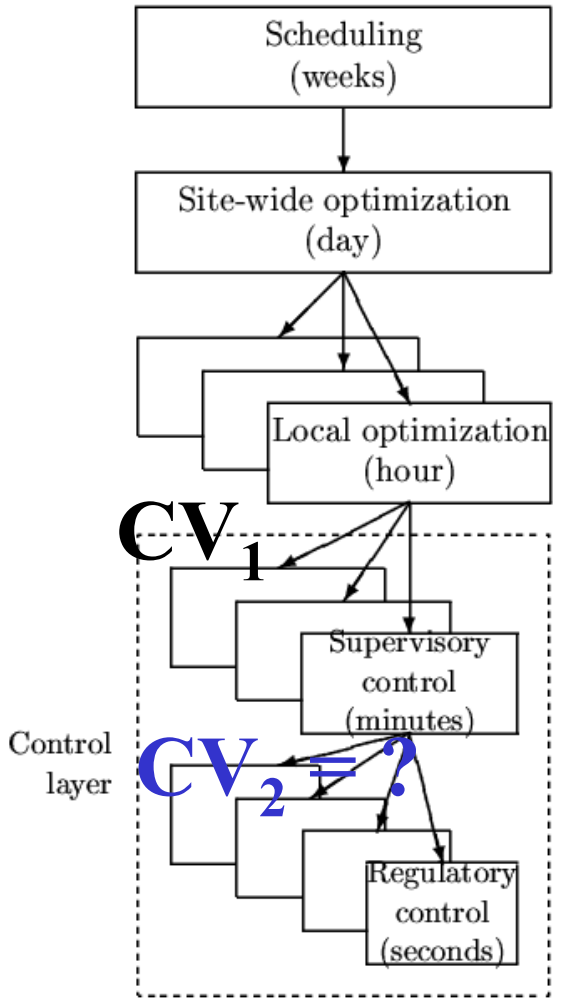
LOCATION OF SENSORS

- Location flow sensor (before or after valve or pump): Does not matter from consistency point of view
  - Locate to get best flow measurement
    - Before pump: Beware of cavitation
    - After pump: Beware of noisy measurement

- Location of pressure sensor (before or after valve, pump or compressor): Important from consistency point of view

Step 5. Regulatory control layer

- *Purpose*: "Stabilize" the plant using a simple control configuration (usually: local SISO PID controllers + simple cascades)
- Enable manual operation (by operators)
- Main structural decisions:
  - What more should we control? (secondary cv's, CV_2, use of extra measurements)
  - Pairing with manipulated variables (mv's u_2)



Structure of regulatory control layer (PID)

Main decisions:

1. Selection of controlled variables (CV2)
2. Pairing with manipulated variables (MV2)

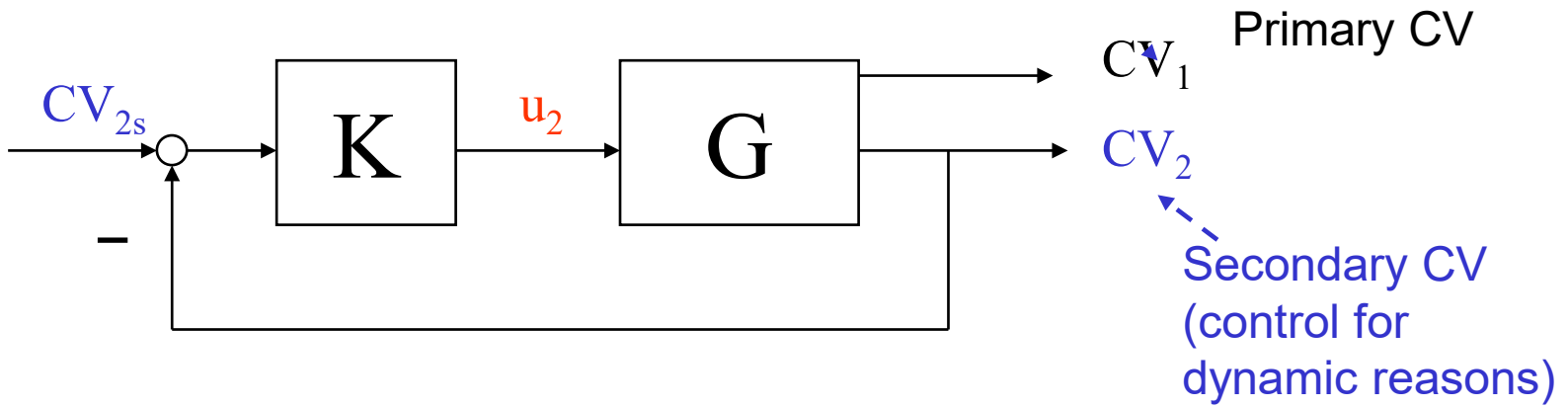
Main rules:

1. **Control drifting variables**
2. **«Pair close"**

CV2
↕
MV2

Regulatory layer

Stabilizing control: Use inputs $MV_2=u_2$ to control "drifting" variables CV_2



Key decision: Choice of CV_2 (controlled variable)

Also important: Choice of MV2=u_2 ("pairing")

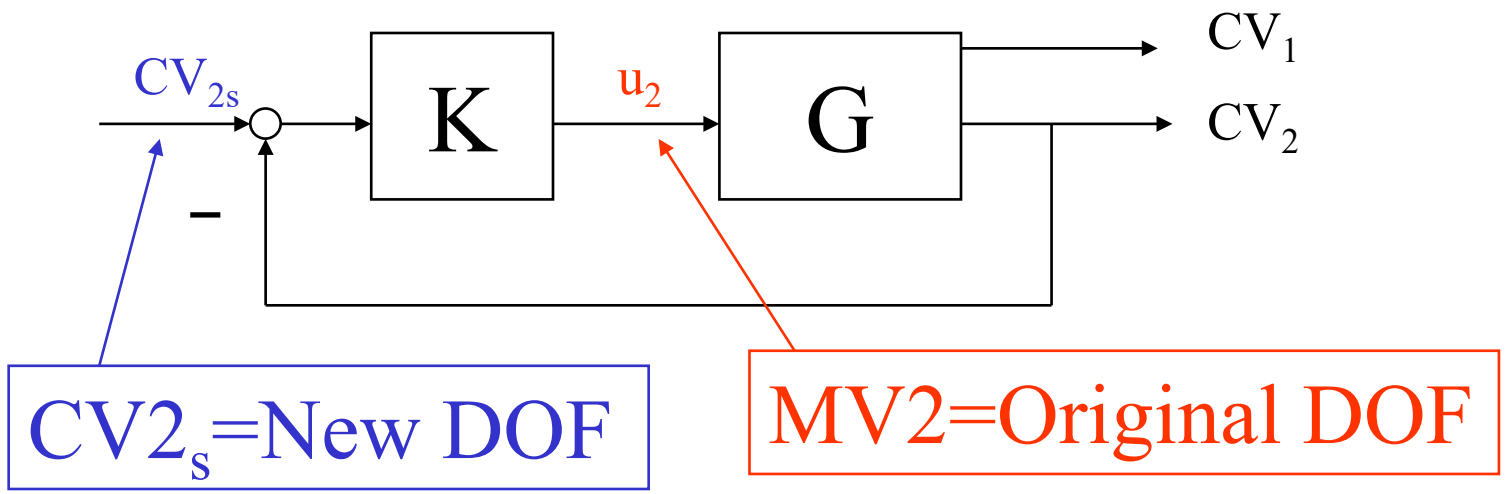
Process control: Typical «drifting» variables (CV2) are

- Liquid inventories (level)
- Vapor inventories (pressure)
- Some temperatures (reactor, distillation column profile)

Degrees of freedom unchanged

- No degrees of freedom lost as setpoints y_{2s} replace inputs u_2 as new degrees of freedom for control of y_1

Cascade control:



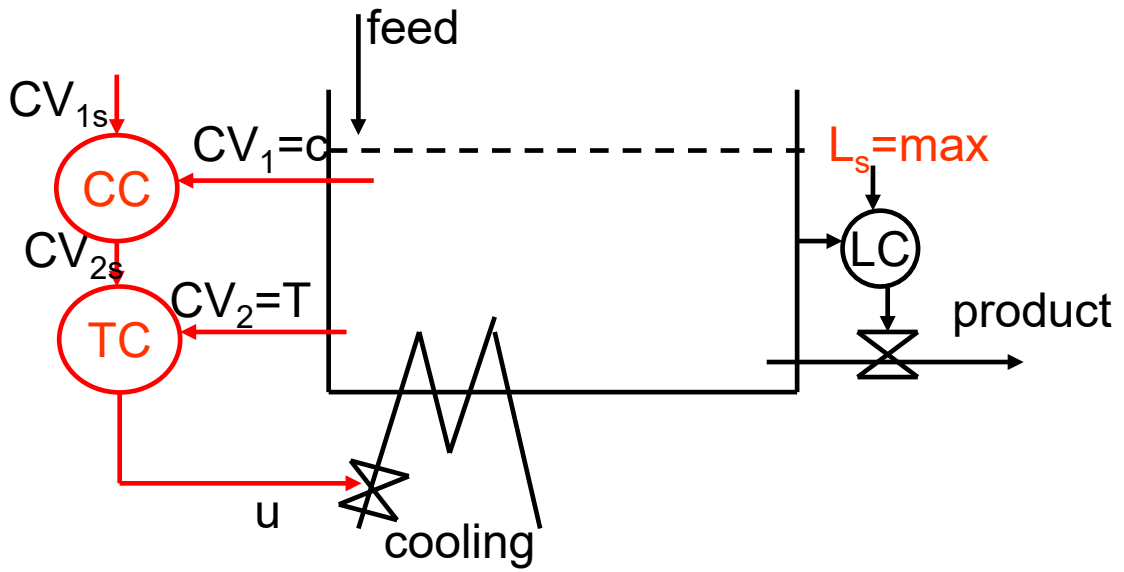
Objectives regulatory control layer

1. Allow for manual operation
2. Simple decentralized (local) PID controllers that can be tuned on-line
3. Take care of "fast" control
4. Track setpoint changes from the layer above
5. Local disturbance rejection
6. Stabilization (mathematical sense)
7. Avoid "drift" (due to disturbances) so system stays in "linear region"
   - "stabilization" (practical sense)
8. Allow for "slow" control in layer above (supervisory control)
9. Make control problem easy as seen from layer above
10. Use "easy" and "robust" measurements (pressure, temperature)
11. Simple structure
12. Contribute to overall economic objective ("indirect" control)
13. Should not need to be changed during operation

Example: Exothermic reactor (unstable)

Active constraints (economics):
Product composition c + level (max)

- u = cooling flow (q)
- CV_1 = composition (c)
- CV_2 = temperature (T)



"Control CV2s that stabilizes the plant (stops drifting)"

A. "Mathematical stabilization" (e.g. reactor):

- Unstable mode is "quickly" detected (*state observability*) in the measurement (y_2) and is easily affected (*state controllability*) by the input (u_2).
- Tool for selecting input/output: *Pole vectors*
  - y_2: Want *large element* in output pole vector: Instability easily detected relative to noise
  - u_2: Want *large element* in input pole vector: Small input usage required for stabilization

B. "Practical extended stabilization" (avoid "drift" due to disturbance sensitivity):

- *Intuitive*: y_2 located close to important disturbance
- *Maximum gain rule:* Controllable range for y_2 is large compared to sum of optimal variation and measurement+control error
- More exact tool: P*artial control analysis*

Regulatory layer

"Control CV2 that stabilizes the plant (stops drifting)"

In practice, control:

1. **Levels** (inventory liquid)
2. **Pressures** (inventory gas/vapor) (note: some pressures may be left floating)
3. **Inventories of components** that may accumulate/deplete inside plant
   - E.g., amine/water depletes in recycle loop in CO2 capture plant
   - E.g., butanol accumulates in methanol-water distillation column
   - E.g., inert N2 accumulates in ammonia reactor recycle
4. **Reactor temperature**
5. **Distillation column profile** (one temperature inside column)
   - Stripper/absorber profile does <u>not</u> generally need to be stabilized

Details Step 5b….

(b) Identify pairings =
Identify MVs (u_2) to control CV2, taking into account:

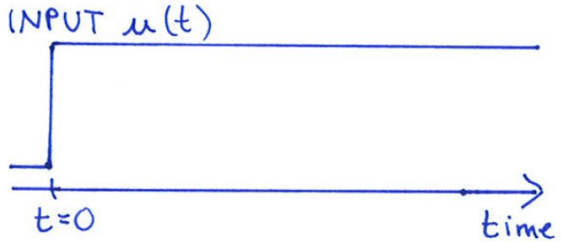
- Want "local consistency" for the inventory control
  - Implies radiating inventory control around given flow

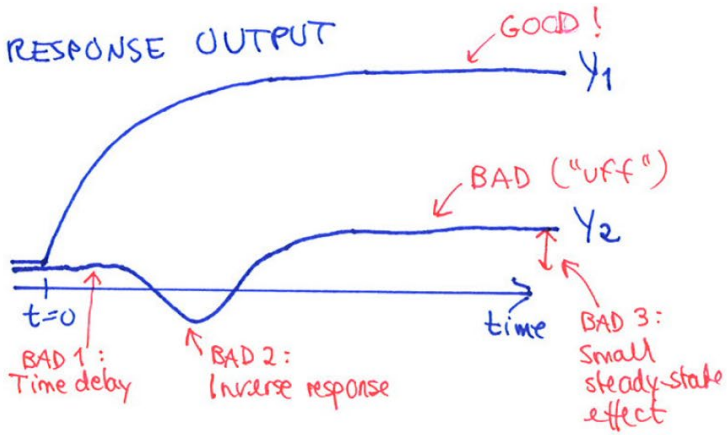
- Avoid selecting as MVs in the regulatory layer, variables that may optimally saturate at steady-state (active constraint on some region), because this would require either
  - reassigning the regulatory loop (complication penalty), or
  - requiring back-off for the MV variable (economic penalty)

- Want tight control of important active constraints (to avoid back-off)

- General rule: **"pair close"** (see next slide)

Main rule: “Pair close”





The response (from input to output) should be fast, large and in one direction.
Avoid dead time and inverse responses!

Advanced/supervisory control layer

- Skogestad procedure for control structure design

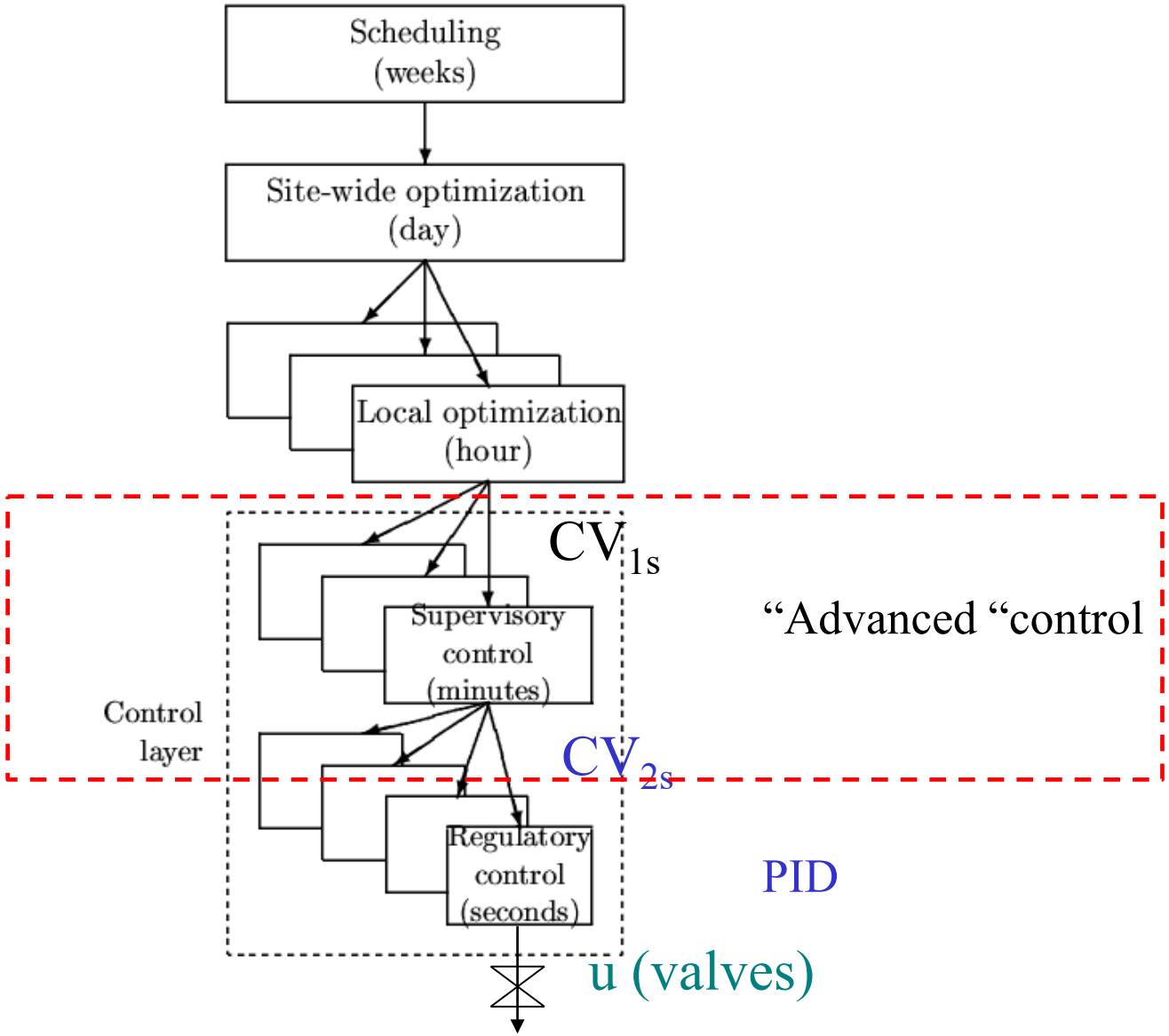
  I Top Down

  - Step S1: Define operational objective (cost) and constraints
  - Step S2: Identify degrees of freedom and optimize operation for disturbances
  - Step S3: Implementation of optimal operation
    - What to control ? (primary CV's)
    - Active constraints
    - Self-optimizing variables for unconstrained, c=Hy
  - Step S4: Where set the production rate? (Inventory control)

  II Bottom Up

  - Step S5: Regulatory control: What more to control (secondary CV's) ?
  - Step S6: Supervisory control
  - Step S7: Real-time optimization

Control layers



STEP S6. SUPERVISORY LAYER

Objectives of supervisory layer:

1. Perform "advanced" economic/coordination control tasks.

- Control primary variables CV1 at setpoint using as degrees of freedom (MV):
  - Setpoints to the regulatory layer (CV2s)
  - "unused" degrees of freedom (valves)
- Feedforward from disturbances
  - If helpful
- Make use of extra inputs
- Make use of extra measurements

2. Keep an eye on stabilizing layer

- Avoid saturation in stabilizing layer

3. Switch control structures (CV1) depending on operating region

- Active constraints
- self-optimizing variables

Implementation:

- Alternative 1: Advanced control based on "simple elements" (decentralized control)
- Alternative 2: MPC

“Advanced control” using simple control configuration elements

- **Control configuration.** *The restrictions imposed on the overall controller by decomposing it into a set of local controllers (subcontrollers, units, elements, blocks) with predetermined links and with a possibly predetermined design sequence where subcontrollers are designed locally.*

Some control configuration elements:

- Cascade controllers
- Decentralized controllers
- Feedforward elements
- Decoupling elements
- Input resetting/Valve position control/Midranging control
- Split-range control
- Selectors

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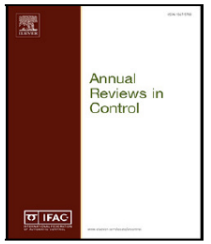

Review article

Advanced control using decomposition and simple elements

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ARTICLE INFO

Keywords:
Control structure design
Feedforward control
Cascade control
PID control
Selective control
Override control
Time scale separation
Decentralized control
Distributed control
Horizontal decomposition
Hierarchical decomposition
Layered decomposition
Vertical decomposition
Network architectures

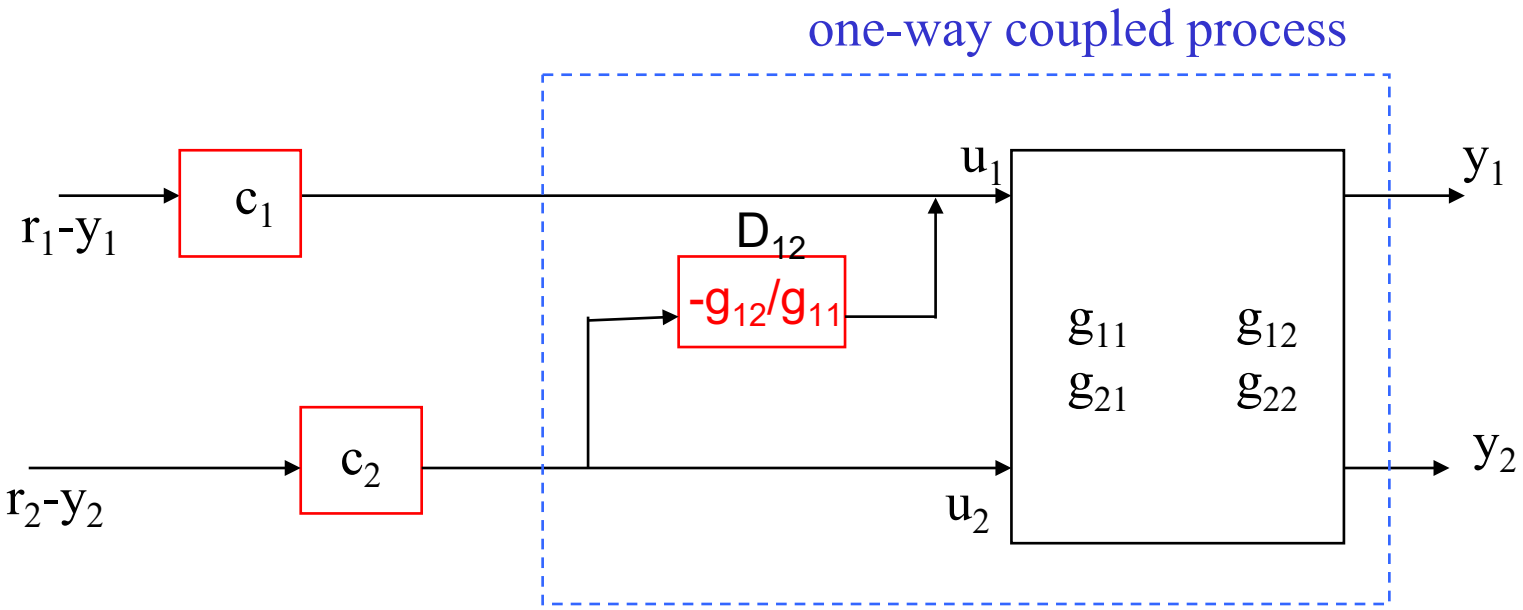
ABSTRACT

The paper explores the standard advanced control elements commonly used in industry for designing advanced control systems. These elements include cascade, ratio, feedforward, decoupling, selectors, split range, and more, collectively referred to as "advanced regulatory control" (ARC). Numerous examples are provided, with a particular focus on process control. The paper emphasizes the shortcomings of model-based optimization methods, such as model predictive control (MPC), and challenges the view that MPC can solve all control problems, while ARC solutions are outdated, ad-hoc and difficult to understand. On the contrary, decomposing the control systems into simple ARC elements is very powerful and allows for designing control systems for complex processes with only limited information. With the knowledge of the control elements presented in the paper, readers should be able to understand most industrial ARC solutions and propose alternatives and improvements. Furthermore, the paper calls for the academic community to enhance the teaching of ARC methods and prioritize research efforts in developing theory and improving design method.

“Advanced control” using simple control configuration elements

1. Cascade control (measure and control internal variable, y2)
2. Feedforward control (measure disturbance, d)
    - Including ratio control
3. Multivariable control (decoupling)
    - For interactive process (where RGA is unfavorable)
4. Changes in active constraints
    - Selectors
    - Input resetting (valve position control)
    - Split range control

3. One-way Decoupling (improved control of y_1)



DERIVATION

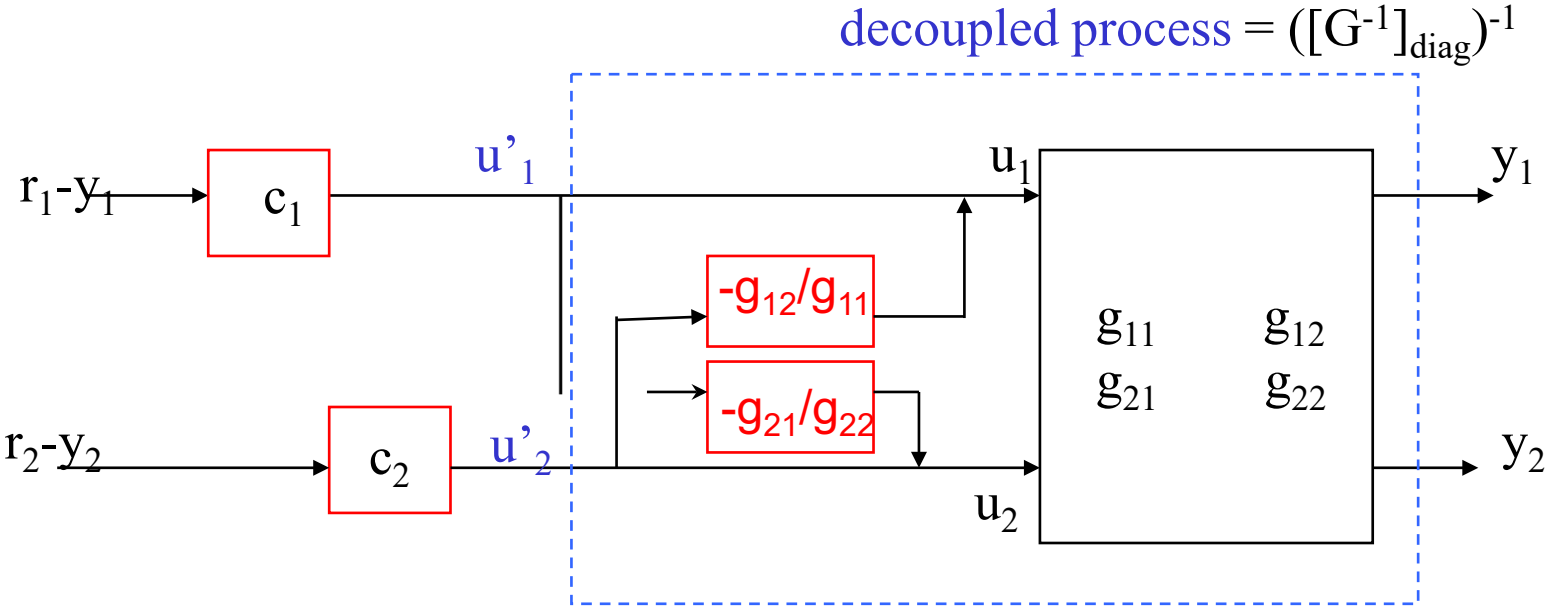
Process: $y1 = g11\ u1 + g12\ u2$ (1)

$y2 = g21\ u1 + g22\ u2$ (2)

Consider u2 as disturbance for control of y1.

Think «feedforward»: Adjust u1 to make y1=0. (1) gives u1 = - (g12/g11) u2

Two-way Decoupling: Standard implementation (Seborg)

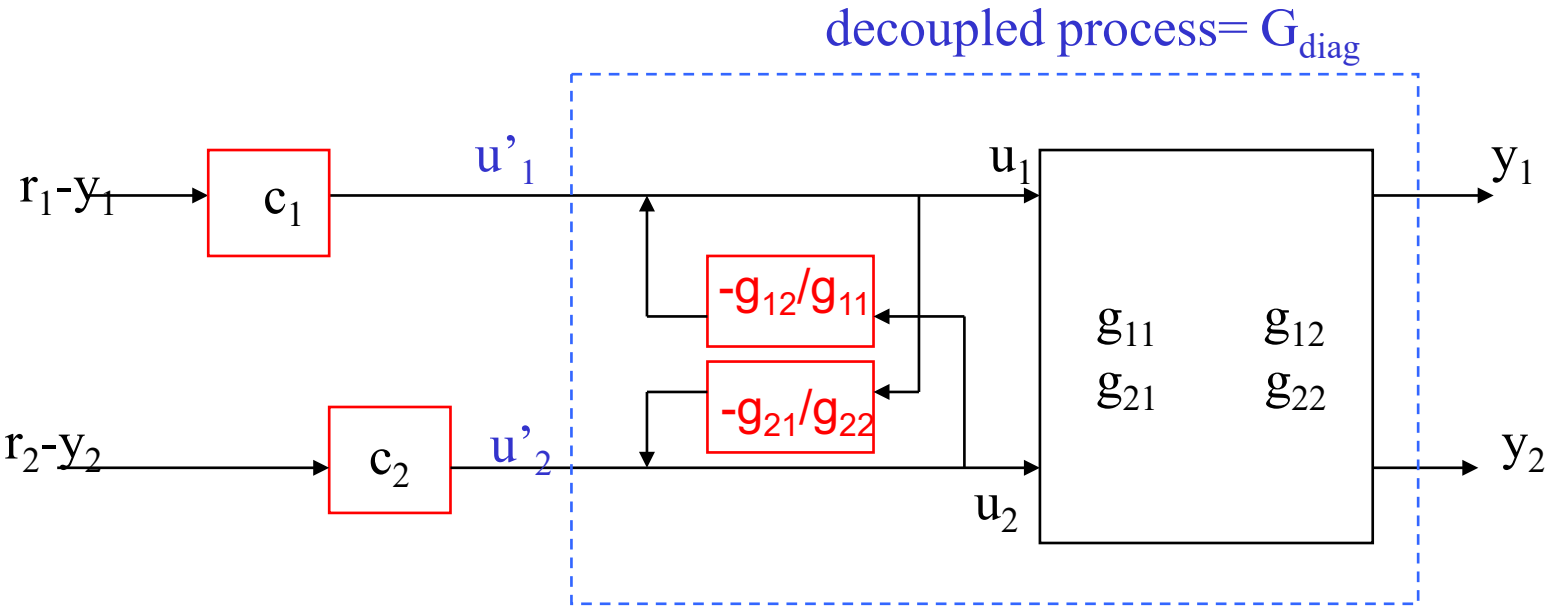


… but note that diagonal elements of decoupled process are different from G
Problem for tuning!

Process: y1 = g11 u1 + g12 u2
Decoupled process: y1 = (g11-g21*g12/g22) u1' + 0*u2'
Similar for y2.

Sigurd recommends this alternative!

Two-way Decoupling: «Inverted» implementation (Shinskey)



Advantages: (1) Decoupled process has same diagonal elements as G. Easy tuning!
(2) Handles input saturation! (if u1 and u2 are actual inputs)

Proof (1): $y_1 = g_{11} u_1 + g_{12} u_2$, where $u_1 = u_1' - (g_{12}/g_{11})u_2$.
Gives : $y_1 = g_{11} u'_1 + 0^* u_2'$
Similar: $y_2 = 0^* u_1' + g_{22} u_2'$

Pairing and decoupling

- To get ideal decoupling, offdiagonal elements should have smaller effective delay than the diagonal elements
- Thus, we should pair on elements with small effective delay (“pair close rule”)
- Pairing on negative steady state RGA elements is not a problem if we use decoupling
  - Because negative RGA-elements are caused by interactions, which is what we are cancelling with decoupling

Multivariable control: MPC versus decoupling

- Both MPC and decoupling require a multivariable process model
- MPC is usually preferred instead of decoupling because it can also handle feedforward control, nonsquare processes (cascade, input resetting) etc.

MPC = Model predictive control

4. Changing active contraints

Procedure for maintaining optimal operation when changing between active constraint regions

Step 1: Define all the constraints

Step 2: Identify relevant active constraint combinations and switches

Step 3: Propose a control structure for the nominal operating point.

Step 4: Propose switching schemes

Step 5: Design controllers for all cases (active constraint combinations)

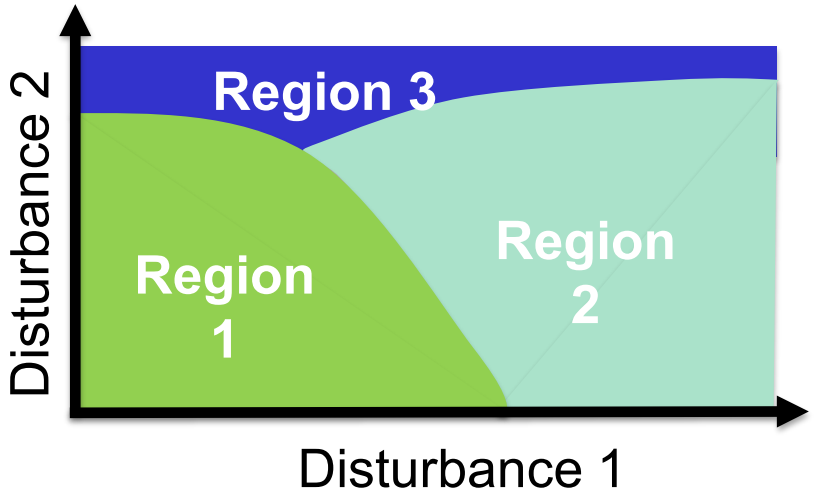
Step 1: Define all the constraints

- Identify the type of constraints
  - **Input constraints:**
    - Manipulated variables (MV)
      - e.g. valve fully open or fully closed.
  - **Output constraints:**
    - Controlled variables (CV)
      - e.g. maximum temperature or pressure.

- Unconstrained optimum:
  - Identify Self-optimizing variables.

Step 2: Identify relevant active constraint combinations and switches

- **Active constraints:**
  - variables that should optimally be kept at their limiting value.
- **Active constraint region:**
  - region in the disturbance space defined by which constraints are active within it.



Note: Not necessary to generate this diagram!

Step 2: Identify relevant active constraint combinations and switches

- **Maximum number of active constraint combinations (regions):**

  $n_r^{max} = 2^{nc}$

  nc: number of constraints

- **In practice, fewer regions**
  - Certain constraints are always active (reduces effective n_c)
  - Some combinations are infeasible:
    - Only n_u can be active at a given time
      - n_u = number of MVs (inputs)
    - Certain constraints combinations are not possible
      - *Cannot have both max* and *min* on the same variable (e.g. flow)
  - Certain regions are not reached by the assumed disturbance set
- **Furthemore, not all switches occur or are feasible**
  - Only neighboring switches need to be considered, that is, only one constraint is changing

Tool: Organize constraints in priority list

P1: MV inequality constraints (can never be violated)

P2: CV inequality constraints (may sometimes be given up)

P3: MV or CV equality constraints (may often be given up)

P4: Desired throughput (give up when reach bottleneck)

P5: Self-optimizing variables (can be given up)

A. Reyes-Lúa, C. Zotică, S. Skogestad, 2018. *Optimal Operation with Changing Active Constraint Regions using Classical Advanced Control*. In: 10th ADCHEM. IFAC, Shenyang, China.

Step 3: Design control structure for normal operation

Try to follow **Input saturation pairing rule:**

- Pair a manipulated variable (MV) that is likely to saturate
- With a low-priority controlled variable (CV) (can be given up)

Step 4. Design control structures for switching of active constraints

- Three main cases:
  1. Output to output (CV-CV) switching (SIMO)

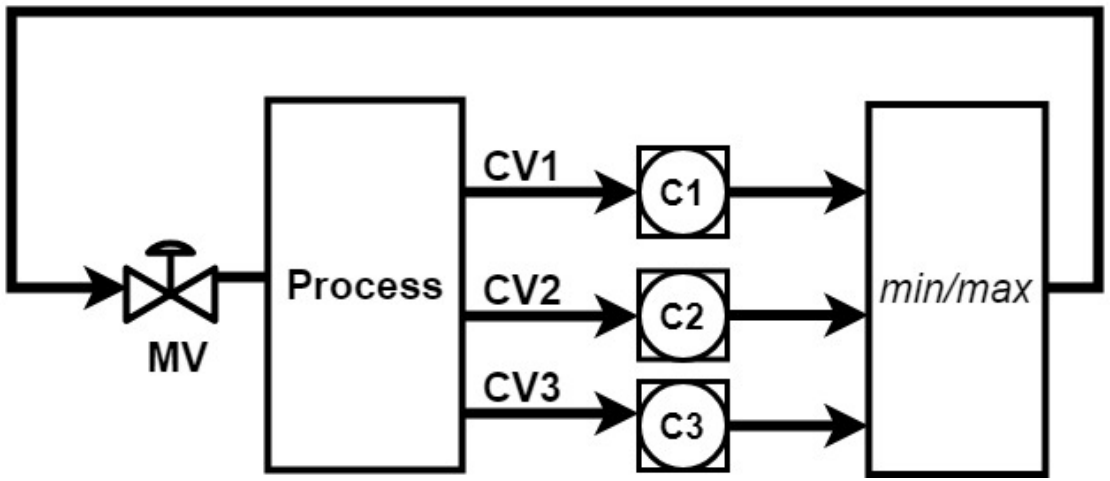
     Selectors
  2. Input to input (MV-MV) switching (MISO)

     Split range control (+ 2 more alternatives)
  3. Input to output (MV-CV) switching

     Nothing (if we followed input pairing rule)

1. CV-CV switching (SIMO)

- MV is used to control CV1
- Problem: CV2 (so far uncontrolled) reaches constraint
- Solution: Use MV to control CV2 instead («give up» controlling CV1).
  - One MV used for several CVs (SIMO).
  - Design one controller for each CV.
  - Switching: Use *min/max* selector on controller output
  - Self-optimizing CV: Only track neighboring regions.



Design of selector structure

Rule 1 (max or min selector)

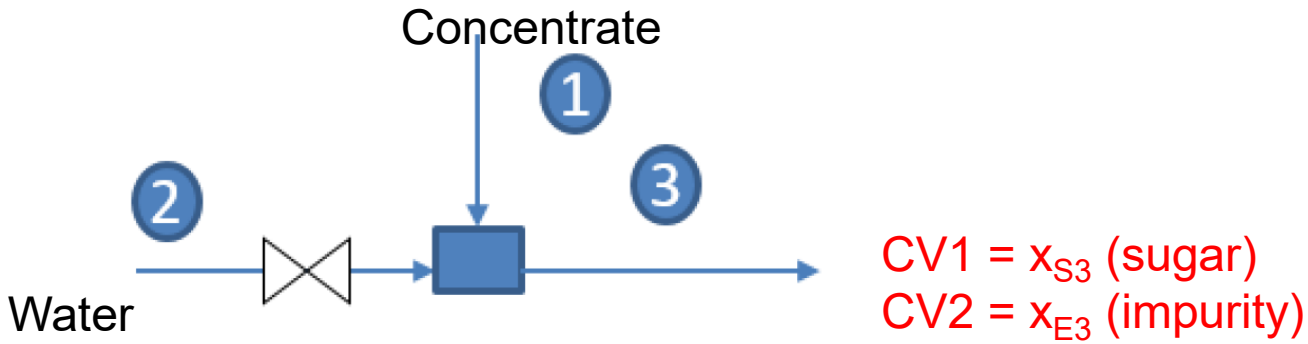
- Use max-selector for constraints that are satisfied with a large input
- Use min-selector for constraints that are satisfied with a small input

Rule 2 (order of max and min selectors):

- If need both max and min selector: Potential infeasibility
- Order does not matter if problem is feasible
- If infeasible: Put highest priority constraint at the end

"Systematic design of active constraint switching using selectors."
Dinesh Krishnamoorthy , Sigurd Skogestad. Computers & Chemical Engineering, Volume 143, (2020)

Problem 4. Mixing tank with changing control objective (40%)



You are mixing two streams. Stream 1 contains water (W), sugar (S) and some preservative (E). Your task is to mix the feed (stream 1) with pure water (stream 2) to get a product (stream 3) that satisfies:

Desired sugar content (want to keep product close to this value): $x_{s3} = 0.1$

Maximum E in product (required at all times): $x_{E3} \leq 0.001$

The water flow (F2) is limited to F2max

(a) Design a control system for the nominal case with little impurity E (X_{E3} small)

(b) Design a control system that can handle also the case when CV2 goes above the max. value of 0.001

(a)

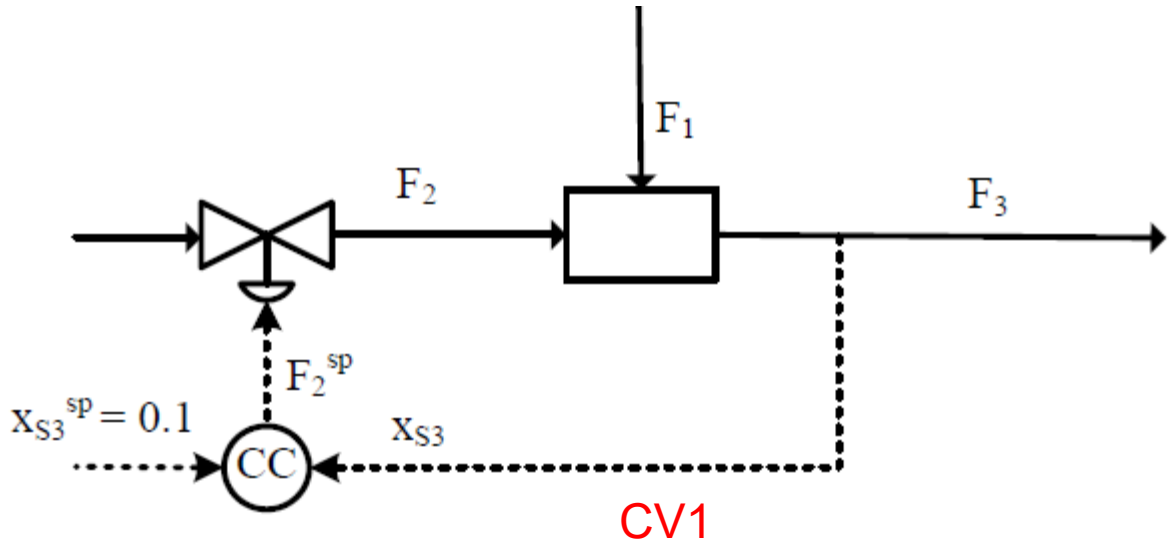


Figure 8: Control structure for the nominal point

This follows «input pairing rule»: Pair a MV that is likely to saturate (F2) with a CV that can be given up (x_{S3})

Important: Since we follow «input pairing rule» no special action is needed when F2 saturates (fully open valkve) except that controller CC should have anti windup

(b)

CV-CV switching using selector

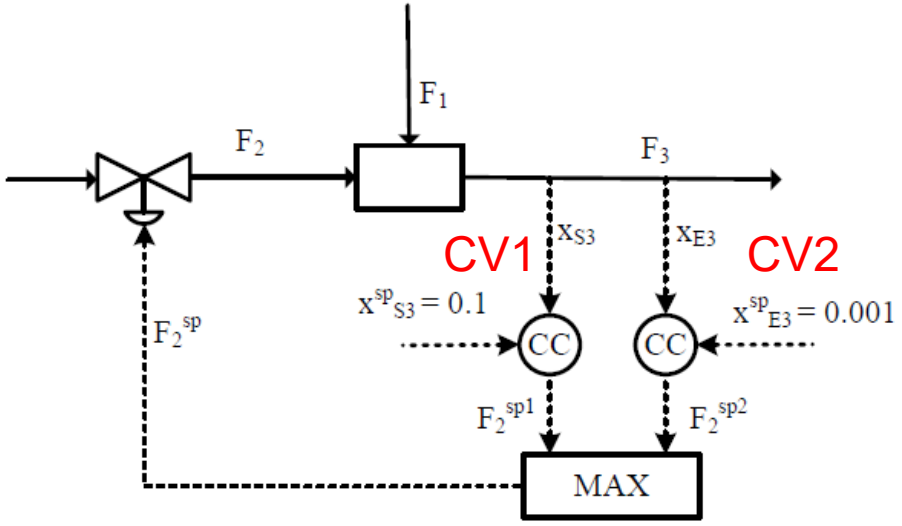


Figure 9: Control structure that handles both the nominal and the extreme cases

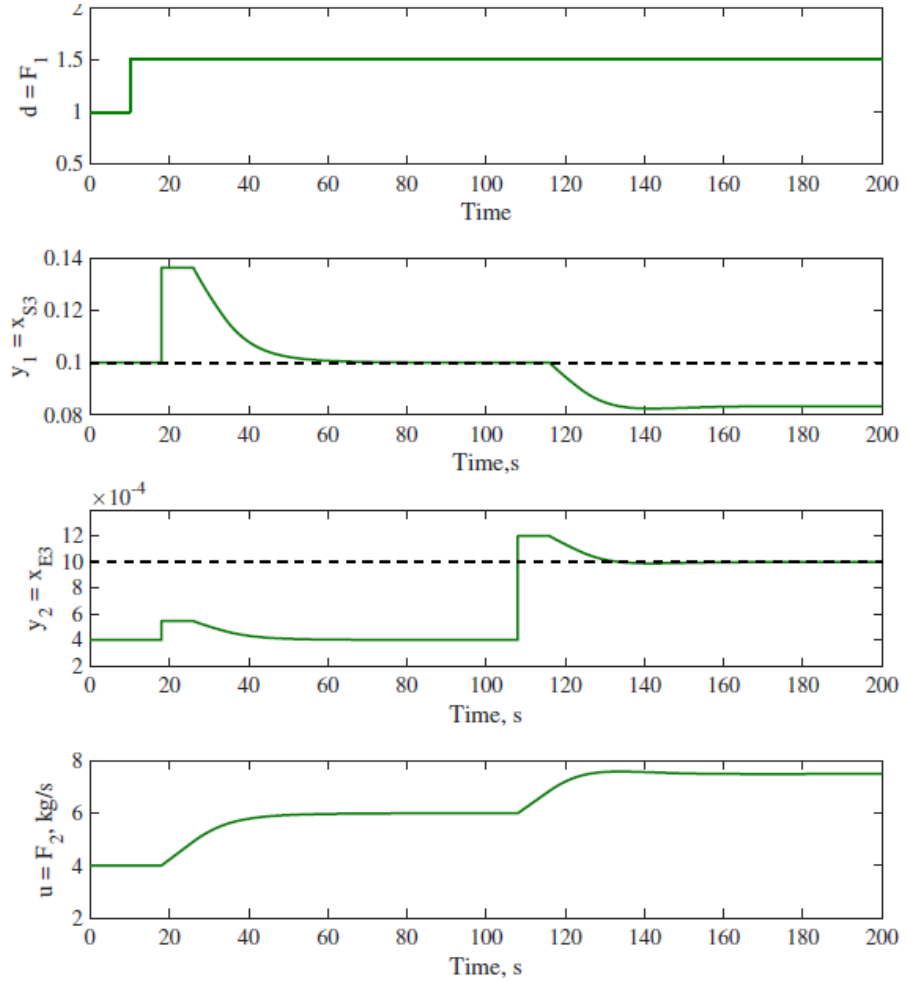


Figure 10: Simulation results for a step disturbance $F_1 = 1.5\,kg/s$ at $t = 10\,s$ and $x_{E1} = 0.006$ at $t = 100\,s$ (extreme case). The black dotted lines show the concentration specification for x_{S3} and x_{E3} respectively. In the normal case, the controller is controlling $y_1 = x_{S3}$ at $y_{1s} = 0.1$, while in the extreme case, the controller is controlling $y_2 = x_{E3}$ at $y_{2s} = 0.001$.

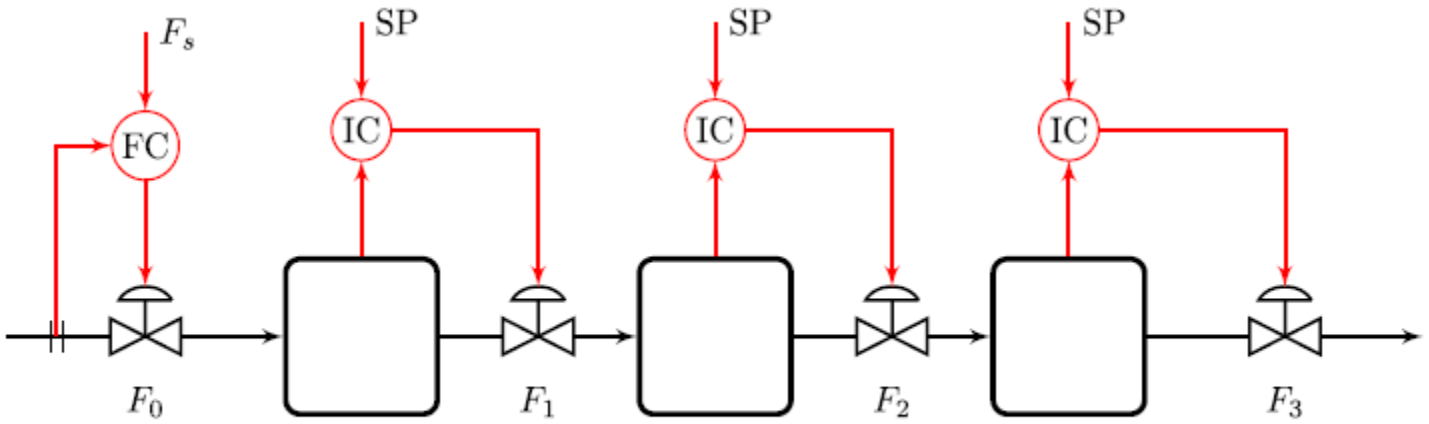
Selector notation

- MAX = HS = >
- MIN = LS = <

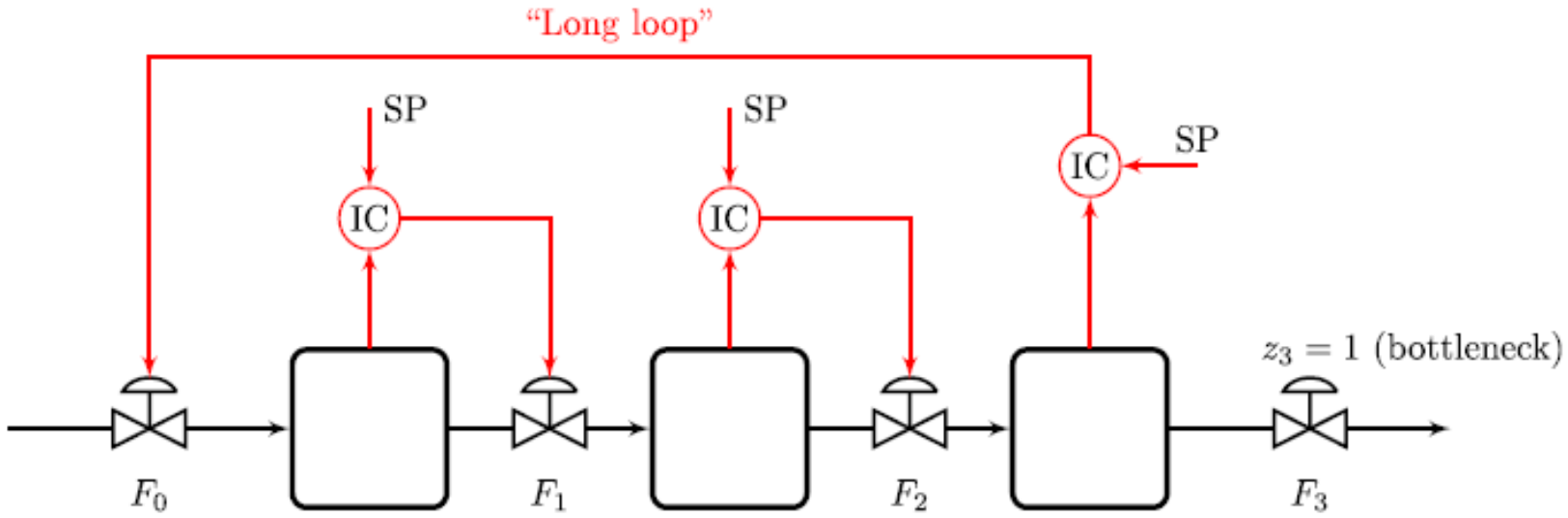
Dynamic issues

- Use of selectors to avoid «long loop»

Radiation rule for Inventory control



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

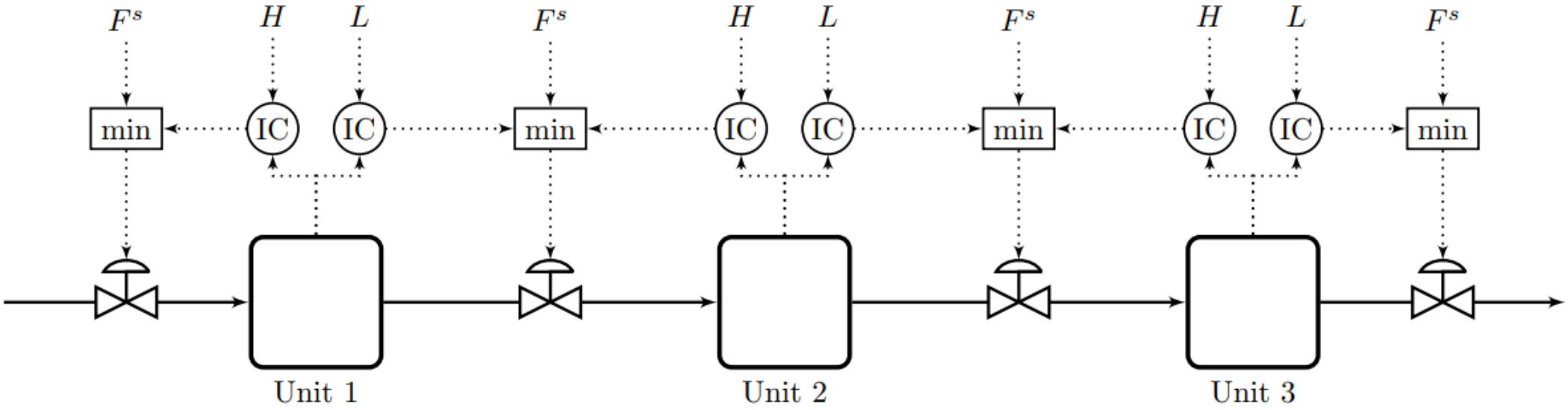


(d) Inventory control with undesired "long loop", not in accordance with the "radiation rule" (for given product flow, TPM= F_3)

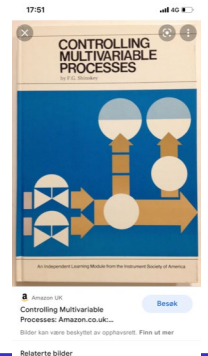
TPM = throughput manipulator

Example . Very smart selector strategy: **Bidirectional inventory control**

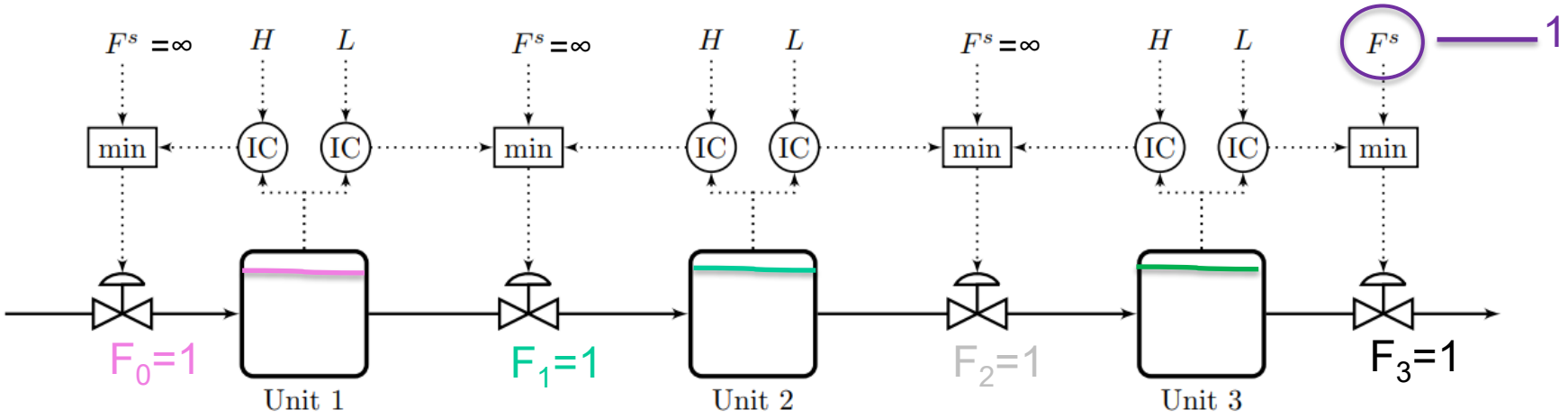
Reconfigures automatically with optimal buffer management!!

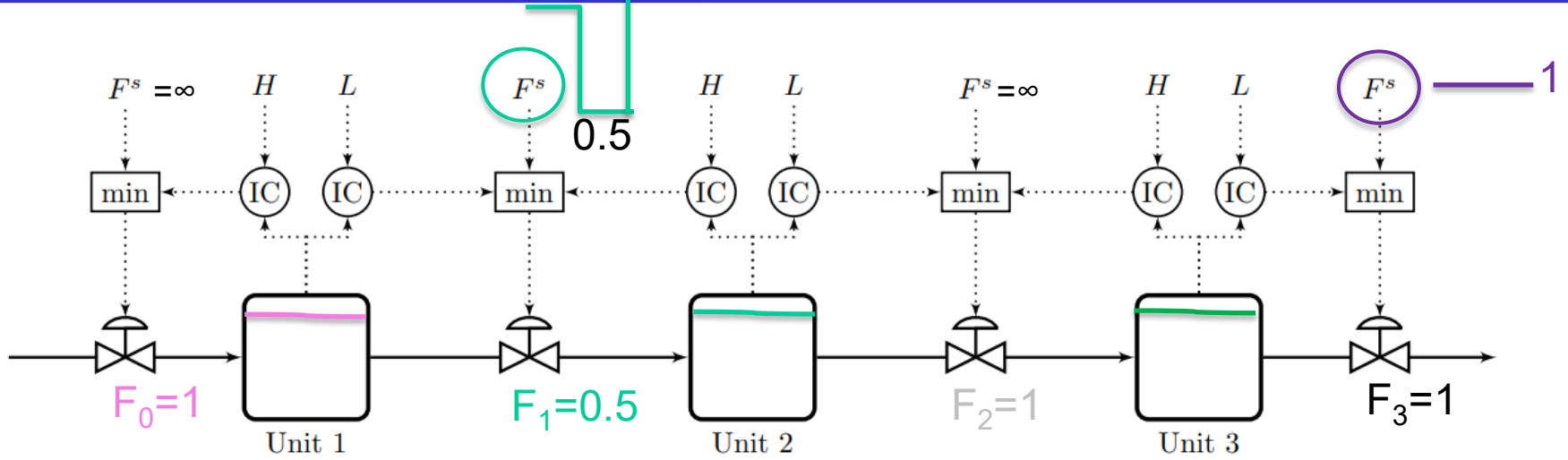


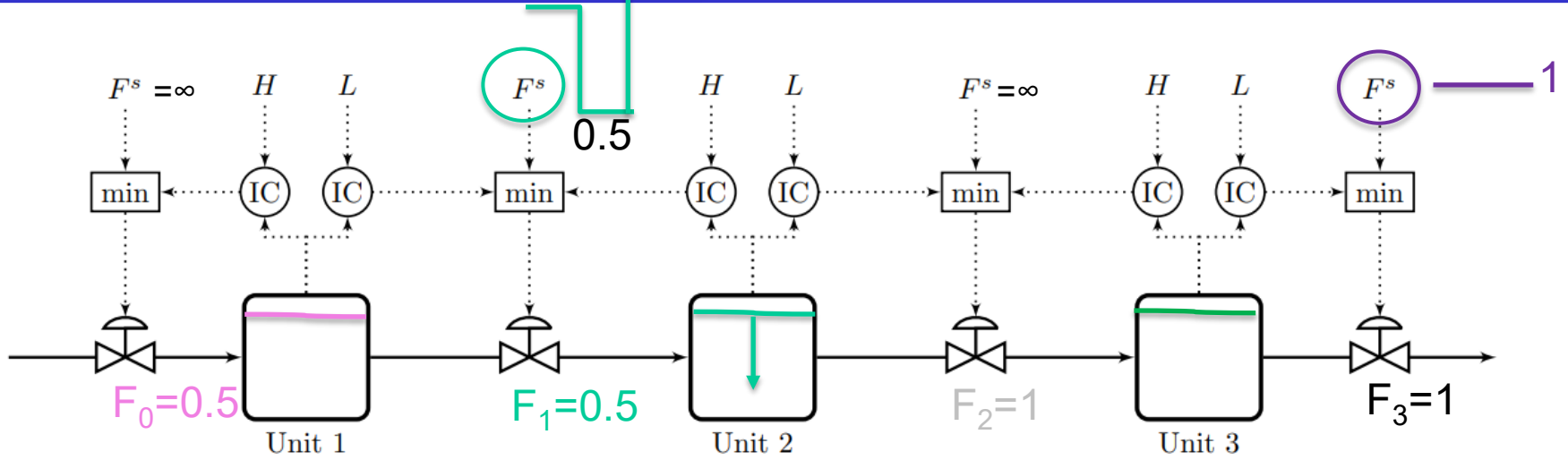
Max flow:
$F^s = \infty$

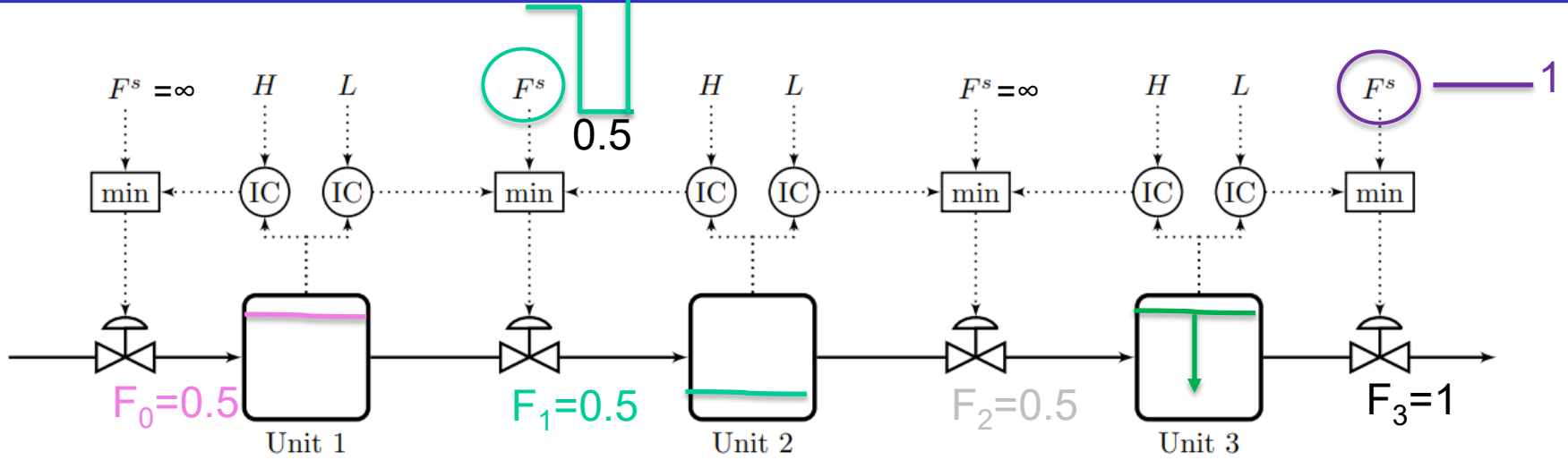


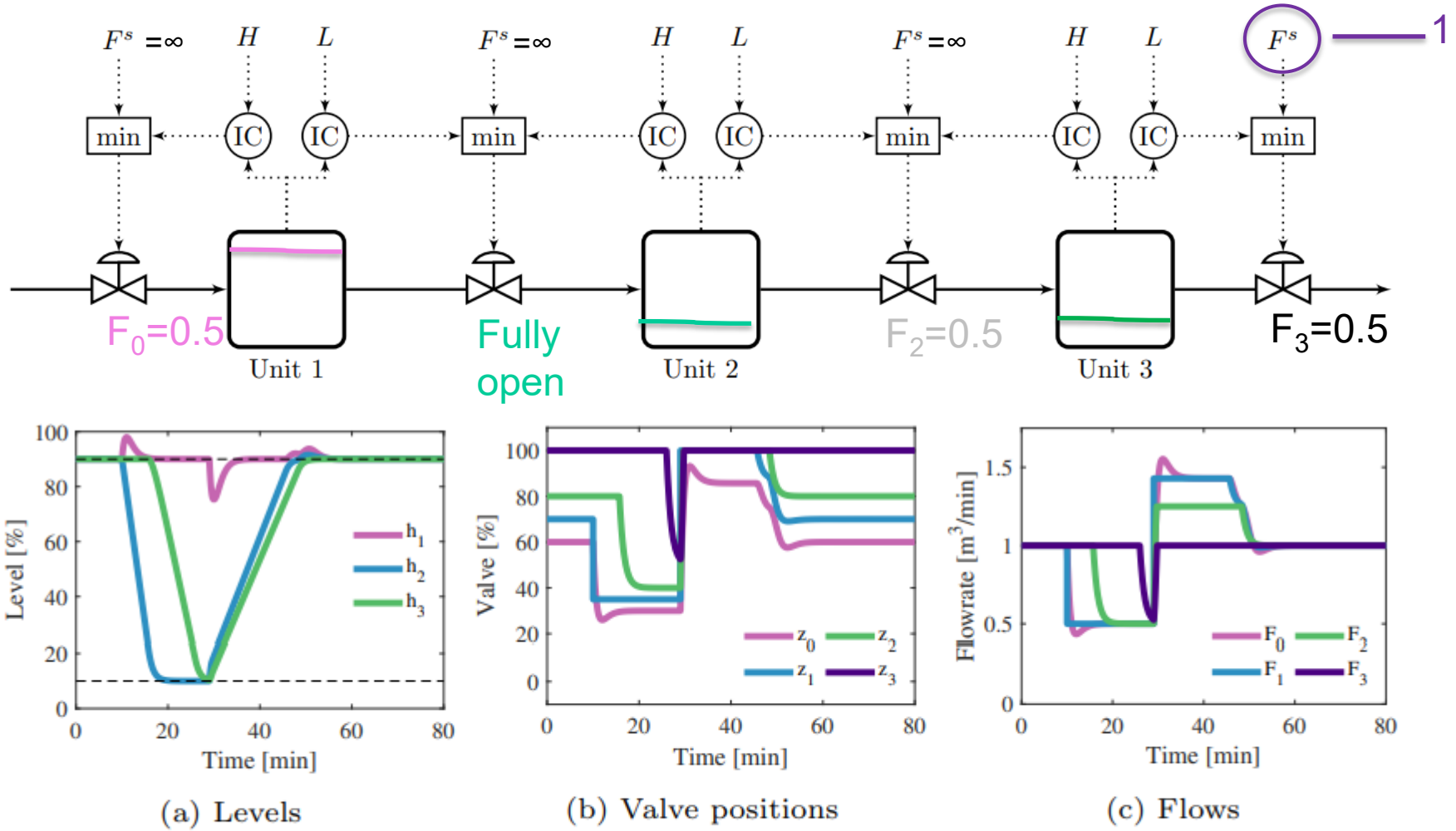
F.G. Shinskey, «Controlling multivariable processes», ISA, 1981
C. Zotica, S. Skogestad and K. Forsman, Comp. Chem. Eng, 2021


$F^s = \infty$
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
F_1=1
F_2=1
F_3=1
Unit 1
Unit 2
Unit 3


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
F_1=0.5
F_2=1
F_3=1
Unit 1
Unit 2
Unit 3

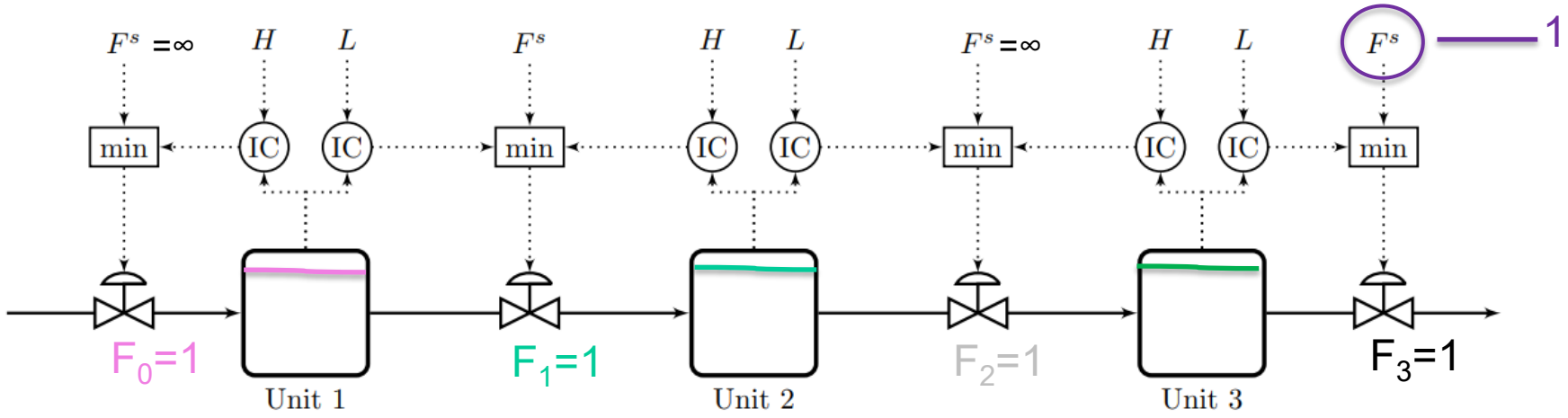

F^s =∞
H
L
F^s
0.5
H
L
F^s =∞
H
L
F^s
1
min
IC
IC
min
IC
IC
min
IC
IC
min
F_0=0.5
Unit 1
F_1=0.5
Unit 2
F_2=1
Unit 3
F_3=1


$F^s = \infty$
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
F_1=0.5
F_2=0.5
F_3=1
Unit 1
Unit 2
Unit 3



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

Figure 12: Simulation of a 19 min temporary bottleneck in flow F_1 for the control structures in Fig. 3d with the TPM downstream of the bottleneck.

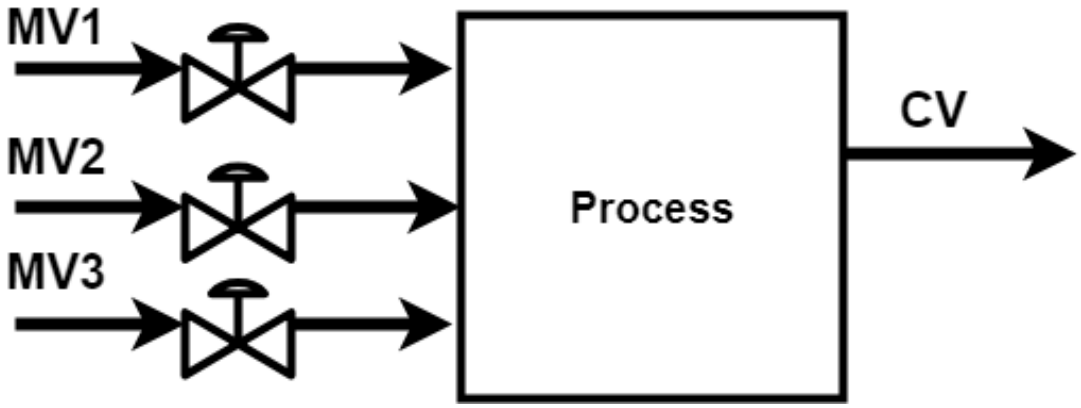


Challenge: Can MPC be made to do his? Optimally reconfigure loops and find optimal buffer? I doubt it. We tried.

2. MV-MV switching (MISO)

- Problem: We are using MV1 to control CV, but MV1 saturates
- Solution: Let MV2 take over (re-pairing of MVs)

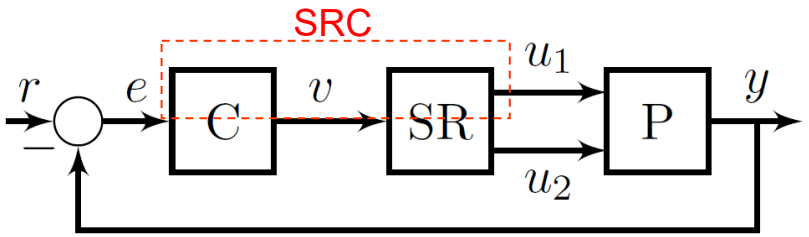
- Alternative MV-MV switching strategies:
  1. **Split-range control (SRC)**
  2. **Several controllers for same CV, but with different set points CV_s**
  3. **Input (valve) position control**



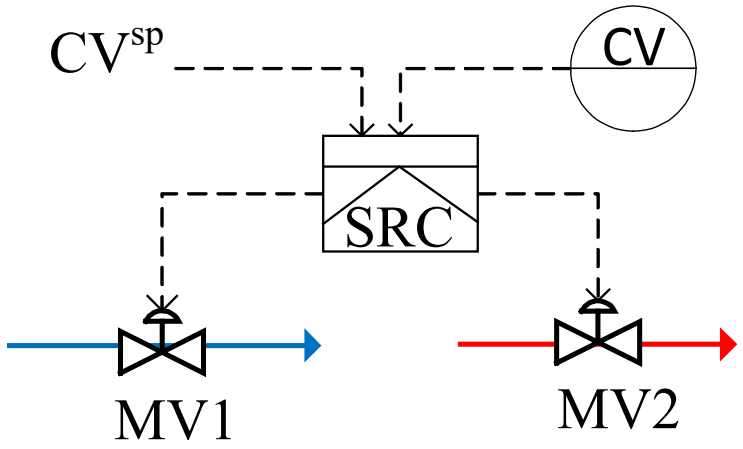
2. MV-MV switching

Alt. 1. Split-Range Control

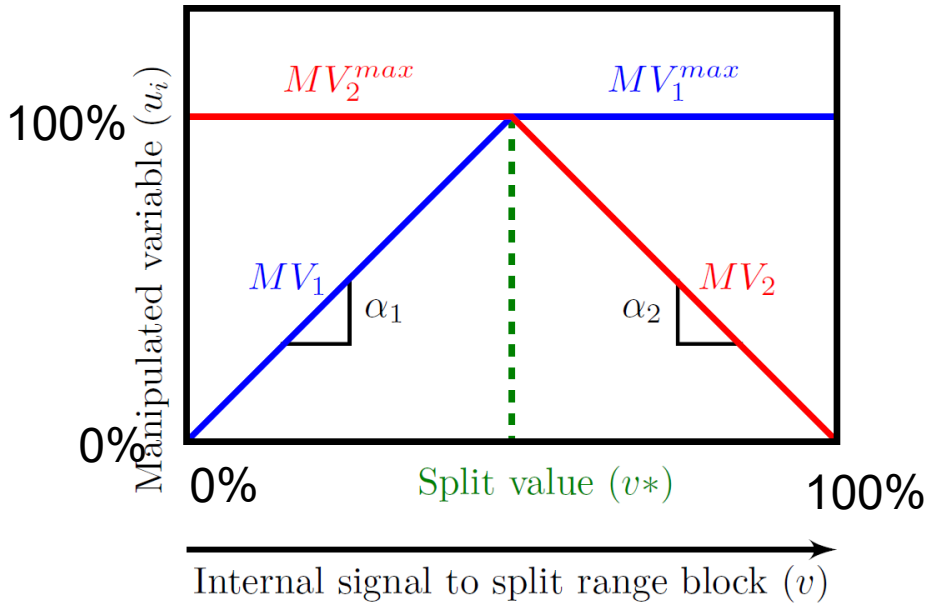
Block diagram:



Flowsheet:



Inside split range /SR) block:

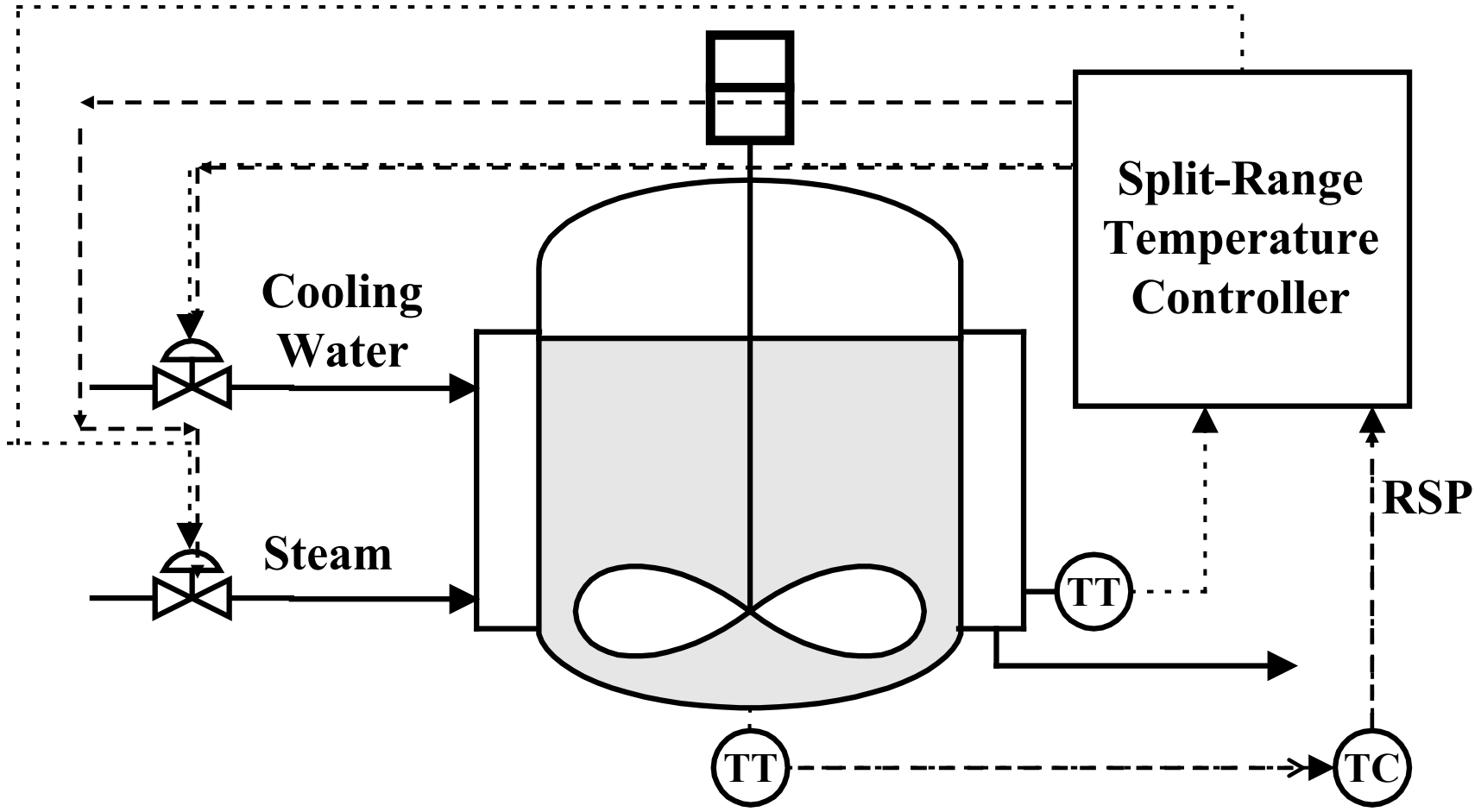


Note: One controller C is used for two MVs but v* is a design parameter which can be used to correct for different process gains

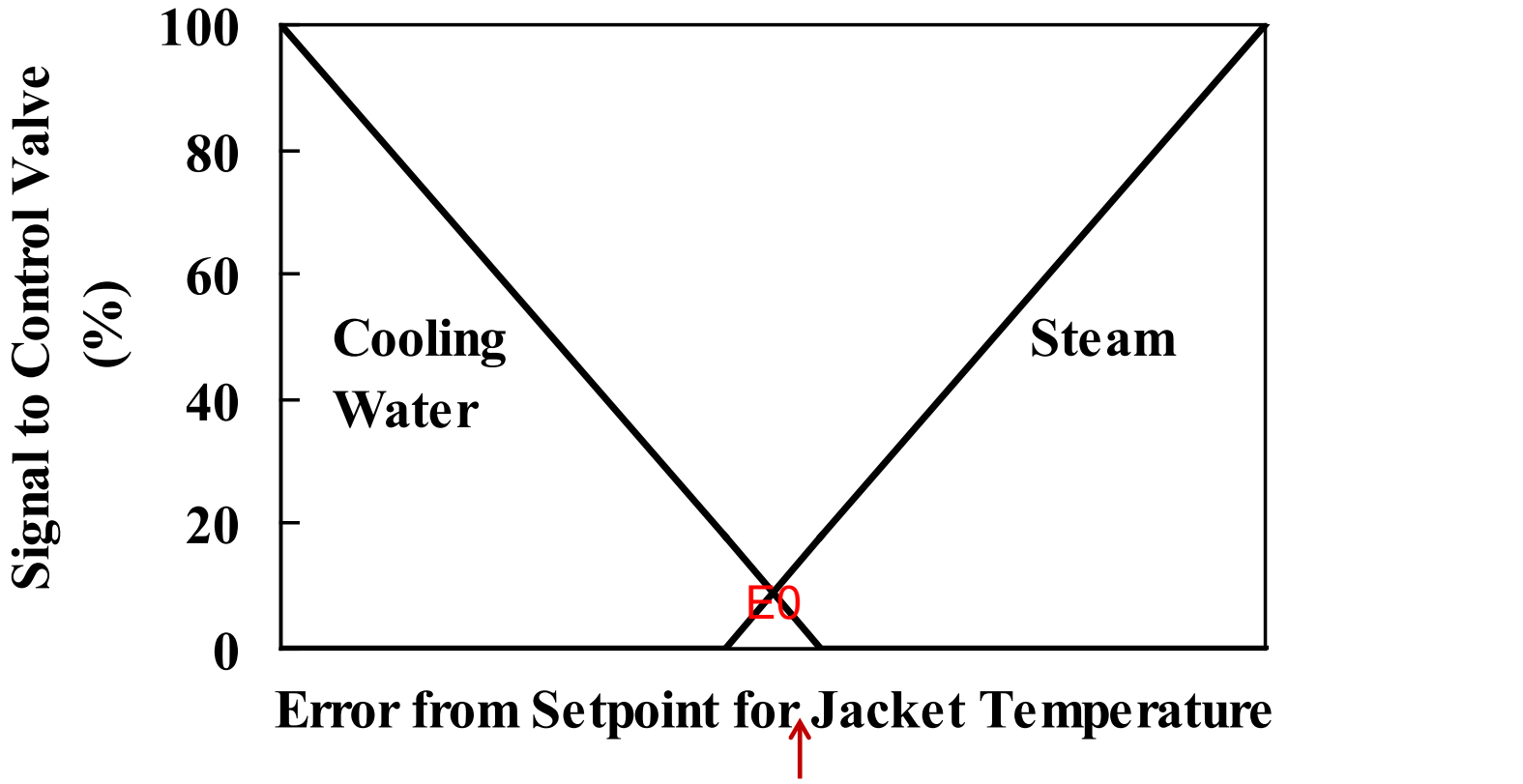
Example: MV-MV switching using Split Range Temperature Control

(Two MVs needed to cover whole range, one CV)

Split range control is used when we need to inputs to cover the whole output range (at steady state), for example, we need both heating and cooling in a house to control temperature.
The range is split so that only one input is active for control at a time



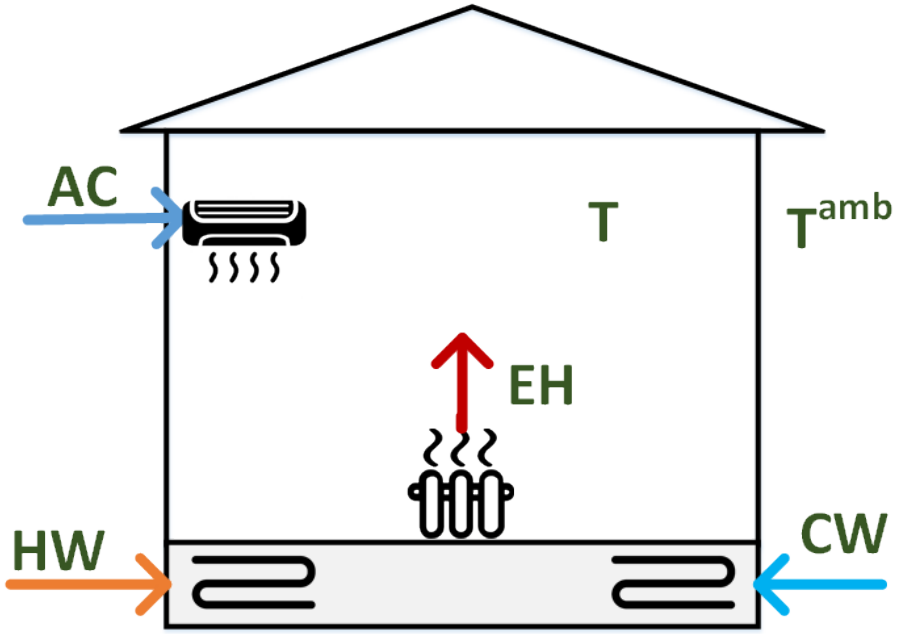
Split Range Temperature Control

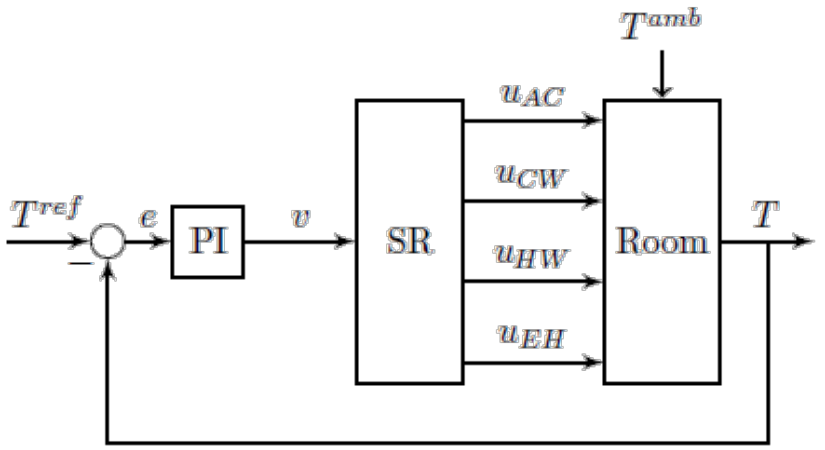


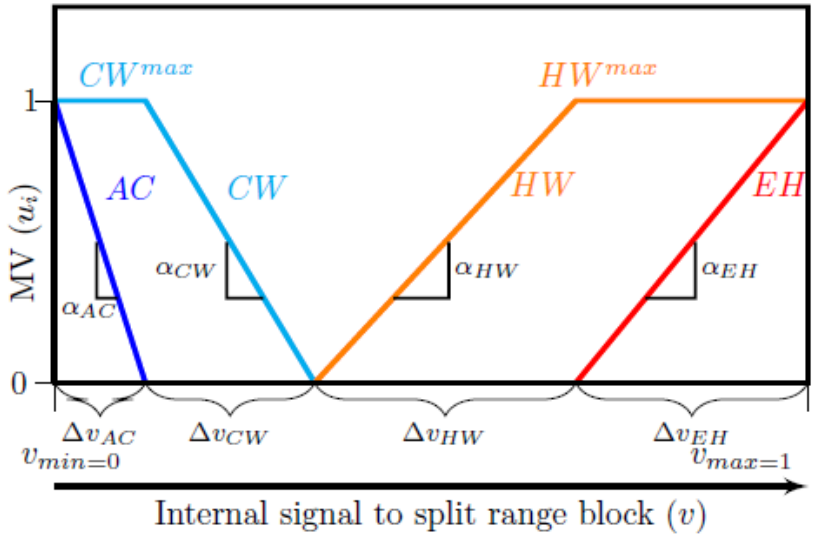
Note: may adjust the location er E0 to make process gains equal

A more complicated example using SRC

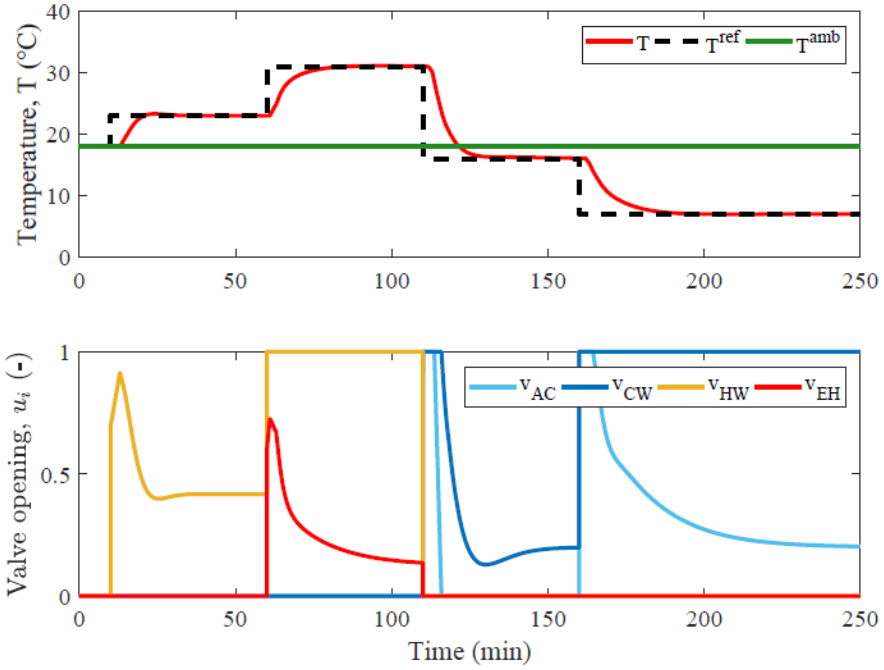
- Room temperature control
  - **4 MVs:** AC, CW, HW, EH
  - **1 CV:** room temperature (T)
    - $T_s = 21°C$

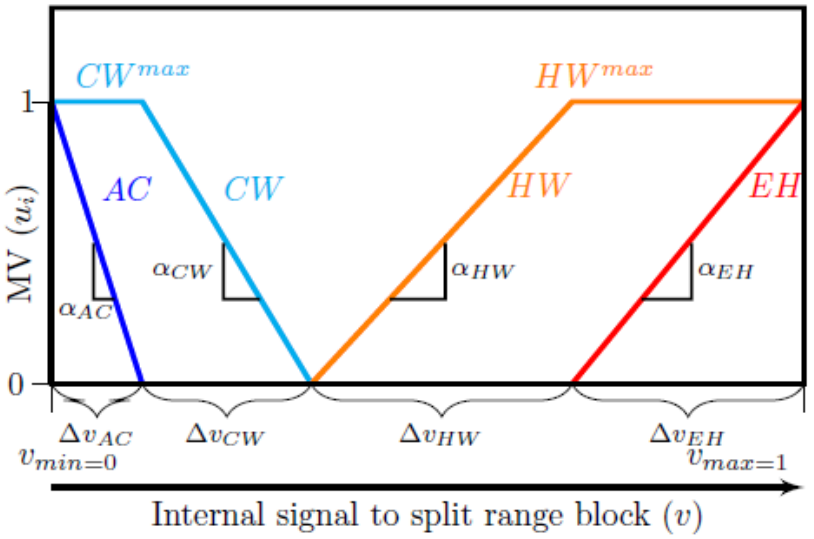






Simulation

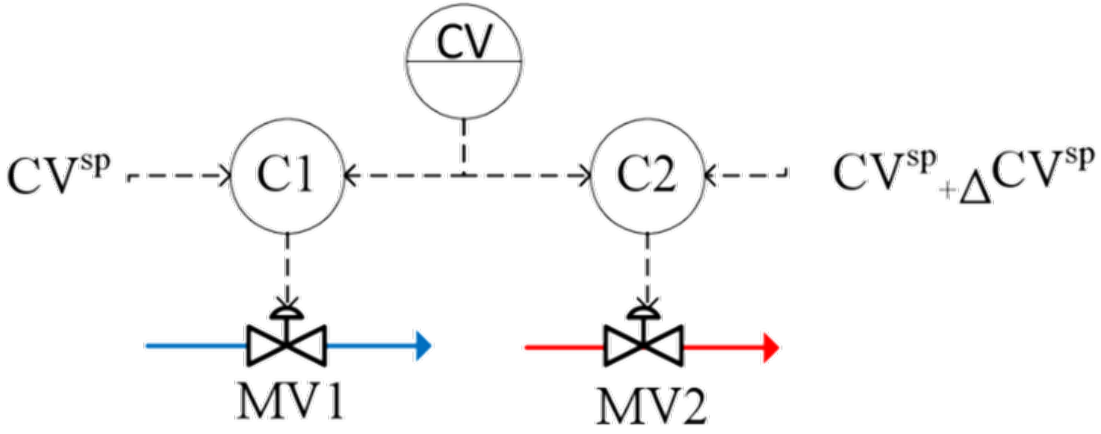

Temperature, T (°C)
T
T^ref
T^amb
Valve opening, u_i (-)
v_AC
v_CW
v_HW
v_EH
Time (min)


CW^max
HW^max
AC
CW
HW
EH
MV (u_i)
Δv_AC
Δv_CW
Δv_HW
Δv_EH
v_min=0
v_max=1
Internal signal to split range block (v)

MV-MV switching:

Alt. 2. Several controllers with different setpoints

- Two or more controllers with same CV
- Different setpoints ⇒ Only one controller active at a time.



Example

CV= room temperature

- MV1 = cooling
  CV^{sp} = 22°C

- MV2 = heating
  CV^{sp} = 20 + 2 = 20°C

Between 20°C and 22°C:
Temperature drifts with
Heating off (saturated) and
cooling off (saturated)

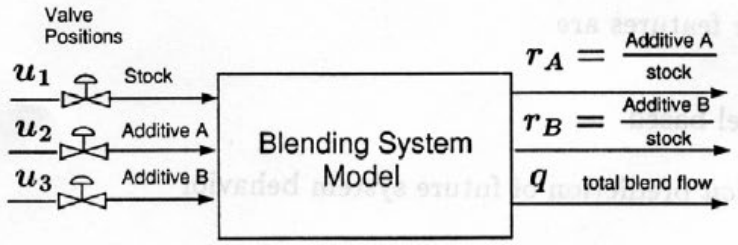
MV-MV switching
Alt. 3. Input (valve) position control (VPC)

- Keep the original loop (MV1-CV)
- Use MV2 to avoid saturation of MV1 (VPC)

- Advantage: No change in control of CV
- Disadvantages: Backoff in MV1 and control of MV1 can be slow

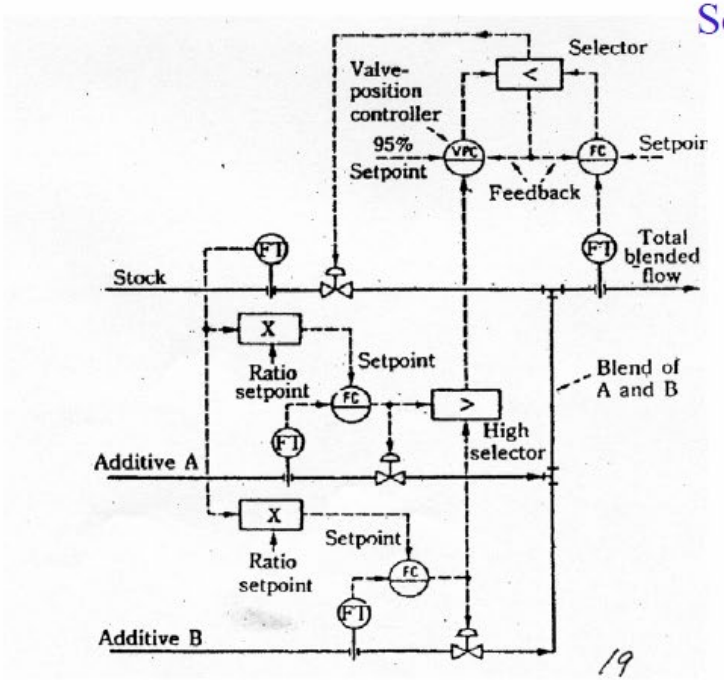
http://cepac.cheme.cmu.edu/pasilectures/lee/LecturenoteonMPC-JHL.pdf

Example 1: Blending System



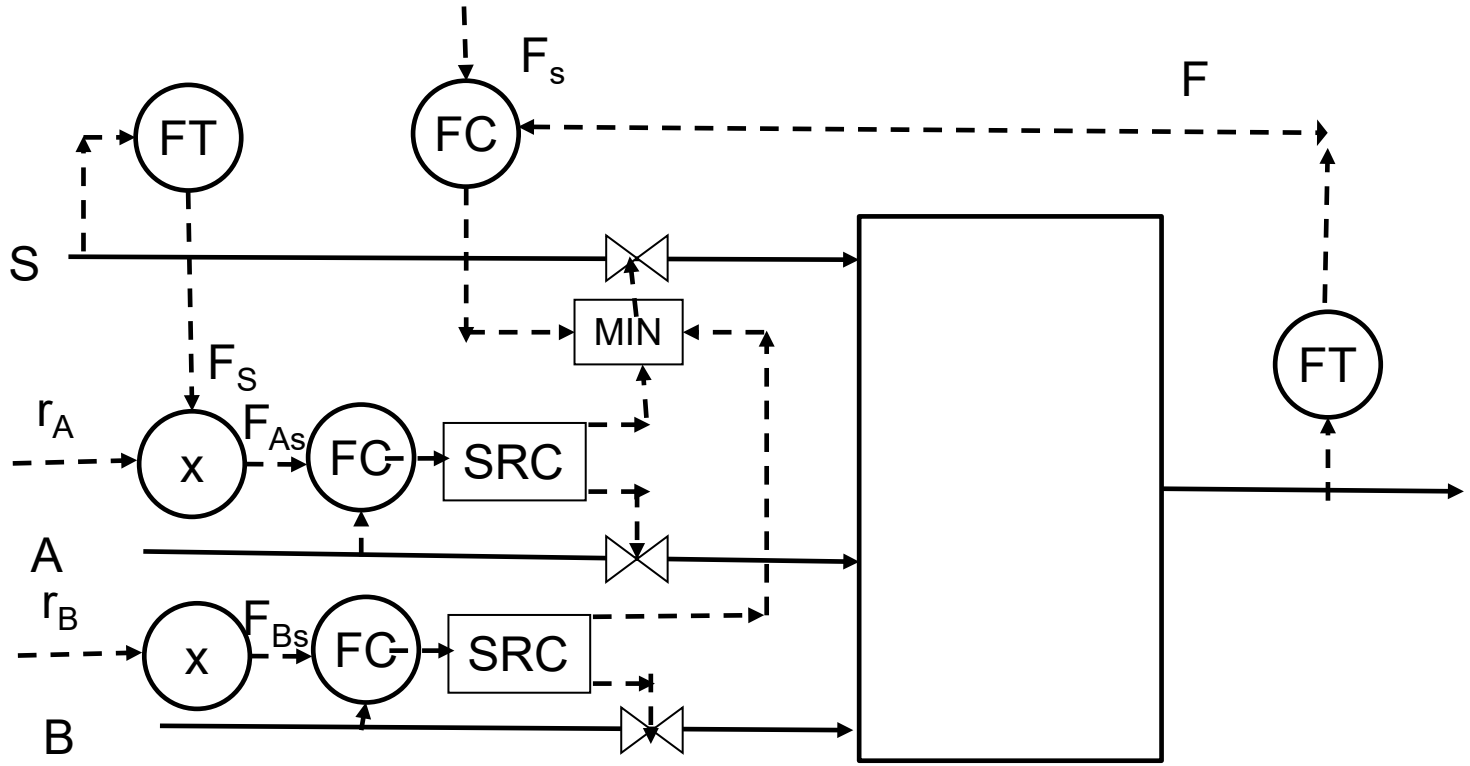
- Control r_A and r_B
- Control q if possible
- Flowrates of additives are limited

Classical Solution



Alt. 3. Valve position control:
- But get some back-off
- 95% of max. valve opening

Blending. Alt. 1. Split range control



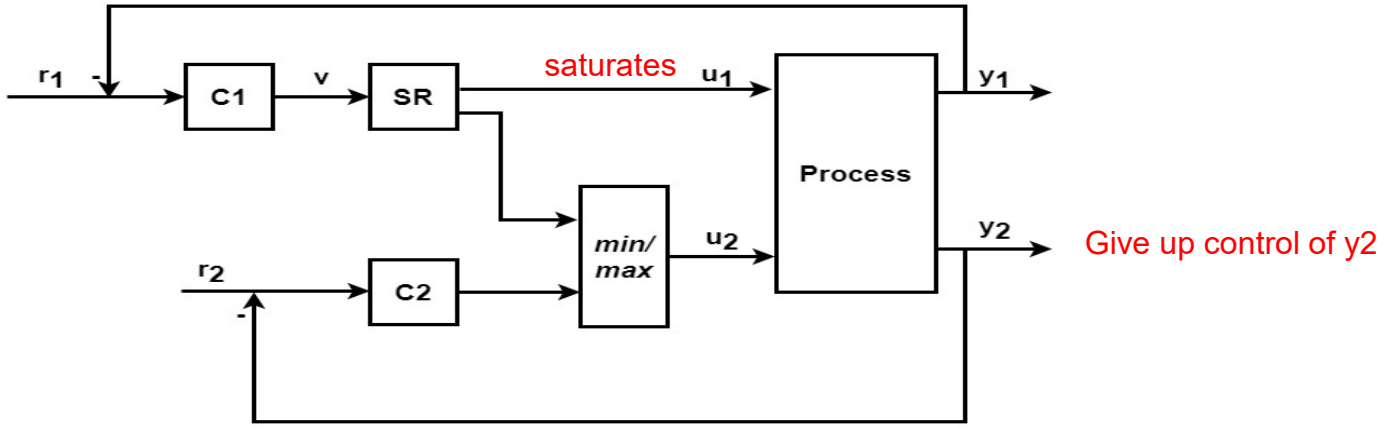
No back-off

3. MV-CV switching

- The MV that we are using to control an output (CV) saturates.

1. *Input saturation pairing rule* was followed (SISO): Do nothing.
   - Why? Because control of this CV should be given up anyway.
2. *Input saturation pairing rule* was **not** followed (MISO):
   - The CV that should be given up (y2) is then controlled by another MV (u2)
   - Implement an MV (u1)-MV (u2) switching strategy to maintain control of y1.

e.g. split range control with a min/max selector.



3. MV-CV switching. Example

Example: Control outlet temperature and flow of heat exchanger

High priority CV:

$y_1=T_H=T_H^{sp}$

Low priority CV:

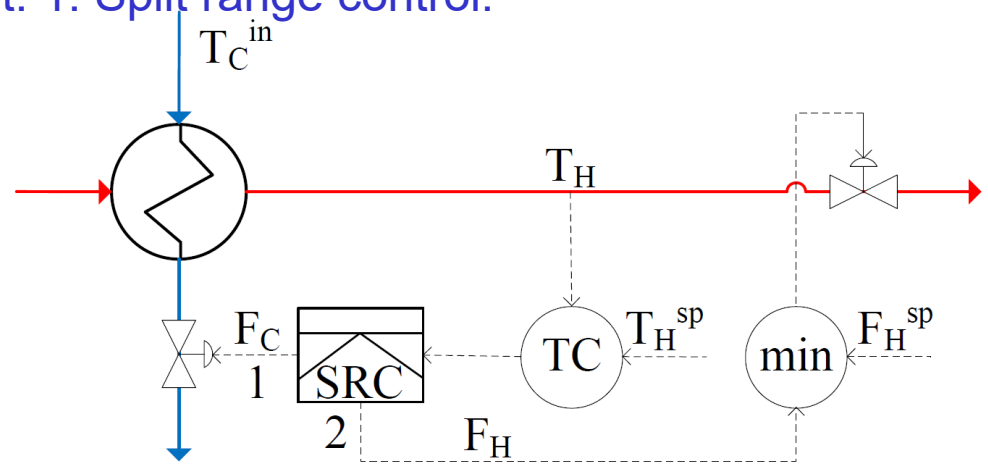
$y_2= F_H=F_H^{sp}$

Available MVs:

$u_1=z_C$, $u_2=z_H$ Both valves may saturate at max

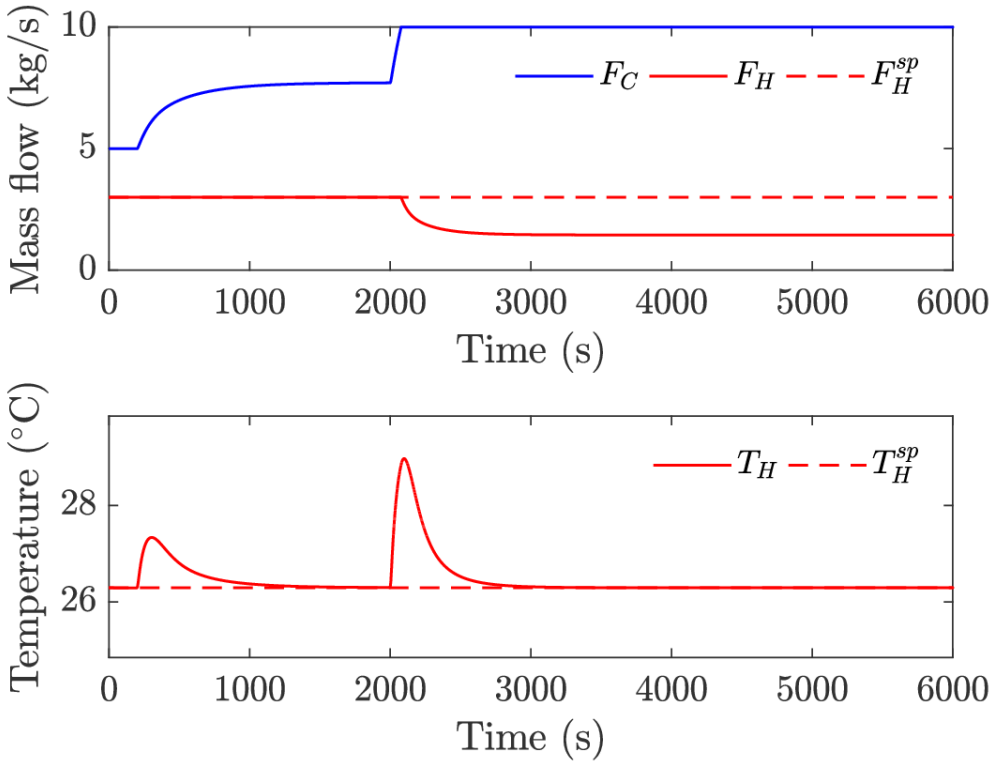
Disturbance: T_C^{in}

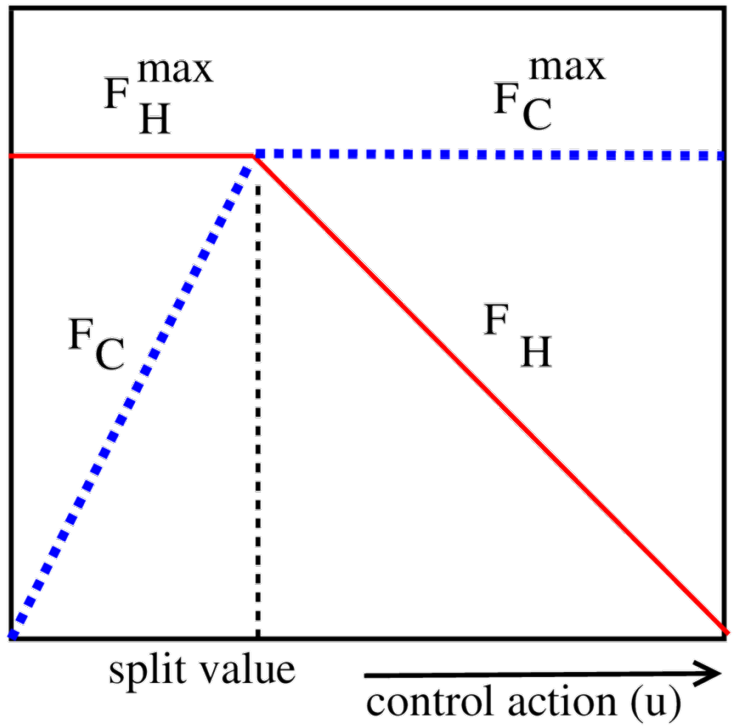
Alt. 1. Split range control:



A. Reyes-Lúa, C. Zotică, S. Skogestad, 2018. *Optimal Operation with Changing Active Constraint Regions using Classical Advanced Control*. In: 10th ADCHEM. IFAC, Shenyang, China.

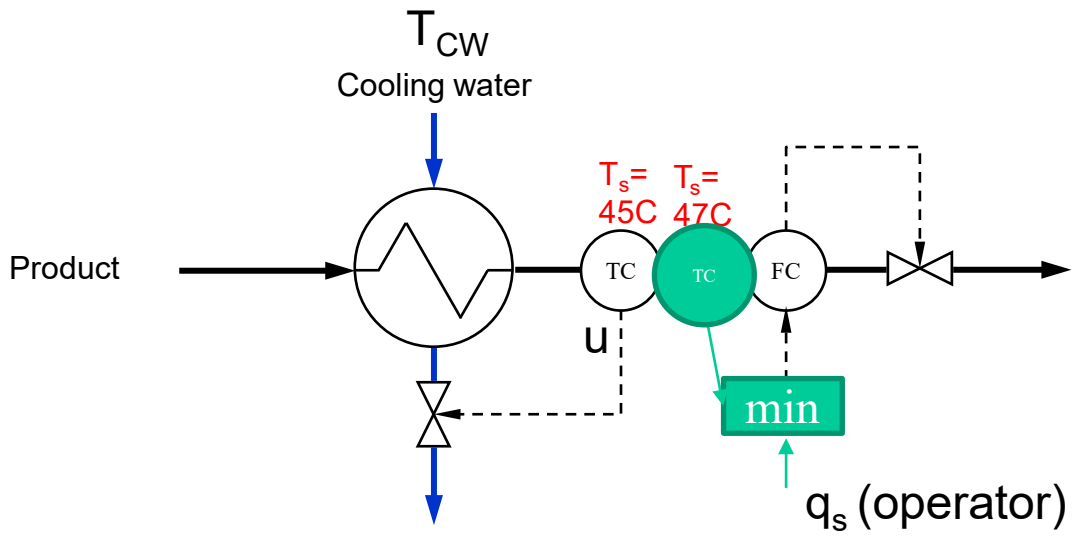
Simulations split range control….





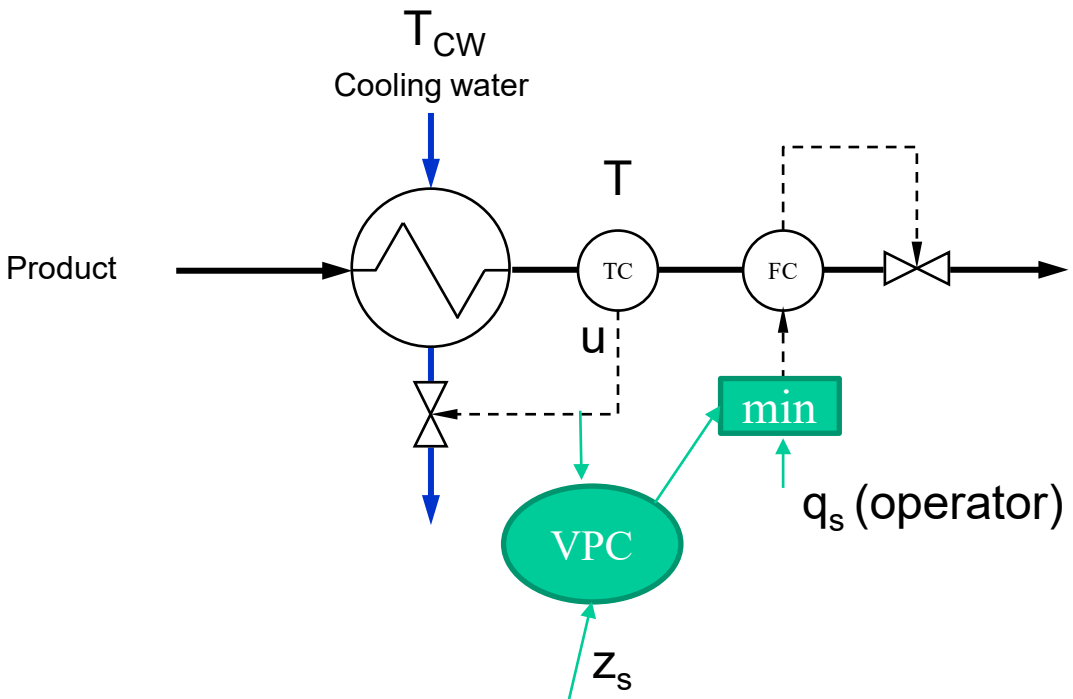
A. Reyes-Lúa, C. Zotică, S. Skogestad, 2018. *Optimal Operation with Changing Active Constraint Regions using Classical Advanced Control*. In: 10th ADCHEM. IFAC, Shenyang, China.

Alt. 2. Two temperature controllers with different setpoints (slightly suboptimal).



Comment: 1. Similar to SRC, but avoids the SRC block.
2. Advantage: Two separate controllers
3. Disadvantage: Temperature a bit higher when we reach CW-constraint

Alt.3 «valve position control» (suboptimal)



Setpoint valve position for CW = at 95% of max. opening (so some backoff)

Comment: 1. Has the advantage of not changing the controller for T.
2. With q_s large (infeasible setpoint) one can have q=qmax (as long as q_{CW} < max)
3. But cannot quite achieve fully open CW valve (so some loss = backoff)

Rules

- Control actice constraints
- MV that may saturate should be paired with CV that may be given up
  - Alternative interpretation of rule:
    - Pair high-priority controlled variable (y, CV) (cannot be given up) with a manipulated variable (u, MV) that is not likely to saturate.
- TPM should be located close to bottleneck
  - Reason: Avoid «long loop» (and resulting backoff) when we have max. throughput
  - Bottleneck: Last constraint to be reached as we increase throughput
- *Arrange the inventory control loops (for level, pressures, etc.) around the TPM location according to the radiation rule (Georgakis)*
- *Select "sensitive/drifting" variables as controlled variables CV_2 for regulatory control.*

More rules

- Never control the cost function J (at fixed value)
  - May give infeasibility and certainly non-optimal operation
- Never do inventory control across TPM-location
  - Corresponds to pairing on zero

Comment: Use of extra inputs

Two different cases

1. **Have extra dynamic inputs (degrees of freedom)**

   Cascade implementation: "Input resetting to ideal resting value"

   Example: Heat exchanger with extra bypass

   Also known as: Midranging control, valve position control

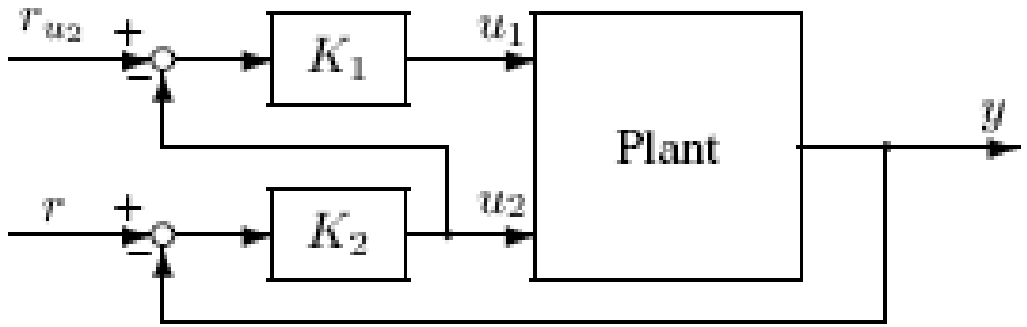
2. Need several inputs to cover whole range (because primary input may saturate) (steady-state)

   Split-range control

   Example 1: Control of room temperature using AC (summer), heater (winter), fireplace (winter cold)

   Example 2: Pressure control using purge and inert feed (distillation)

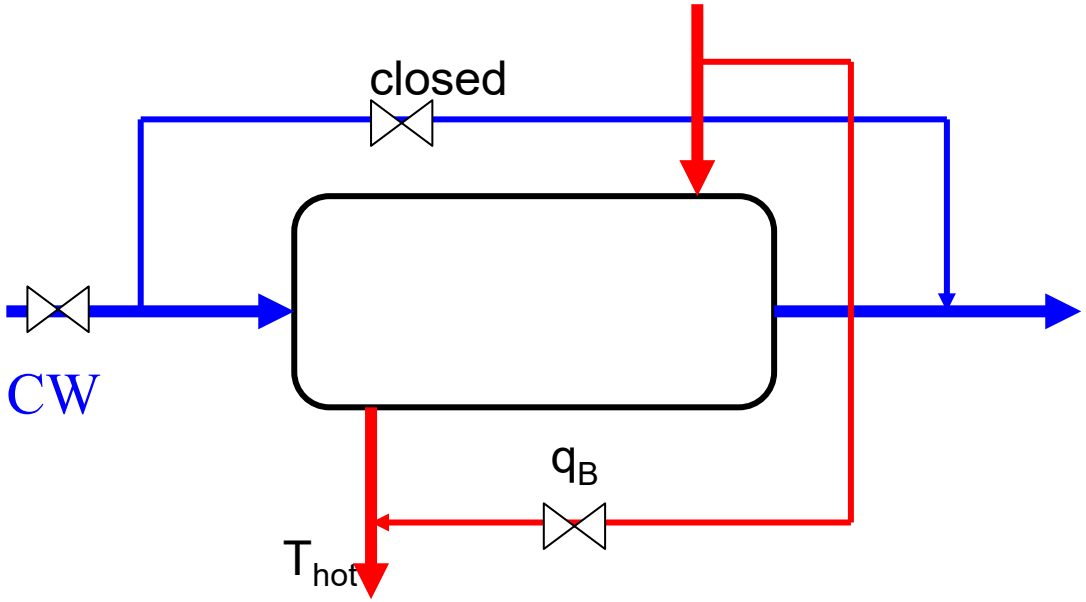
Extra inputs, dynamically



(b) Extra inputs u_2 (input resetting)

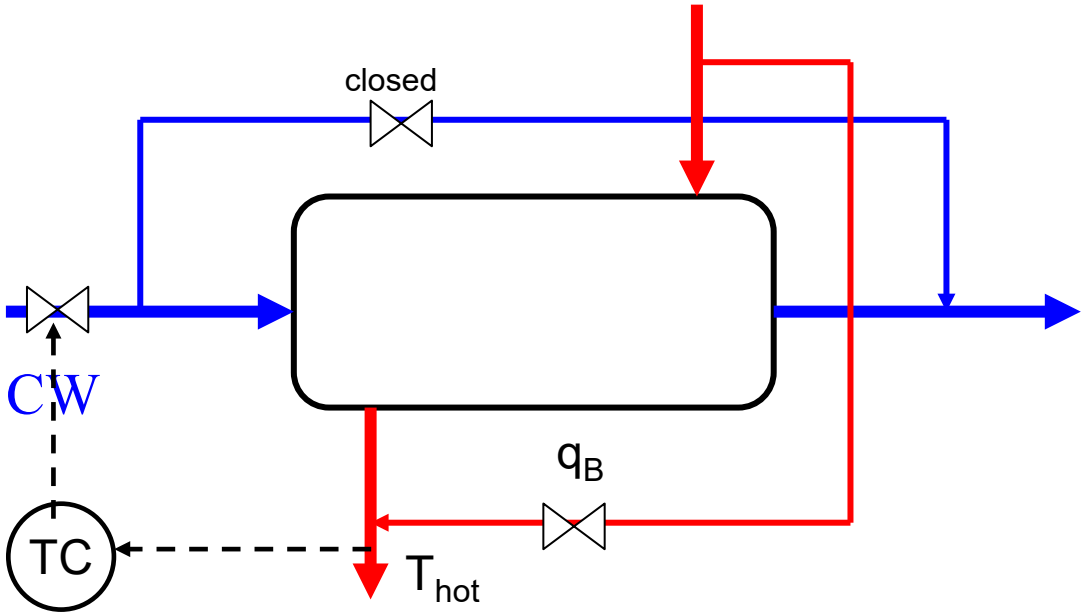
- Exercise: Explain how “valve position control” fits into this framework. As en example consider a heat exchanger with bypass

QUIZ: Heat exchanger with bypass



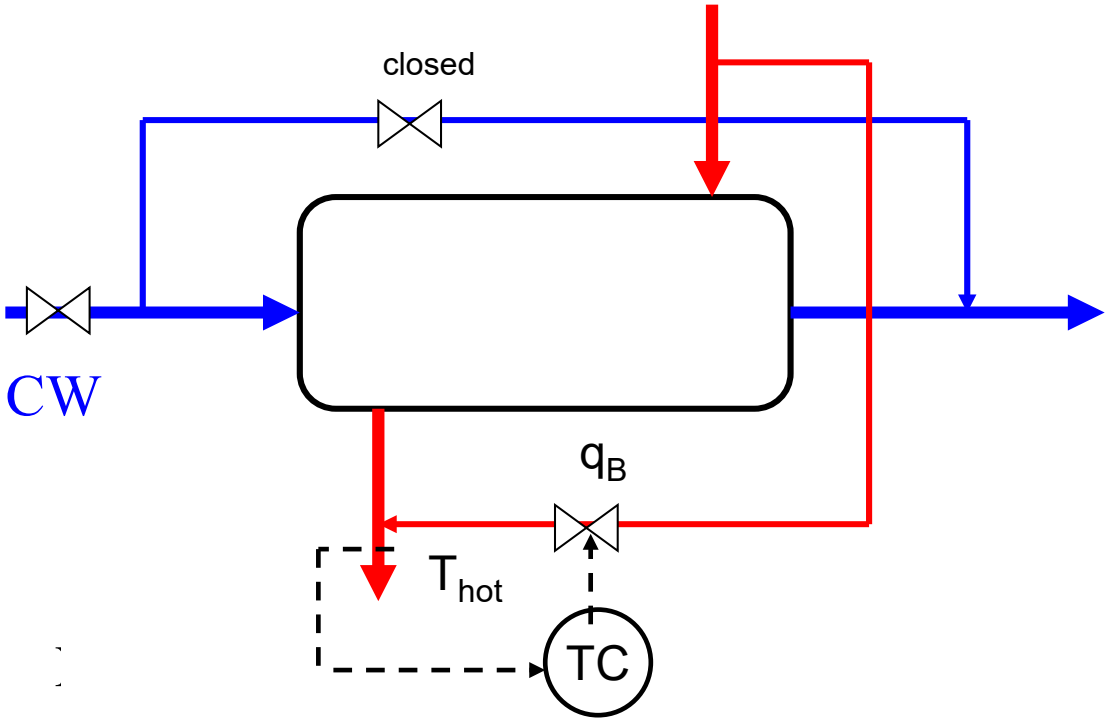
- Want tight control of T_{hot}
- Primary input: CW
- Secondary input: q_B
- Proposed control structure?

Alternative 1



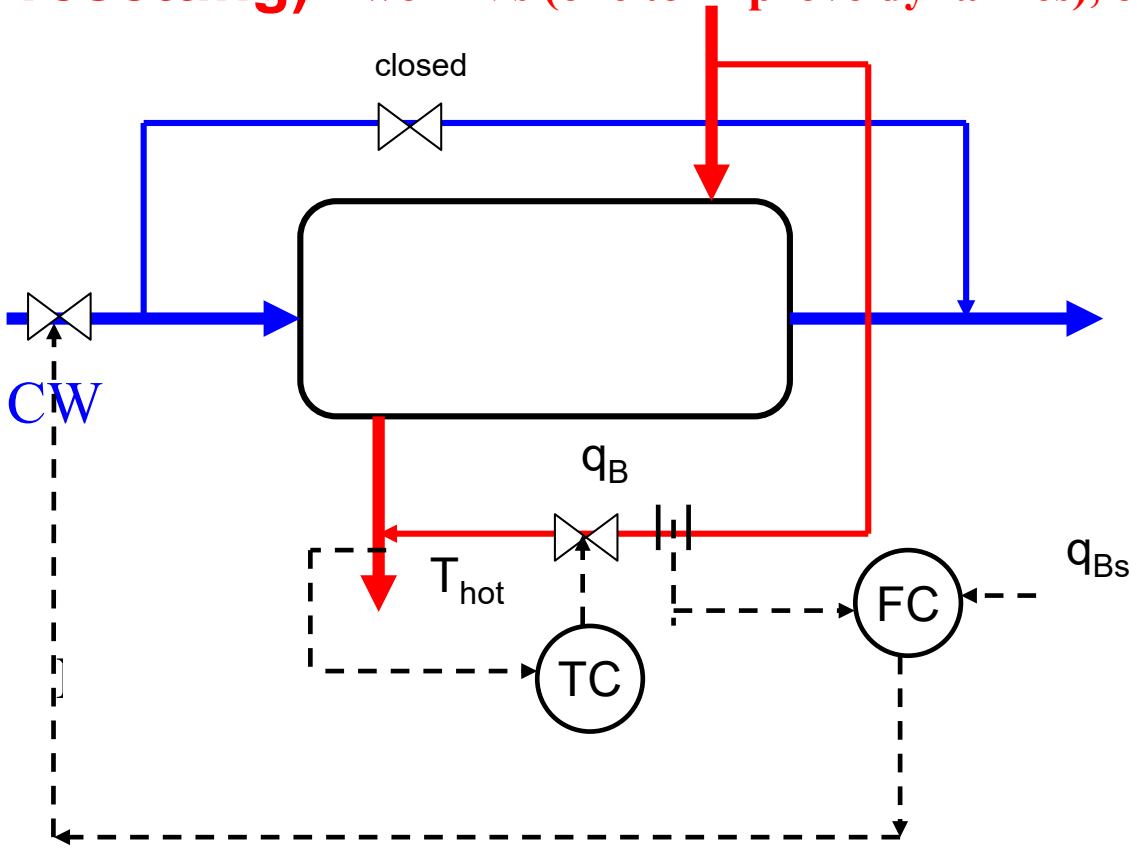
Use primary input CW: TOO SLOW

Alternative 2



Use “dynamic” input q_B
Advantage: Very fast response (no delay)
Problem: q_B is too small to cover whole range
+ has small steady-state effect

Alternative 3: **Valve position control (input resetting)** Two MVs (one to improve dynamics), one CV



TC: Gives fast control of T_{hot} using the "dynamic" input q_B
FC: Resets q_B to its setpoint (IRV) (e.g. 5%) using the "primary" input CW

IRV = ideal resting value

Also called: "valve position control" (Shinskey) and "midranging control" (Sweden)

Outline

- Skogestad procedure for control structure design

I Top Down

- Step S1: Define operational objective (cost) and constraints
- Step S2: Identify degrees of freedom and optimize operation for disturbances
- Step S3: Implementation of optimal operation
  - What to control ? (primary CV's) (self-optimizing control)
- Step S4: Where set the production rate? (Inventory control)

II Bottom Up

- Step S5: Regulatory control: What more to control (secondary CV's) ?
- Step S6: Supervisory control
- Step S7: Real-time optimization

Step S7. Optimization layer (RTO)

- *Purpose:* Identify active constraints and compute optimal setpoints (to be implemented by supervisory control layer)
- *Main structural issue:* Do we need RTO? (or is process self-optimizing)

- RTO not needed when
  - Can “easily” identify change in active constraints (operating region)
  - For each operating region there exists self-optimizing variables