Advanced Process Control

Practical examples from a chemical industry

Krister Forsman

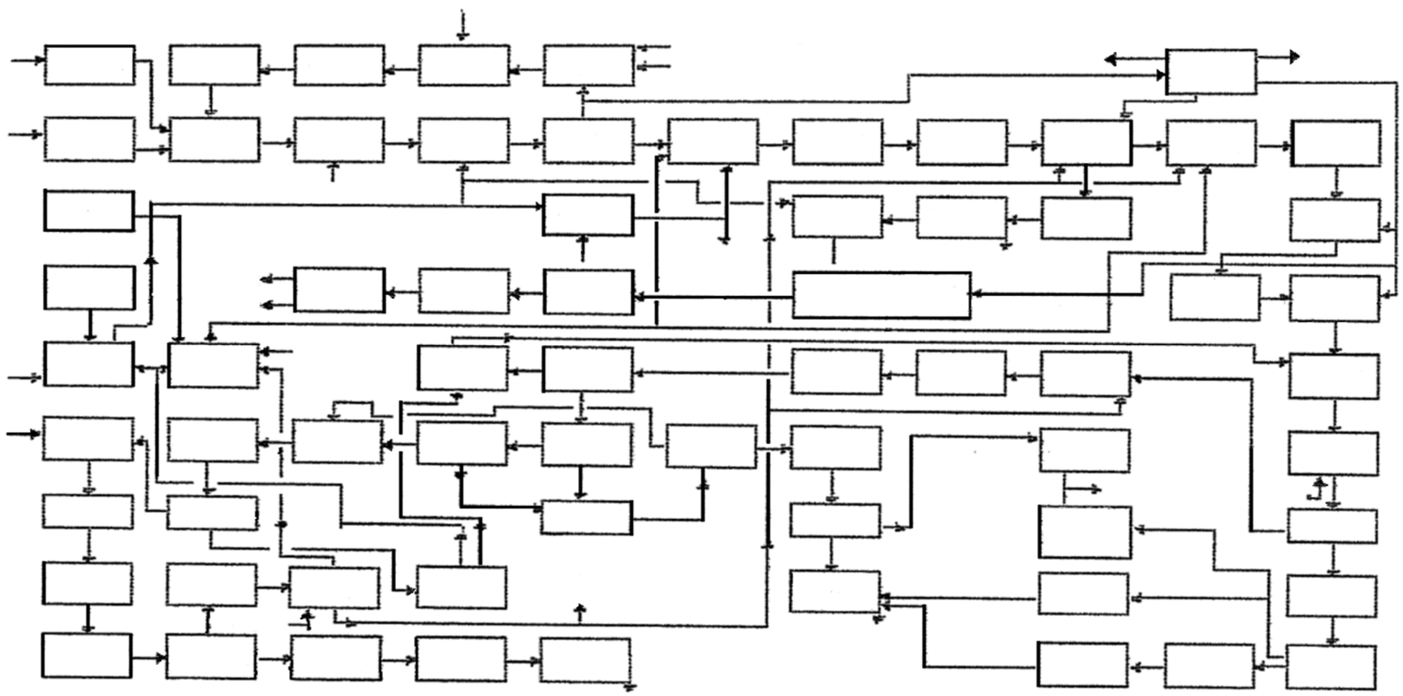
2024-10-16

Many different types of processes to control

- Reactors
  - Tank reactors, Tube reactors, two phase, three phase
  - Continuous, batch, semi-batch
- Heat exchangers
  - Liquid – liquid, steam - liquid
- Distillation columns
  - Continuous, batch
- Evaporators
- Vaporizers
- Crystallizers
- Centrifuges
- Decanters
- Filters
- Dryers
- Boilers
- …

In order to optimize controls you need to have good process knowledge!

Many plants have complex topology



Typical tasks for the control group

Improve productivity by decreased variation and increased automation.

- Smarter control structures, e.g. feedforwards, mid-ranging, cascades, maximizing control, ratio-in-cascade, split-range, conditional control
- PID control parameter tuning
- Plant wide control
- Introduce new controllers
- Support in design and commissioning of new plants

Practical PID control; 1

- The four most important parameters in a PID-controller are
  - Gain
  - Integration time
  - PV filter time constant
  - Beta factor

$$u(s) = K_c \left\{ \beta r(s) - \frac{1}{1+sT_f} y(s) + \frac{1}{sT_i} \left(r(s) - \frac{1}{1+sT_f} y(s) \right) \right\}$$

- The PV filter prevents the controller from acting on noise that is not within control bandwidth anyway.
  - There is no other way to achieve this.

- Example from Perstorp plant: 182 PID-controllers
  - 101 of those have $T_f > 0$.
  - 6 of them have derivative action

Note: PV = process variable = y

Practical PID control; 2

- Derivative action is hardly ever necessary or useful
  - **The filtering paradox**: Since derivation is very sensitive to noise, the noise filtering has to be forceful. But then we also delay the information we want the controller to act on, which is contrary to the motivation for using D action.

- Krister's rule of thumb:
  - If you have to use D-action, you probably have the wrong control structure, or too few measurements.
  - Note: This is not true for other applications of automatic control

- Exception
  - For integrating processes with time constant D-action can provide big control performance gains.

$$P(s) = \frac{k_v}{s(1+sT)} e^{-sL}$$

  - If derivative action is to be used, the controller implementation should be serial, not parallel.

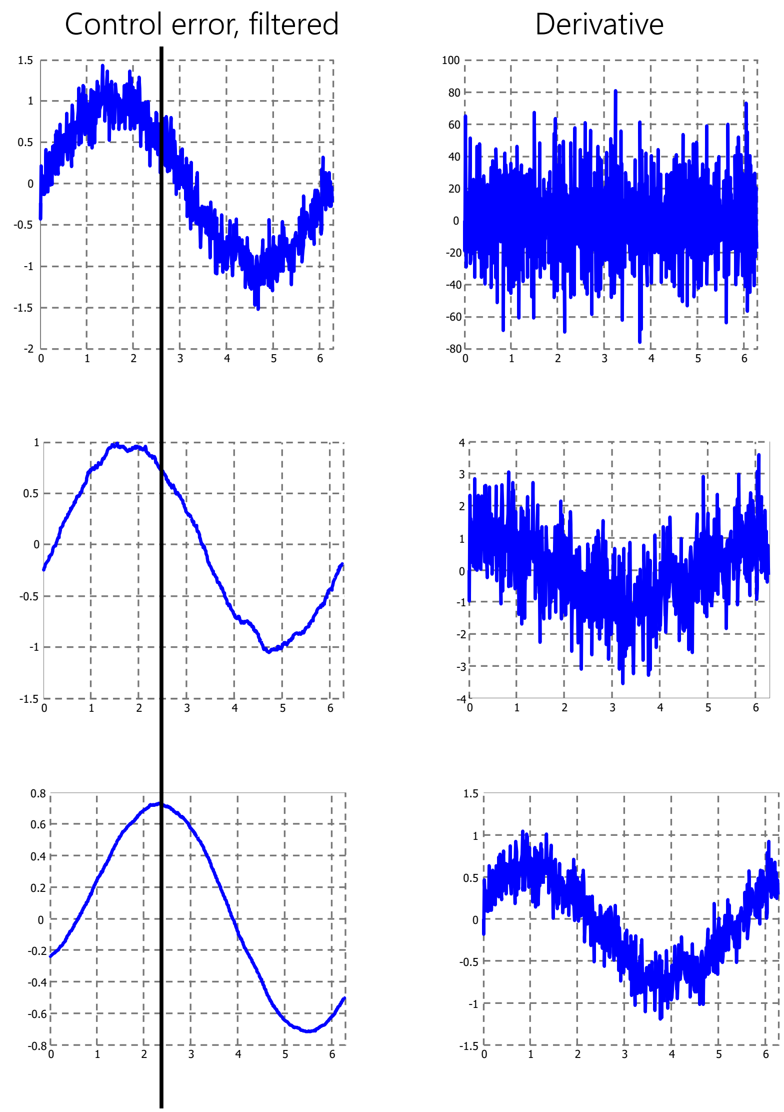
D-action / filtering paradox

No filtering

Some low pass filtering

Heavy low pass filtering

But now the input signal is heavily phase shifted too…



Practical PID control; 3

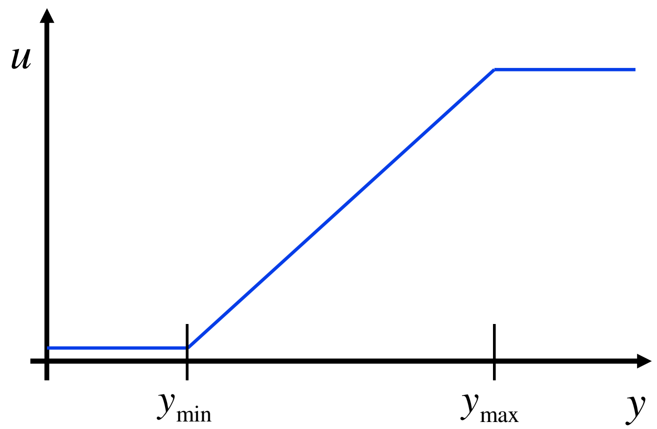
- Purely proportional control (P-only) is very useful in some contexts.
- In some applications setpoint adherence is not important
  - Other aspects are more important, and it is enough to keep y within certain bounds.
  - Main example: buffer levels

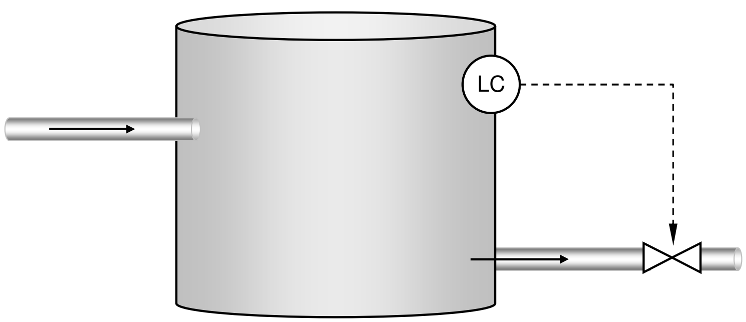
- However, most industrial control systems have a flaw in the implementation:
  - They allow the operator to change setpoint. What we really want is a table.
  - Two parameters: for which value of y should u=0% and when should u=100%
- The classical implementation has three parameters. (I consider the setpoint to be a parameter.)

$$u = K_c(r - y) + b$$

- A more serious problem is that the PID-controller block has "bumpless transfer":
  - Meaning that when the operator switches from MAN to AUTO, the bias is changed automatically.
  - In other words, the entire table is changed.

P-only control for buffer levels





In this application the actual level is not important.
The only thing that matters is that it is not too low or too high.
"There is no setpoint"

The benefit of using P-only control is that there is less variation in the manipulated variable (in this case the outgoing flow).

Variations in the inlet flow are absorbed by the buffer, rather than being passed on to the outgoing flow.

Bumpless transfer

$$u(t) = K_c e(t) + \frac{K_c}{T_i} \int_0^t e$$

- Bumpless transfer is a feature implemented in all modern control system.
- For PI-controllers it is really beneficial:
  - When the operator changes operational mode from AUTO to MANUAL the output u freezes.
  - The PV (y) drifts away from the setpoint.
  - When we switch back to AUTO, we don't want the output to make a sudden step
  - So internally the integral part is set to a value that absorbs the proportional part in such a way that the new output is = to the output we had just before we switched to AUTO.

- But for P-controllers, the only thing available to make the transition smooth is the bias.
  - So if we have bumpless transfer here, then the table changes everytime we go between MAN and AUTO.

$$u = K_c(r - y) + b$$

How many parameters does a PID controller have?

Perstorp
A Subsidiary of PETRONAS Chemicals Group

- In Emerson DeltaV, the standard PID controller has 65 parameters
  - Most of them are binary. We probably use 20-30 of those actively.

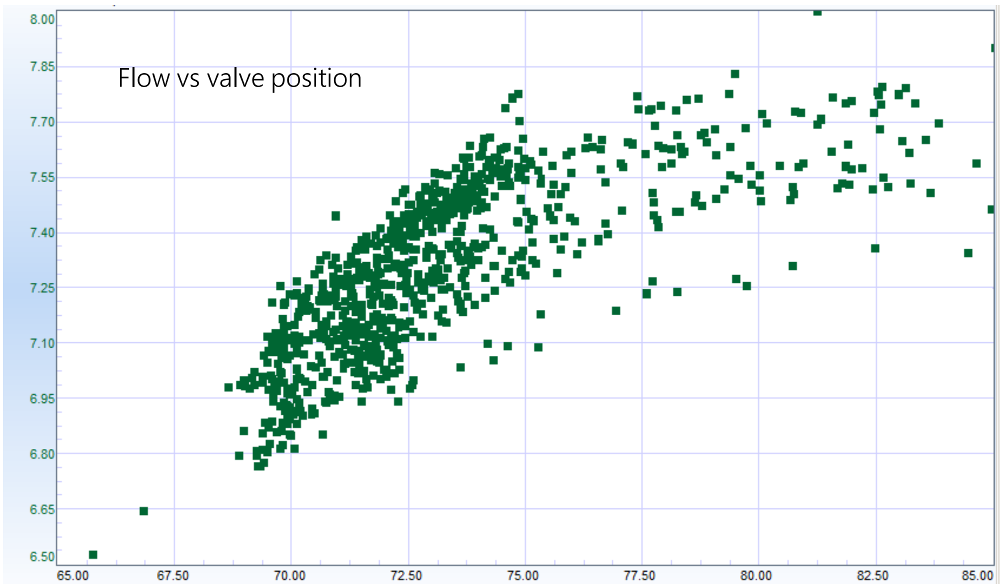
Basics

Feedback control, causality and such

Perstorp

Why we need process control

- Our processes are not perfect, and not perfectly predictable.
  - We need to compensate for disturbances



- If all process equipment, all raw material, all utilities etc were 100% known and predictable, we wouldn't need process control.
  - We wouldn't need any measurements either!

Pitfalls in using process data for modeling

- When modeling a process, using historical data can be very tricky.
- Some very common mistakes are explained by the examples below.
- The common theme is that feedback control ”reverses causality”
  - In the process itself (open loop) the MV is the independent variable and the CV is the dependent variable.
  - For a feedback controlled process, the CV is the independent variable, and the MV is the dependent variable.
- Causality: ”A precedes B in time”

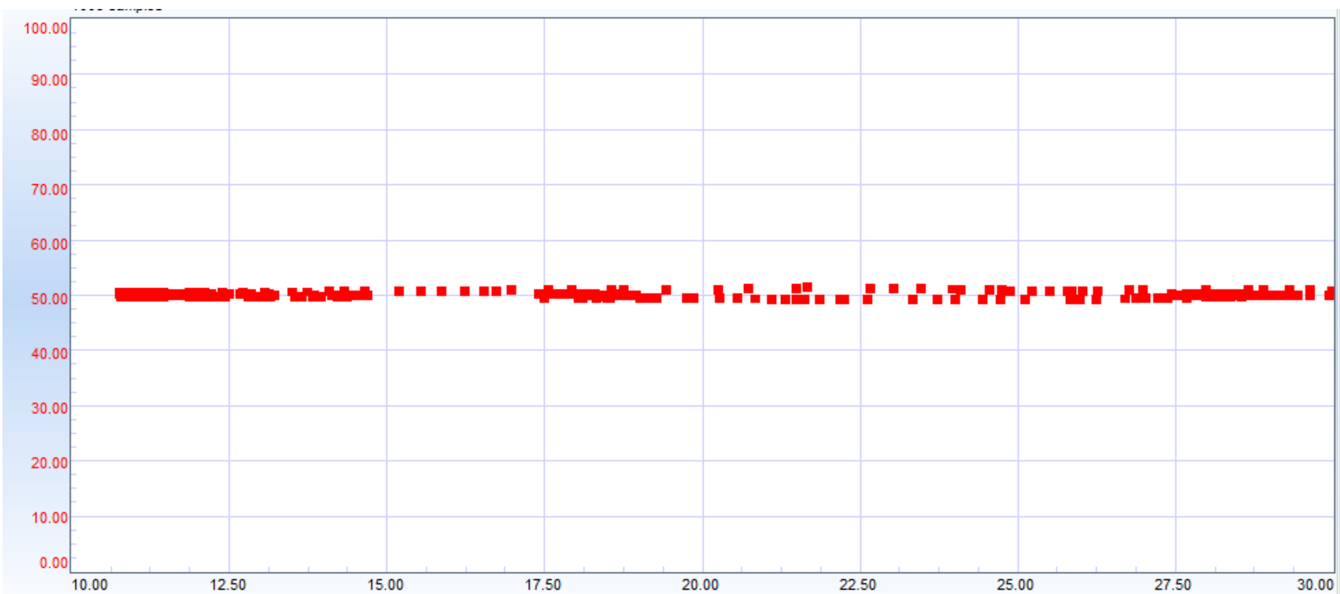
MV = manipulated variable (u)
CV = controlled variable (y)

MV-CV plot; Example 1; Level controller

Perstorp
A Subsidiary of PETRONAS Chemicals Group

What can you say about the process, based on the data below?

CV

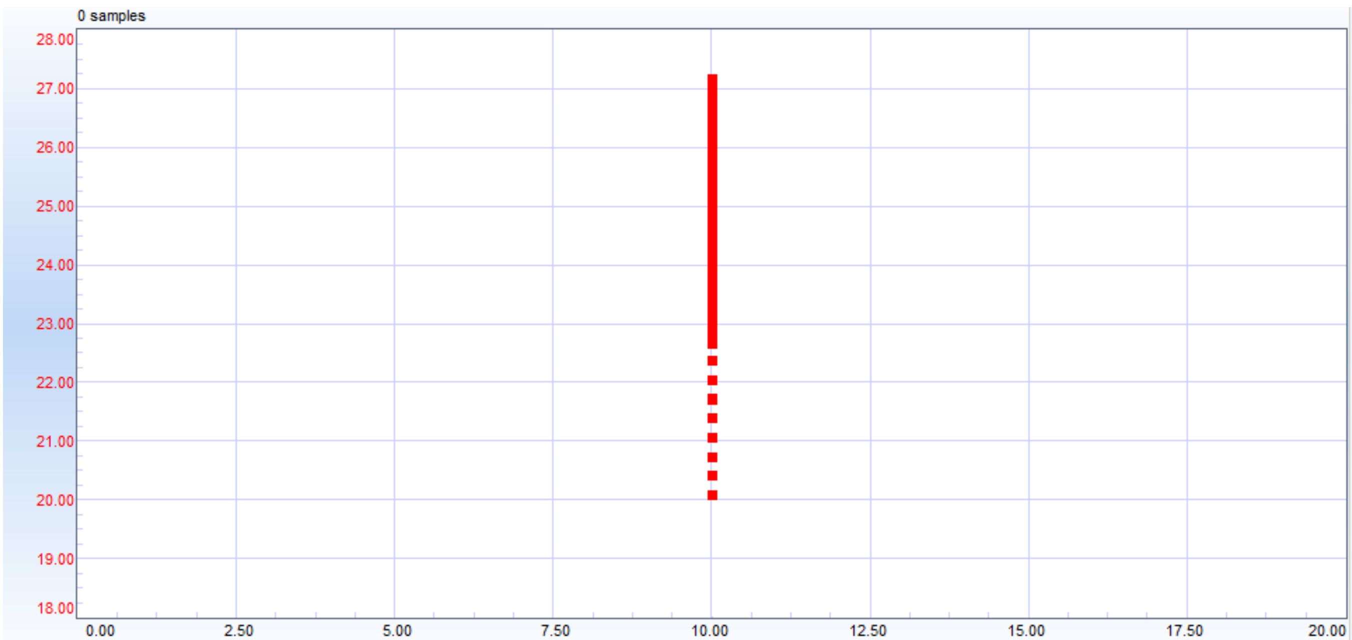


MV

MV-CV plot; Example 2; Temp controller

What can you say about the process, based on the data below?

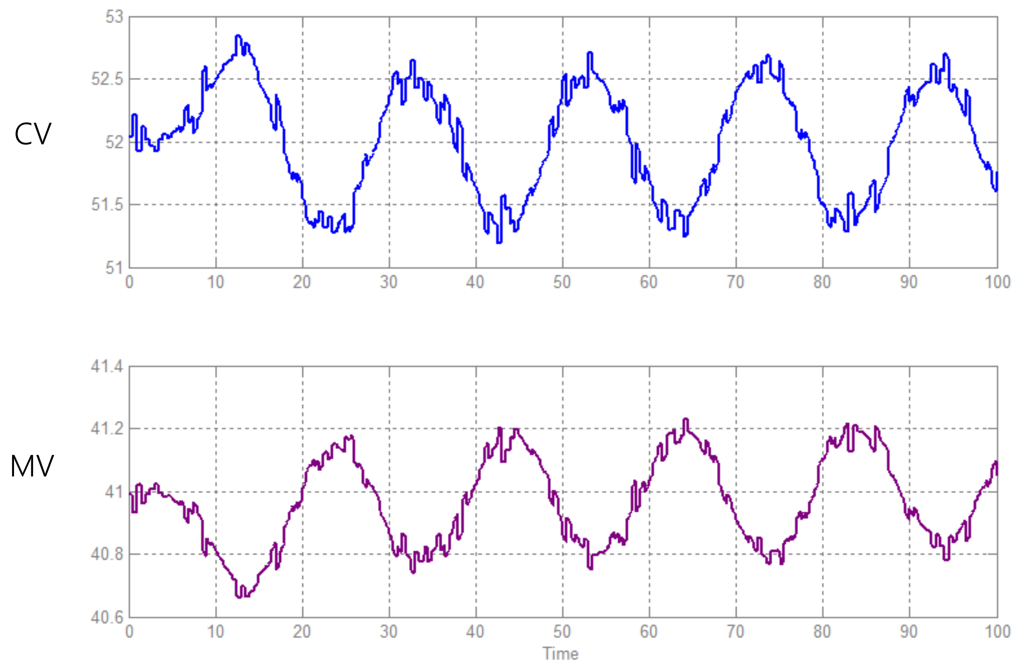
CV

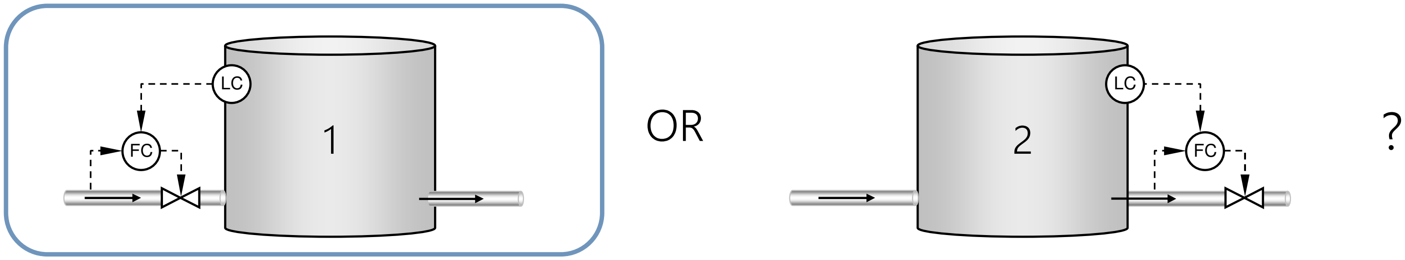


MV

Determine MV action; Example 1

- Data from a level control loop in Auto.
- Determine if the controller manipulates the upstream or the downstream flow.
- Setpoint is constant = 52





Careful when modeling on closed loop data

- Conclusion from these examples:
  Normally, **you can't use historical data from normal operations to model the process**.
  - Not even with advanced methods like anything from machine learning

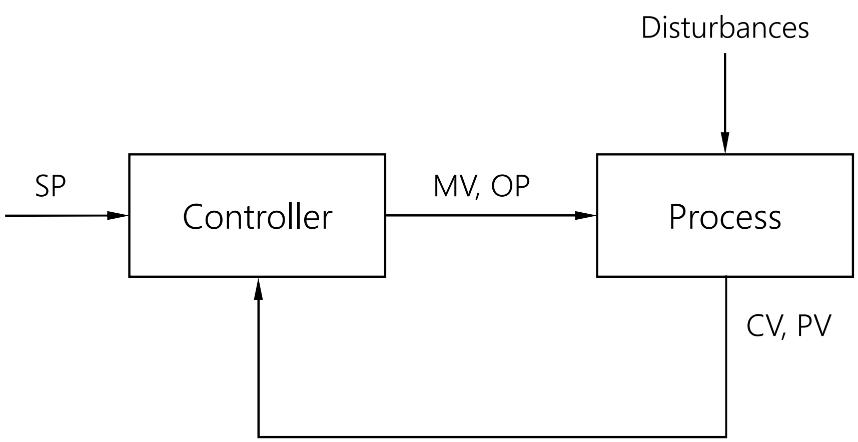
- Almost all variable dependencies known to plant staff and engineers are already used to some extent for controlling the process.

- You will not find the relevant correlations.
- You will find irrelevant correlations.

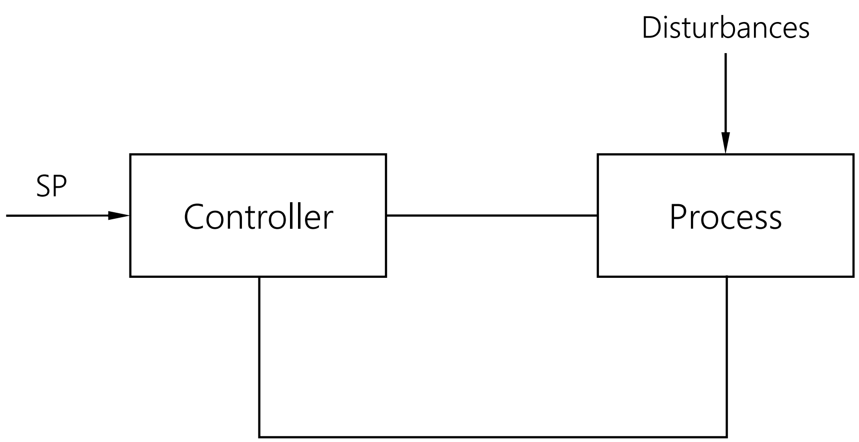
- Not all machine learning / AI specialists are aware of this.

Arrows may be misleading in block diagram

Traditional representation of a feedback loop

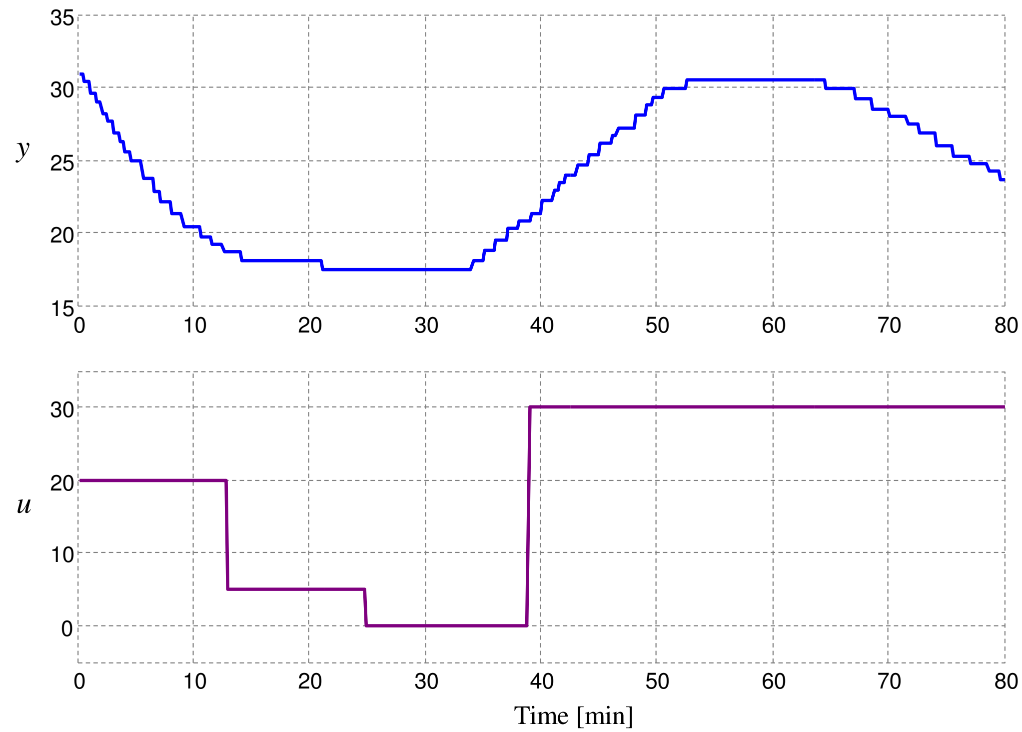


Maybe a more correct picture?



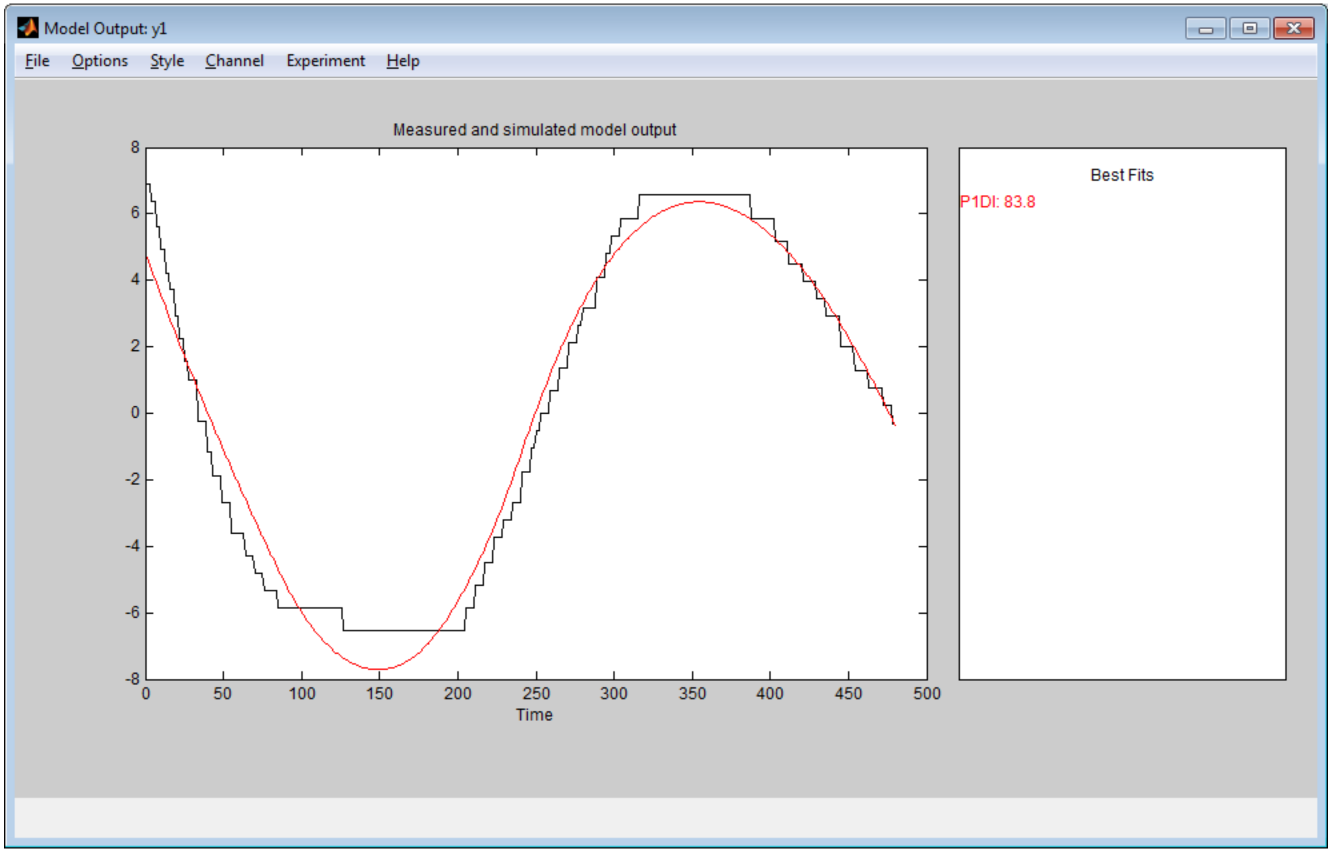
Real world example: is there a causal effect?

Based only on this data, can you tell if y can be controlled by manipulating u?



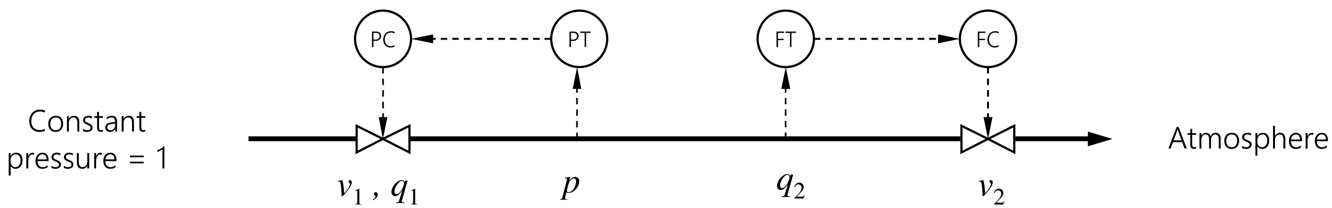
$$\frac{k_v}{s(1+sT)}e^{-sL}$$ provides a very good model structure

Model fit in Matlab



Representation of control structures: P&ID (piping and instrumentation diagram)

Simple example: gas pipe

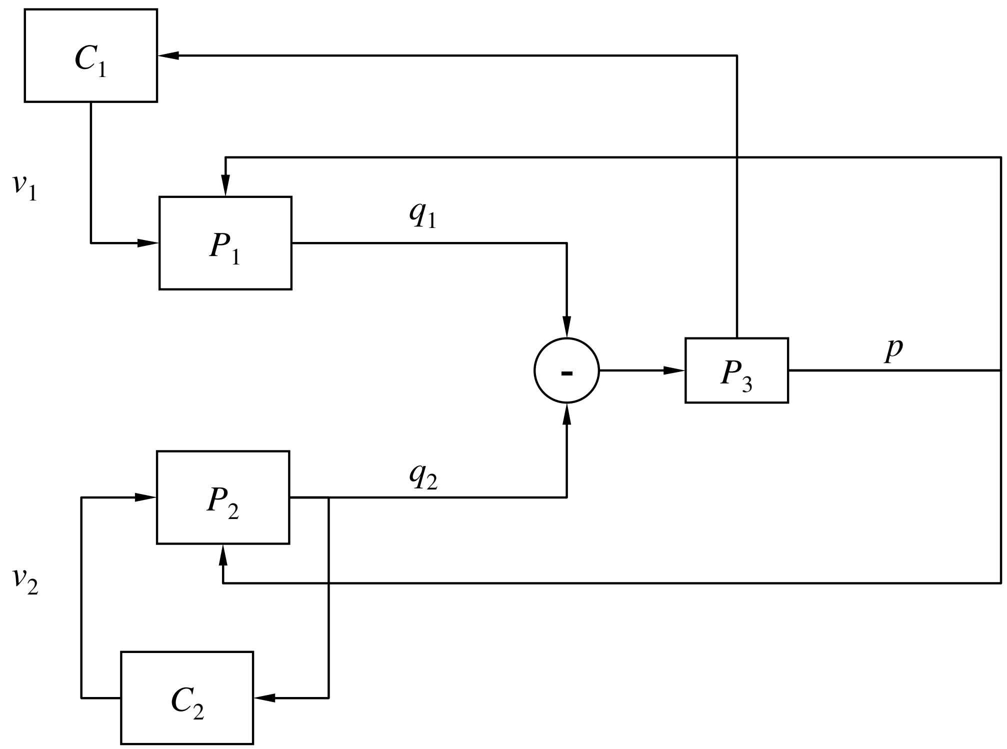


FC = flow controller, PC = pressure controller, LC = level ctrl, TC=temperature ctrl

FT = flow transmitter, etc

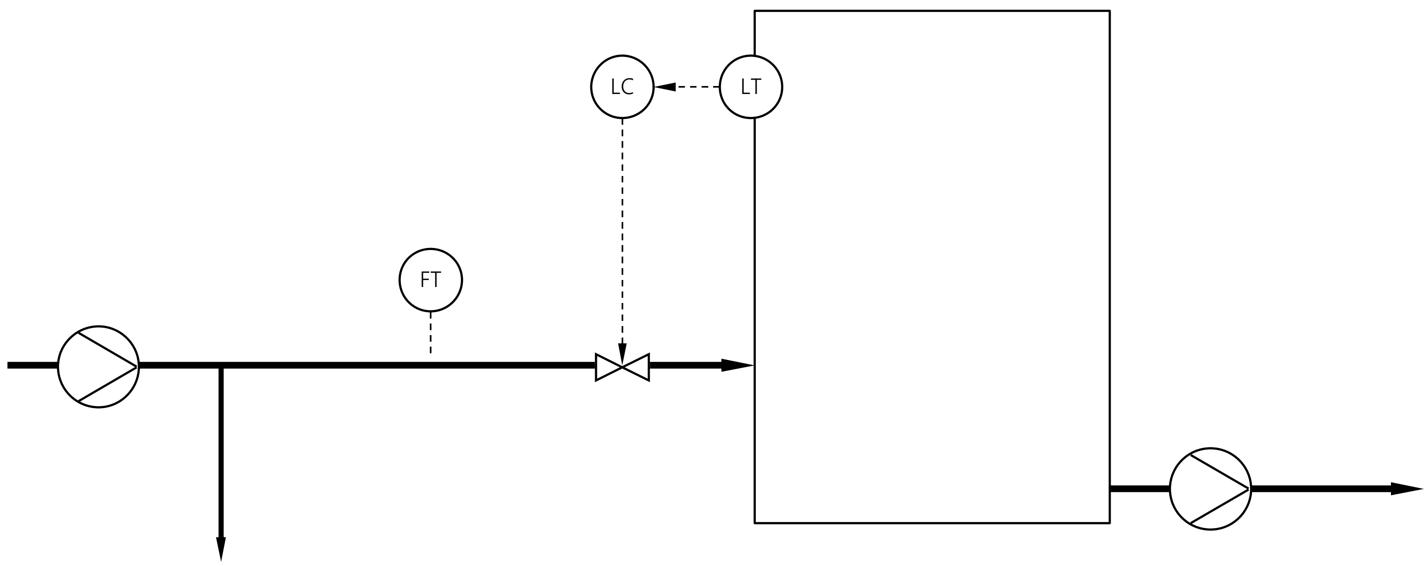
Why not use block diagrams, as in most control textbooks?

Block diagram for the same process



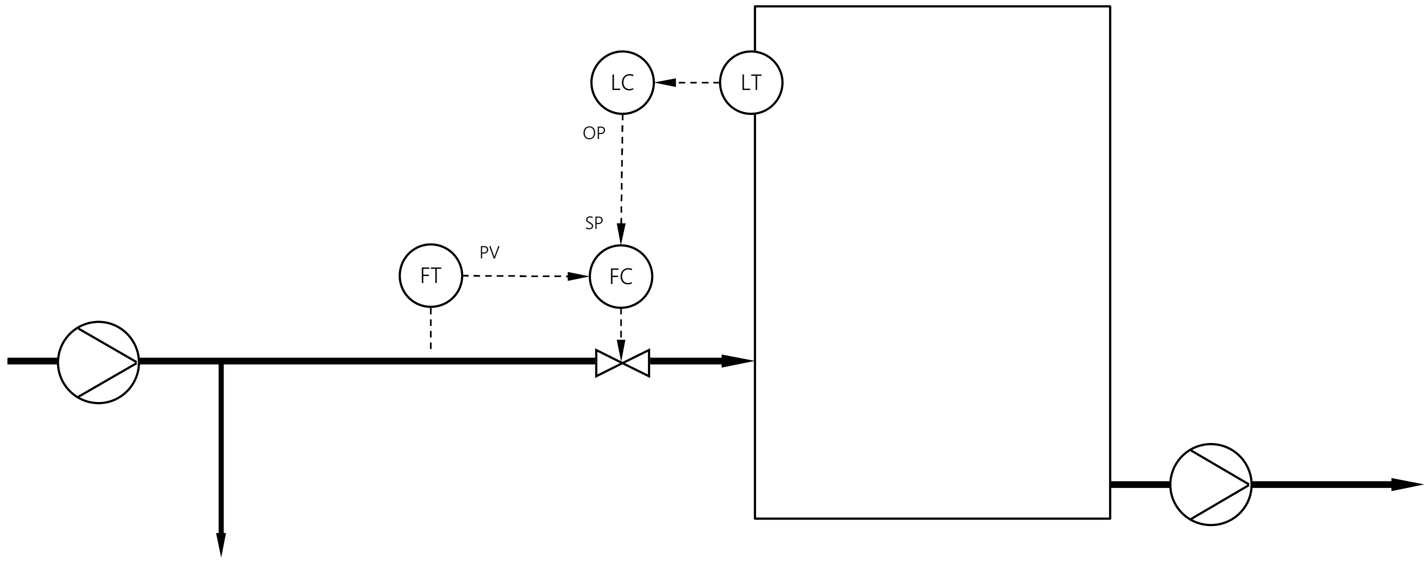
Control structures

Ex: Level control with improvement opportunity



- The level in the tank varies too much, because there are pressure variations in the line for the incoming flow.
- We can't tune the controller more aggressively - then it becomes unstable.
- Can we still improve control performance?

Solution: Control the flow too



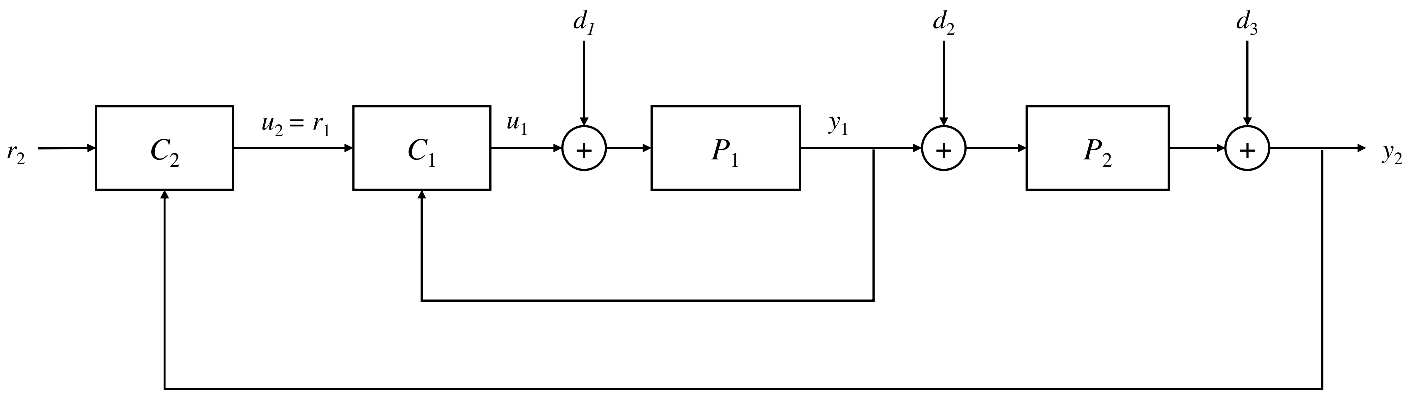
= Cascade control

Important: Motivate by disturbances

- For any control structure, the argument for using it should be based on which disturbances you have.
- In the case above:
  - If level variations were not due to varying feed pressure, then cascade control may not be the right solution.
- In fact this holds for all process control:
  - The reason for using feedback control is disturbances.
- Process control deals with **real** plants.
- Example: A volumetric pump normally delivers a flow that is an exact, repeatable function of its input signal (frequency or current).
  - In that case, you should not use feedback flow control.

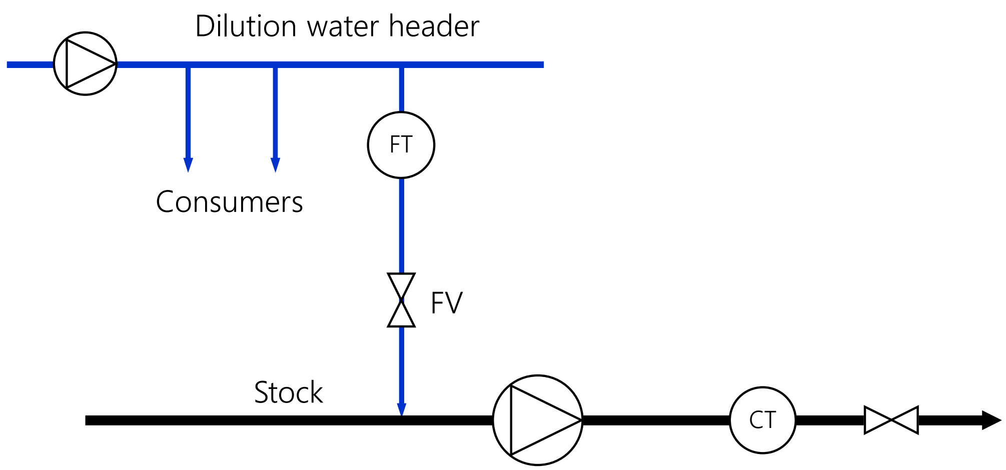
Cascade control block diagram

- Which disturbances motivate the use of cascade control?



Answer: d_1

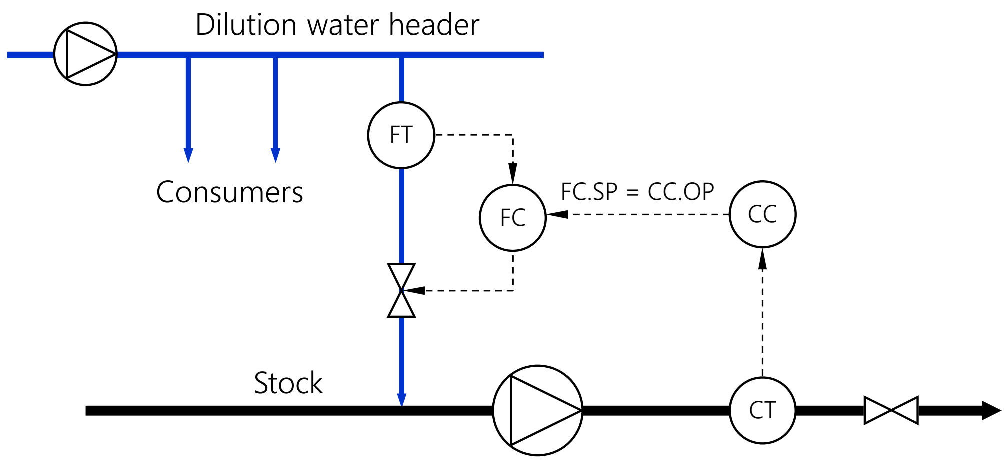
Example: Dilution process



Task: Control the concentration measured by the transmitter CT, by manipulating dilution water valve FV.

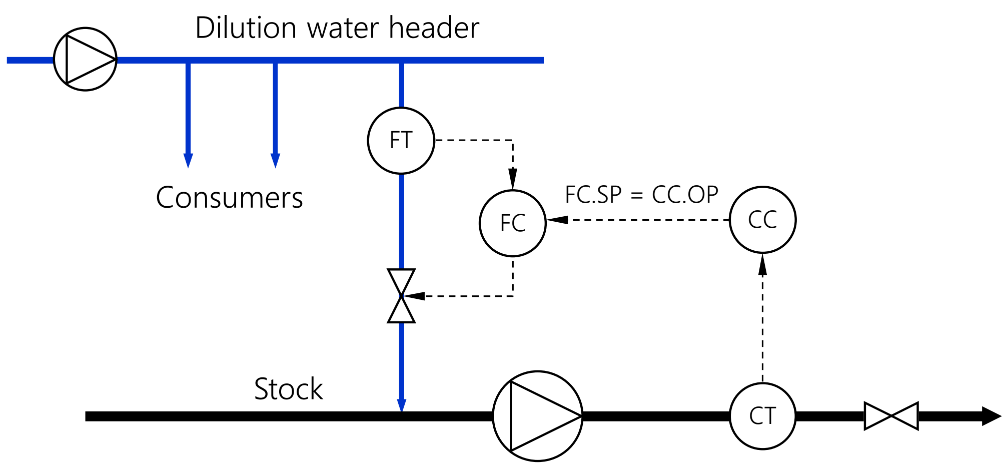
- How would you do that?

Structure for concentration control



- Concentration (consistency) control in cascade against dilution water flow.
- Questions:
  - Which disturbances/variations motivates the use of an FC?
  - Which disturbances/variations motivates the use of a CC?

Conc control; Scenario analysis



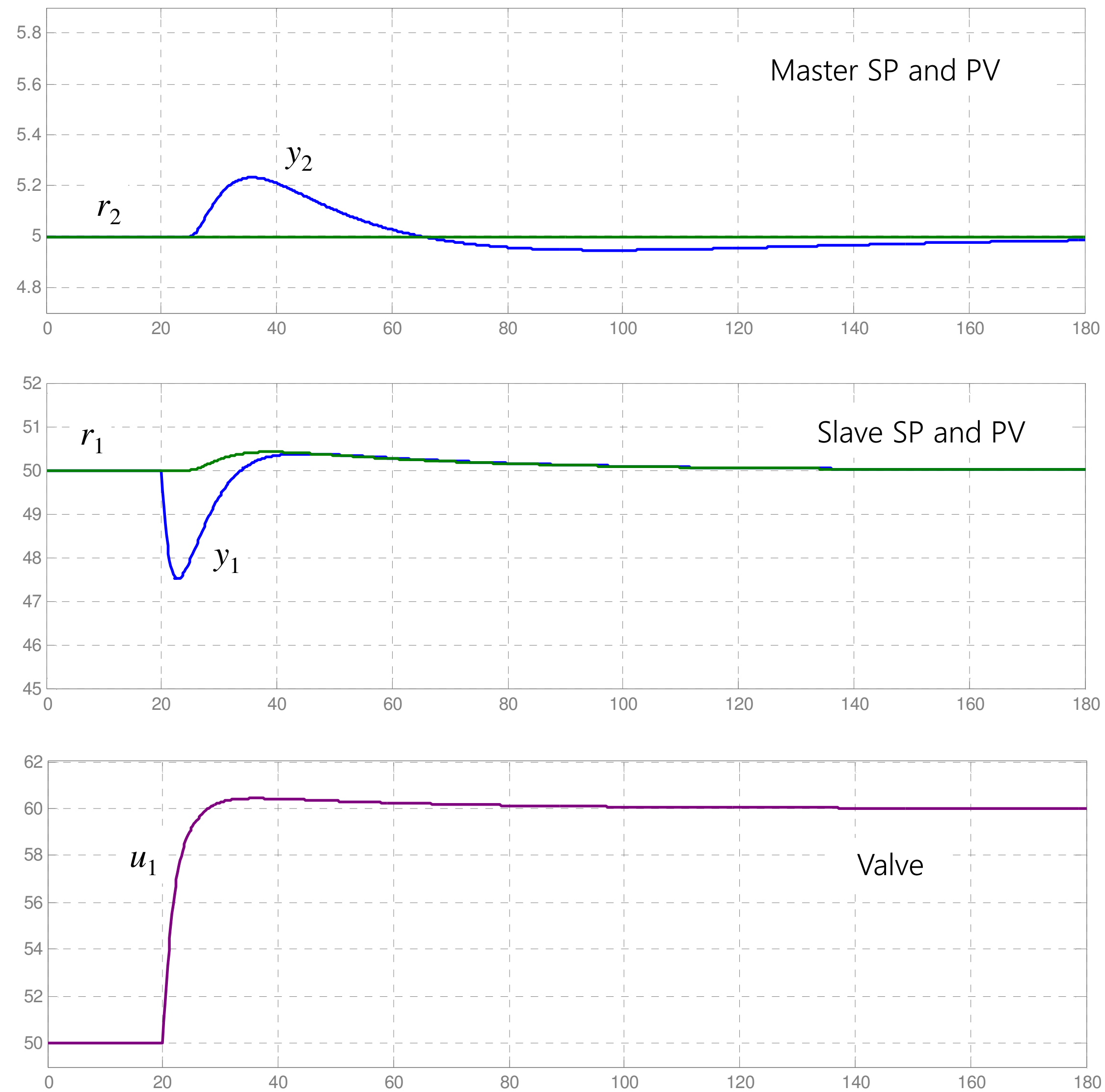
Scenario: There is a pressure drop in the dilution water header, because one of the other consumers suddenly increases its demand.

- We will now see how the cascade controller reacts to this, depending on the tuning of master and slave controller.

Slave controller much faster
than master.

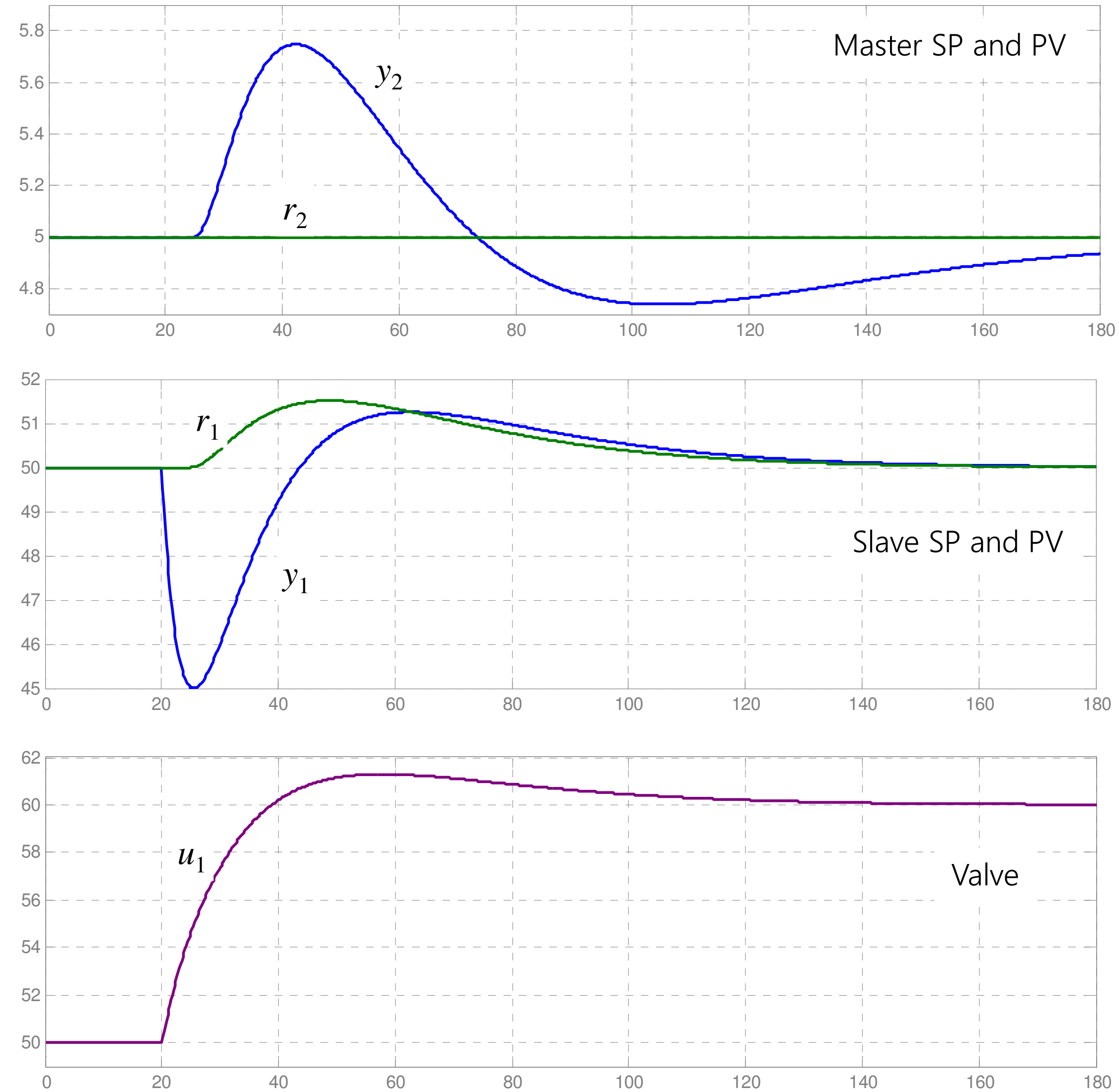
Rule of thumbs for cascade control exist.
Time constant in slave
x times faster than in master.

The disturbance is handled by
the slave controller before the master
controller reacts (in principle).



Difference between slave and master smaller than in the previous slide.

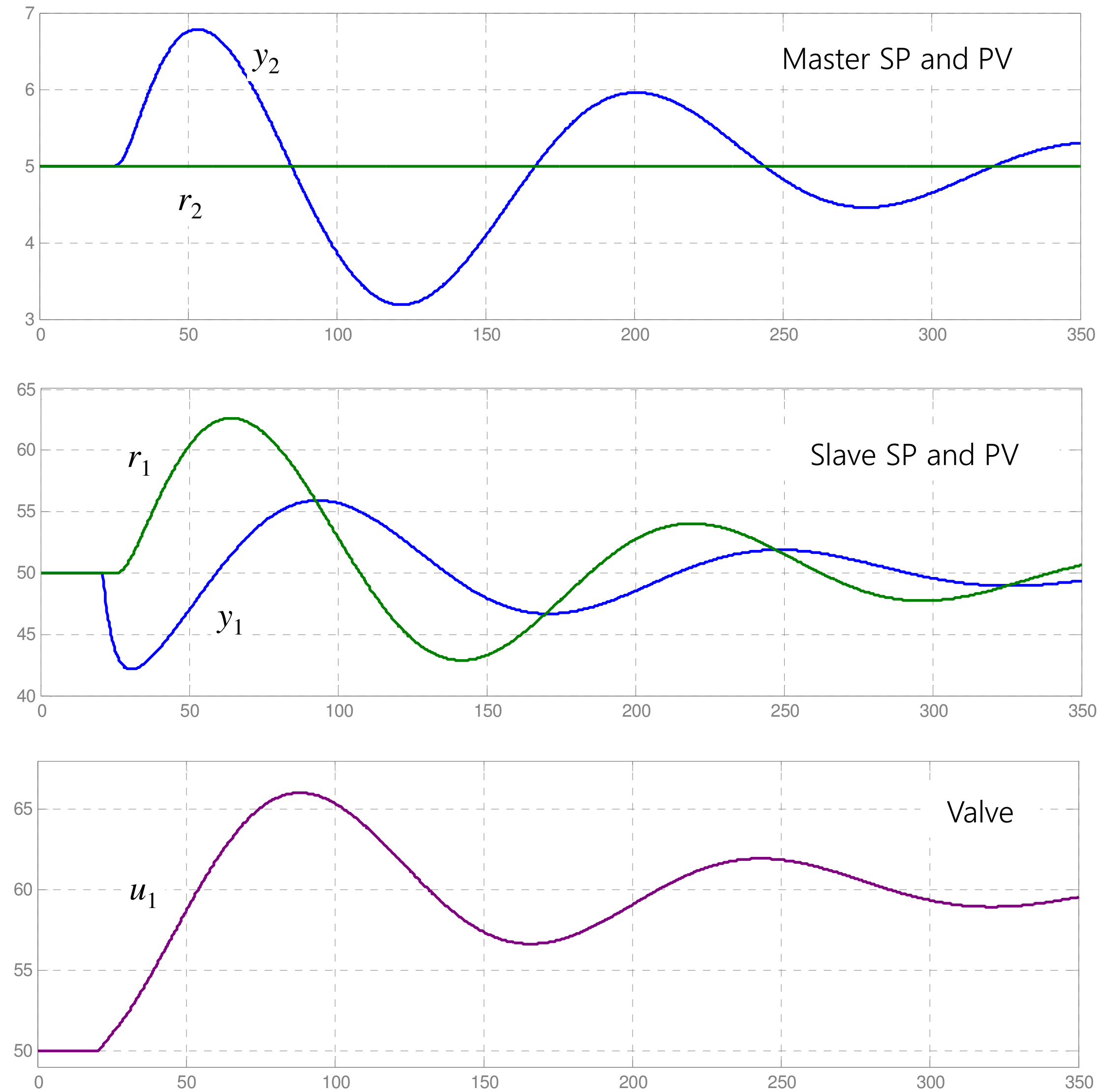
The disturbance is handled by the slave controller but the master controller also reacts, later on.



Master and slave controller almost equally fast.

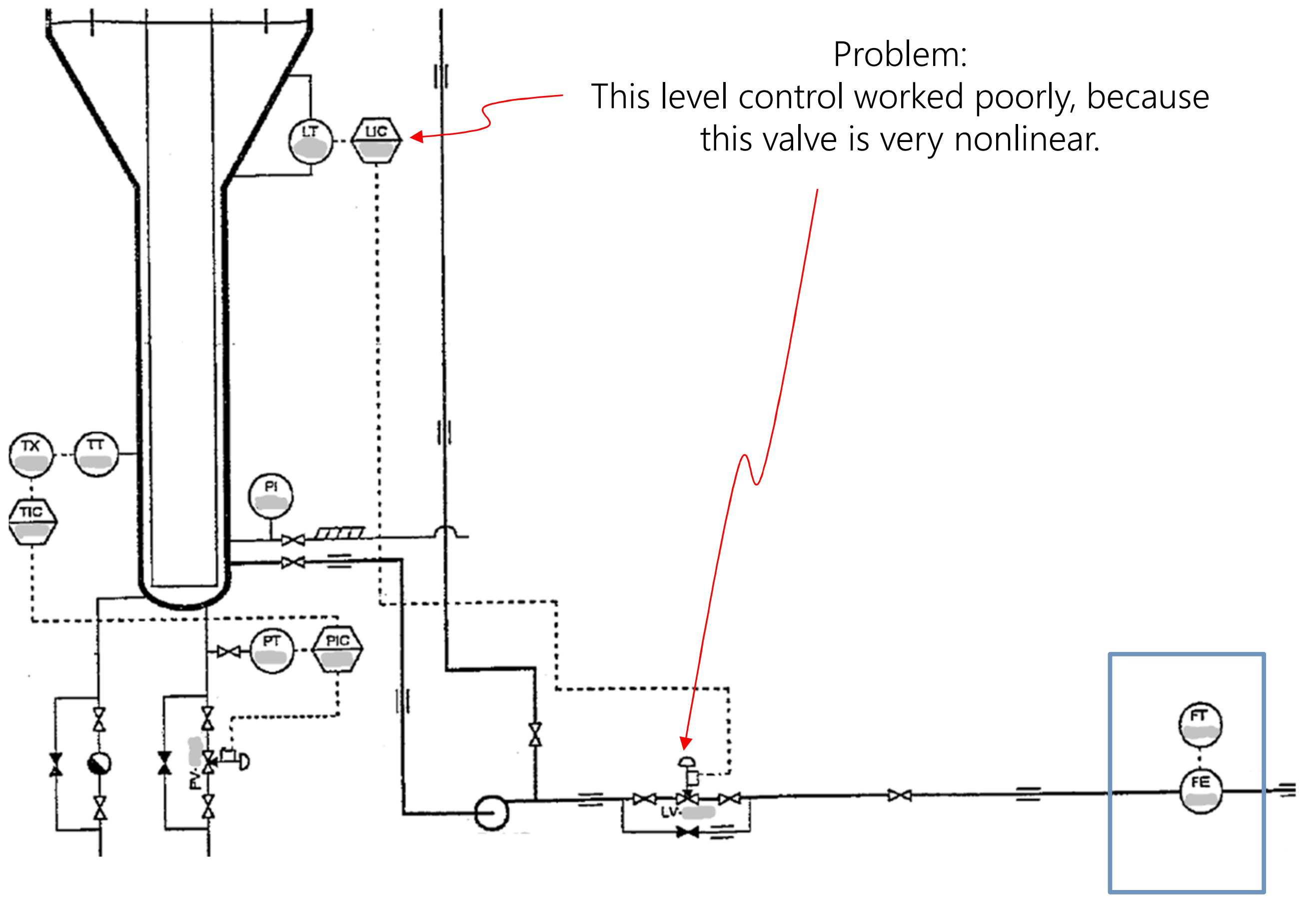
The disturbance is thrown back and forth between master and slave.

Almost unstable.

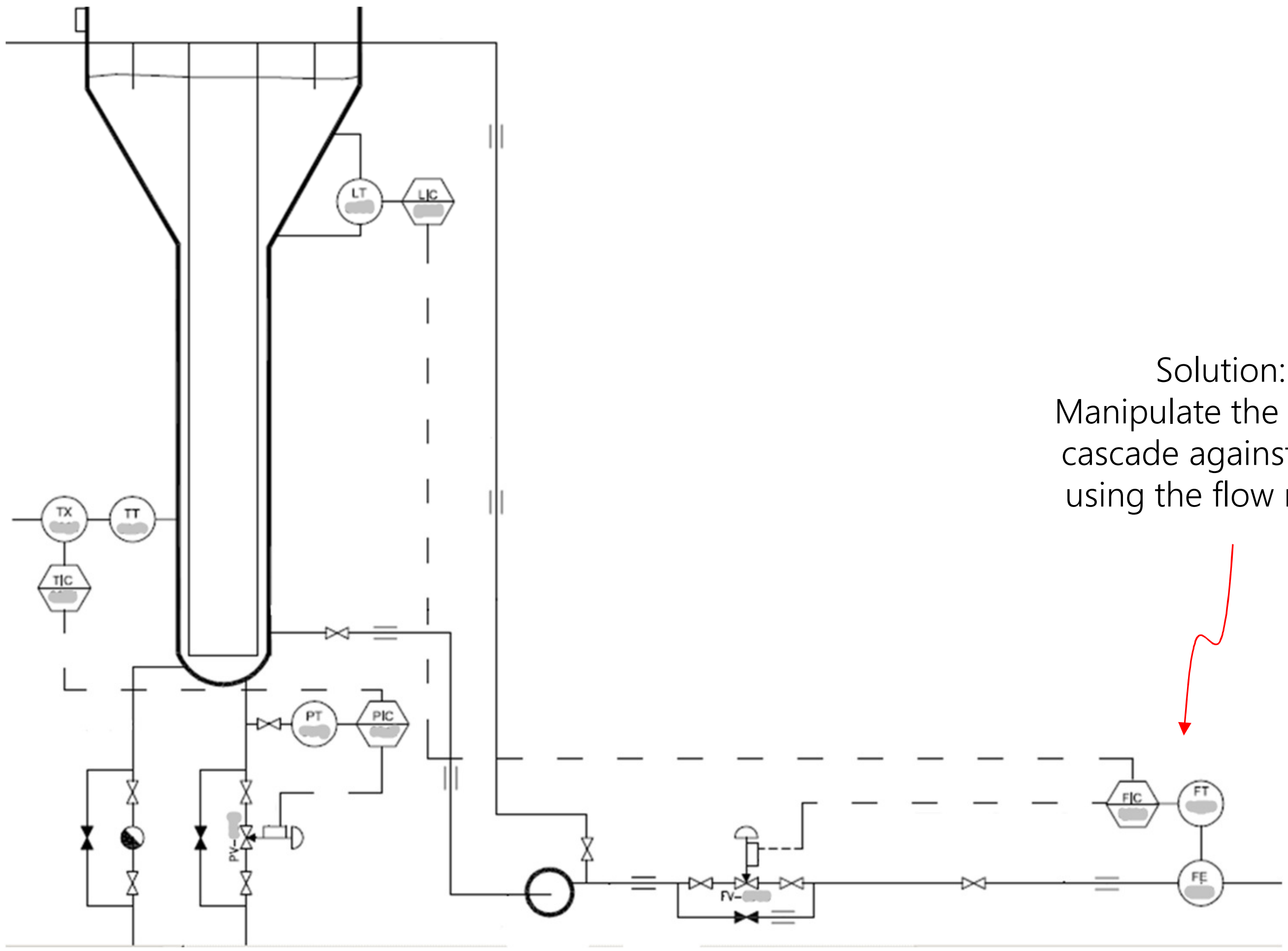


Evaporator with poor level control

Perstorp
A Subsidiary of PETRONAS Chemicals Group

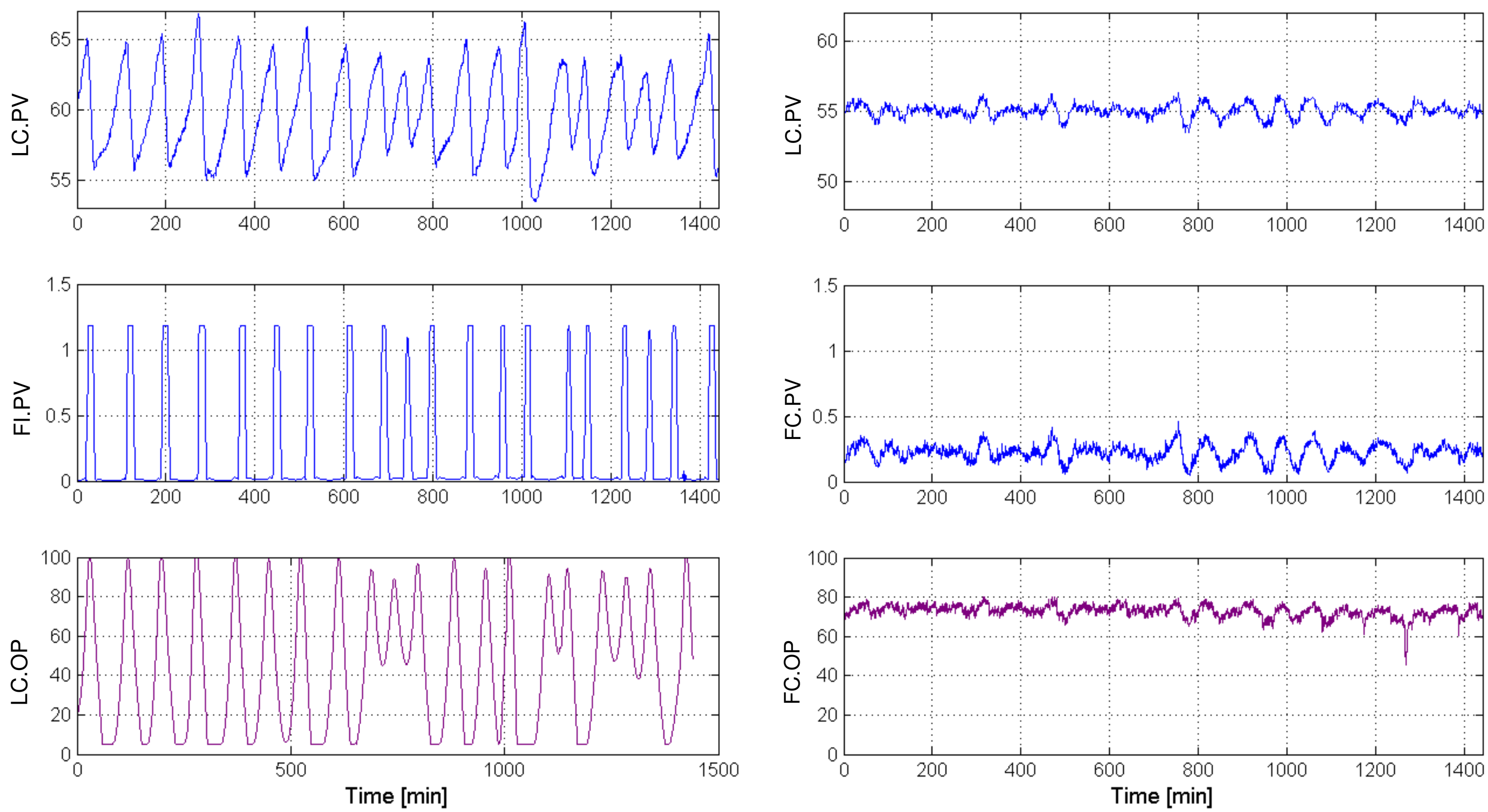


Problem:
This level control worked poorly, because this valve is very nonlinear.



Solution:
Manipulate the flow in cascade against level, using the flow meter.

More stable level and smoother flow using cascade control

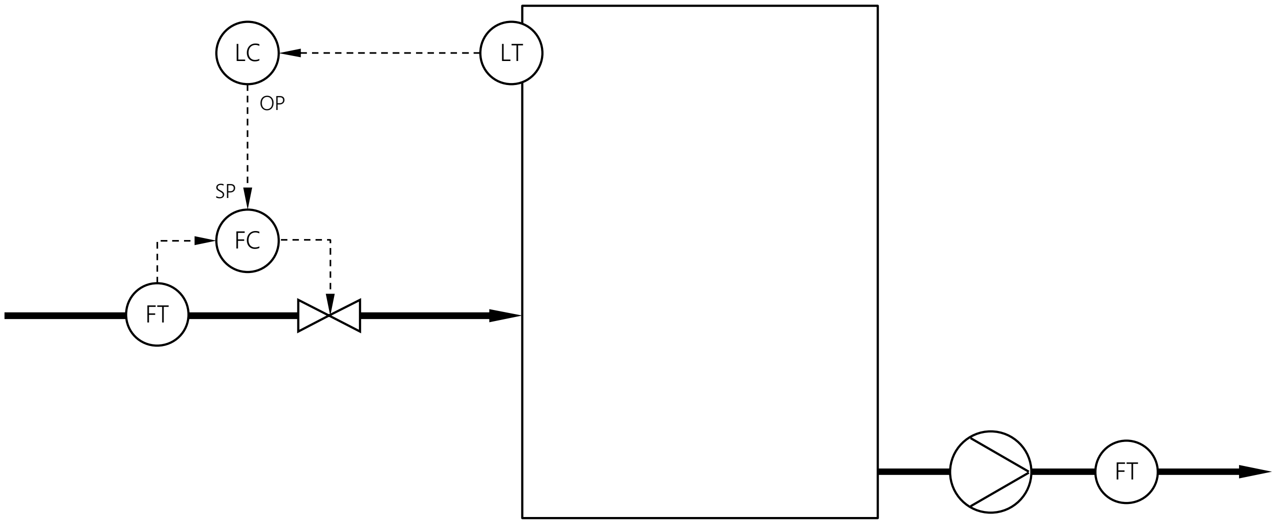


In this case, cascade control is used to linearize the slave process,
rather than for disturbance rejection.

New case

Ex: Level control with improvement opportunity

- The level in the tank varies too much because of variations in output flow.
- We can't tune the controller more aggressively - then it becomes unstable.
- Can we still improve control performance?

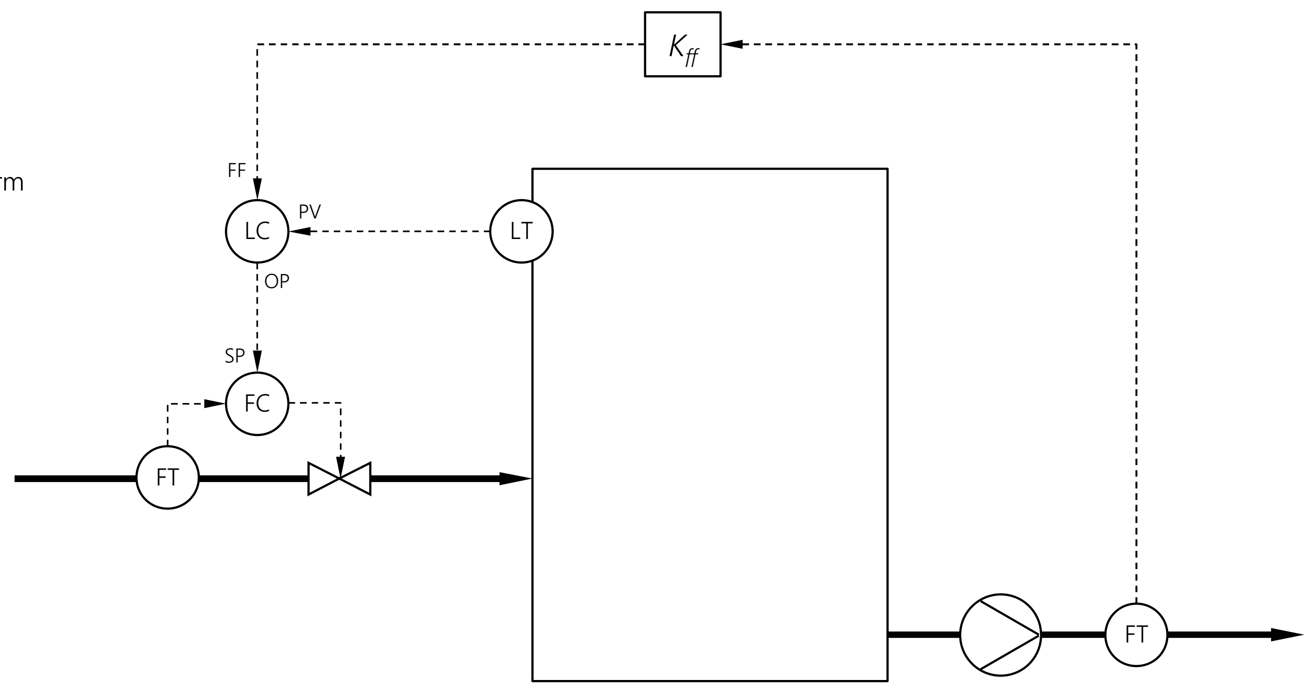


Feedforward: Give early information to the controller

$$u(t) = K_c \left(e(t) + \frac{1}{T_i} \int_0^t e \right) + u_{FF}$$

Feedback term

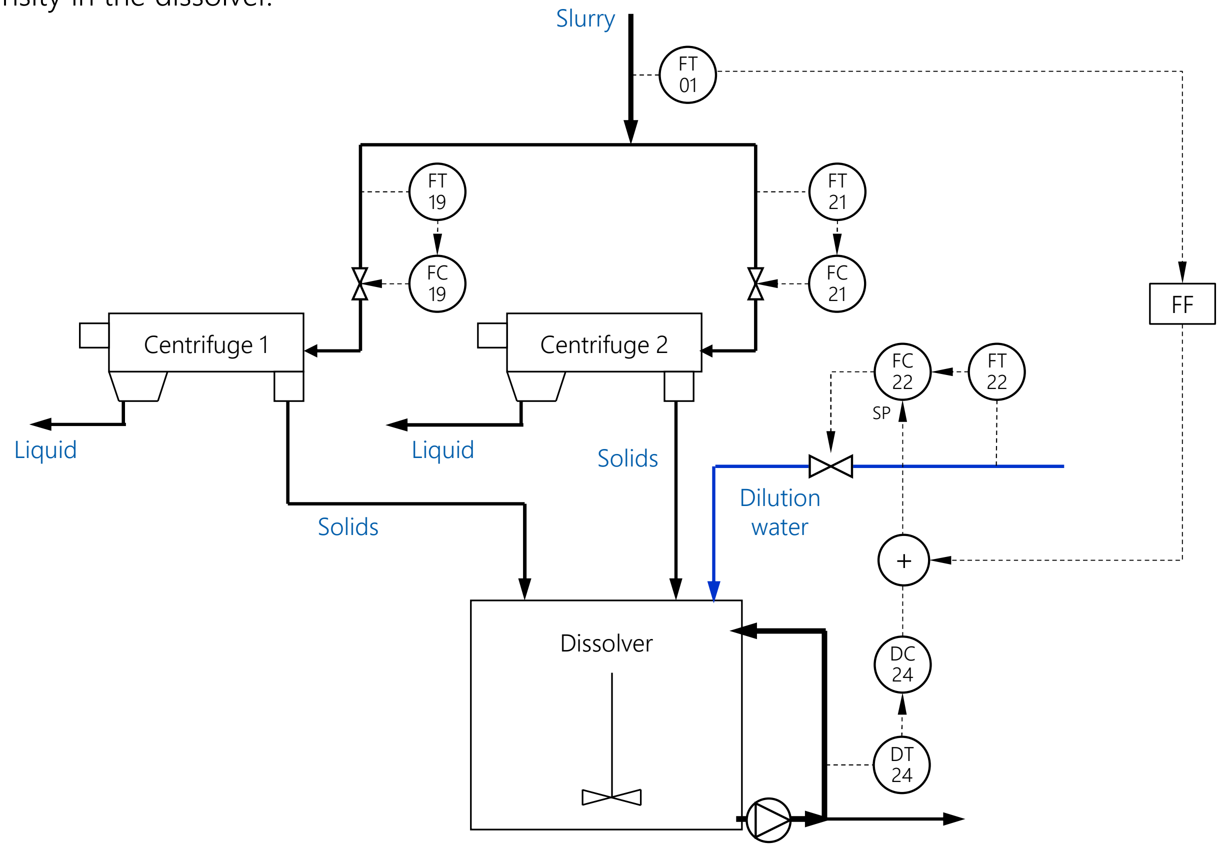
Feedforward term



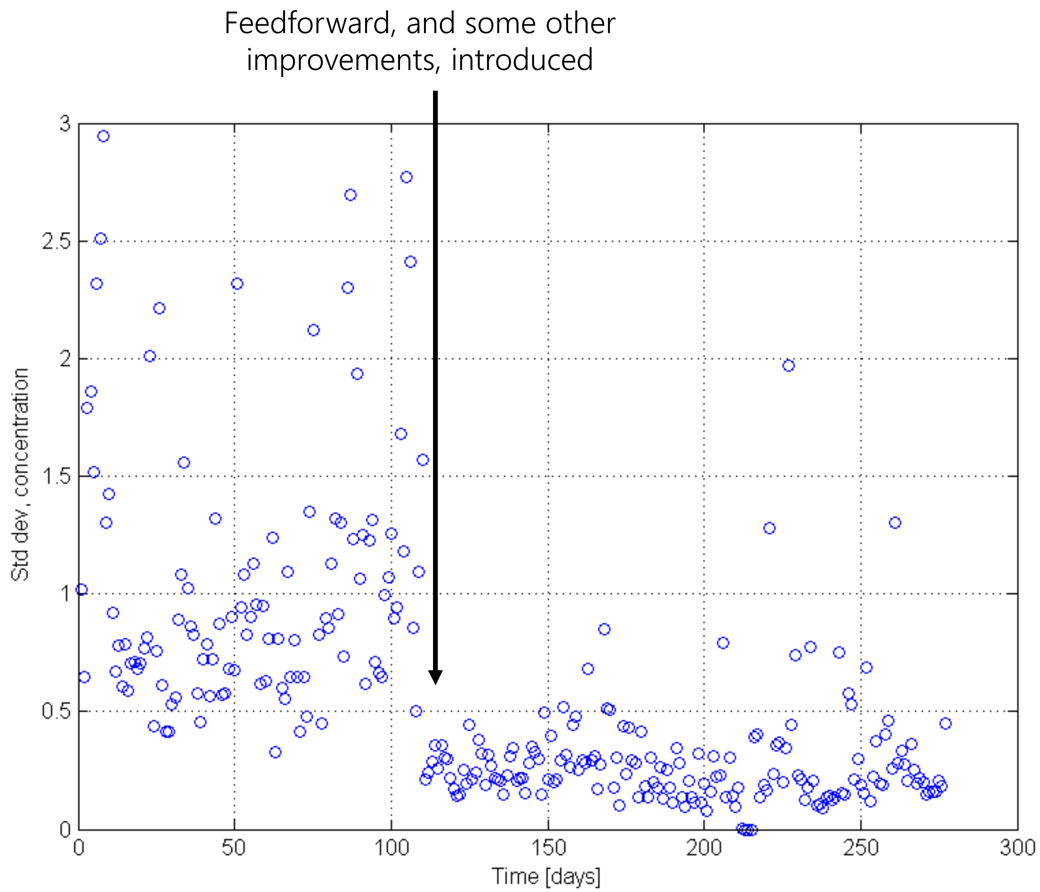
Density control in a dissolver

Issue: Sometimes one of the flows FC-19 or FC-21 is closed for cleaning the centrifuge.

Then there will be a large deviation in density in the dissolver.

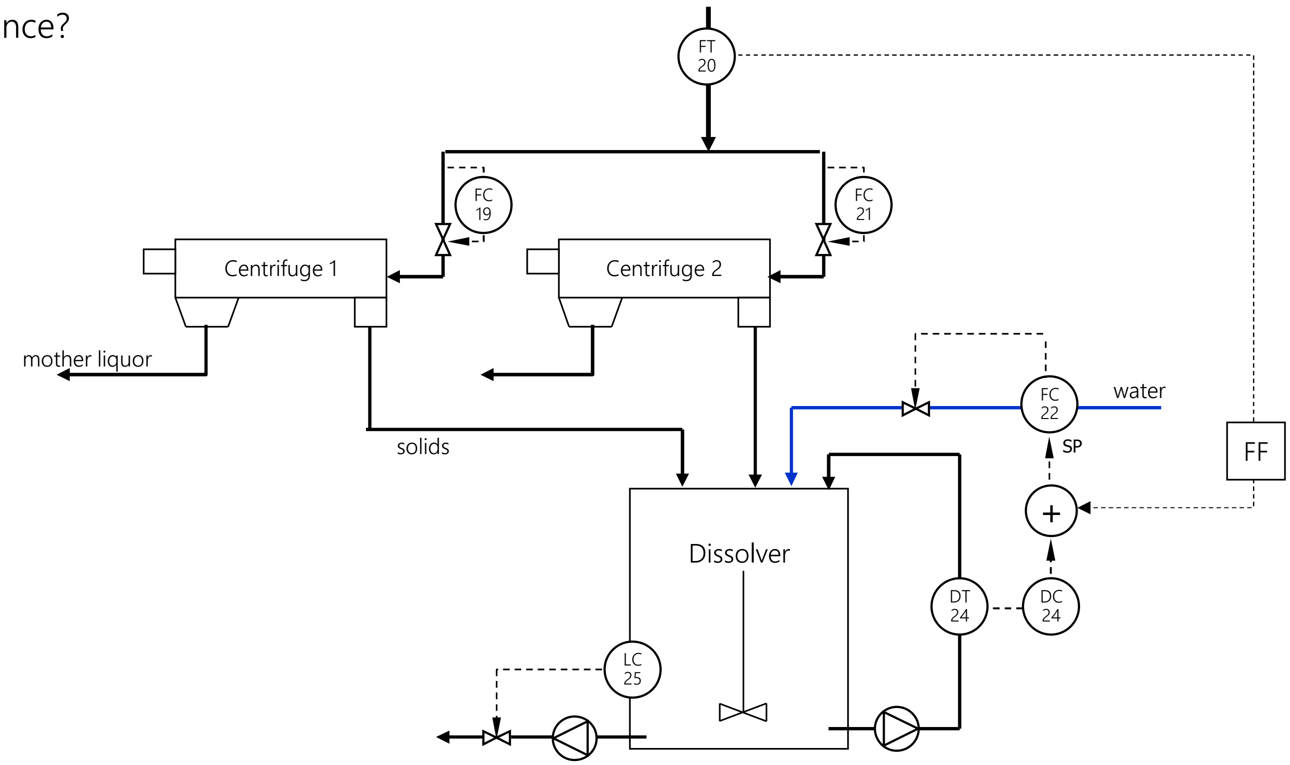


Dissolver: FF and PI tuning reduces variations



Controller job descriptions

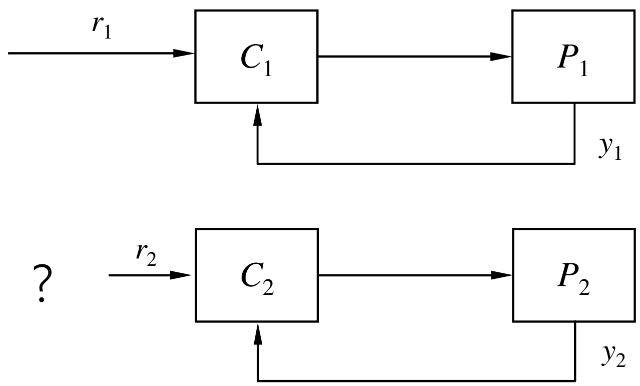
Question: For each of the controllers, what motivates its existence?



Ratio control

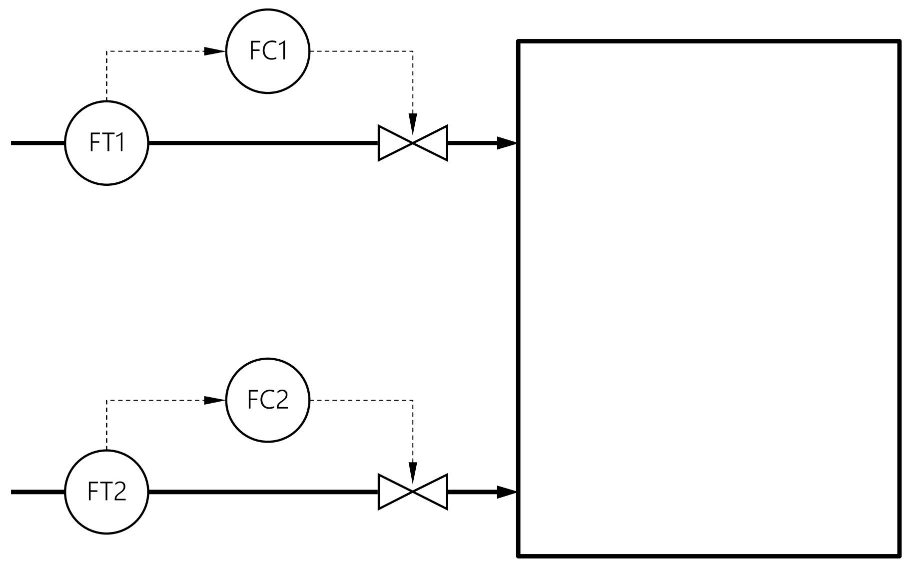
Task: Keep the ratio between two variables $\frac{y_2}{y_1}$ constant

- Typically: Two flow loops.
- The first loop is "master". The SP for y_1 can be set independently.
- Controller C_2 should ensure that the ratio $\frac{y_2}{y_1}$ is kept constant = α.
- How should we choose the SP for controller 2?
- Typical applications:
  - Reactor: Ratio between two reactants
  - Conc control: Dilution water against main stream
  - Heat exchanger: Cooling water or steam against main flow
  - Burner: Oxygen (air) against fuel



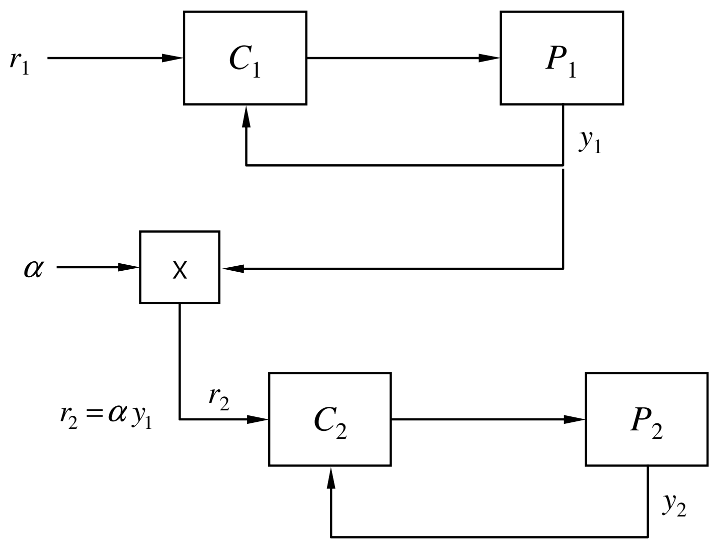
Example

- Two different chemicals mixed in a tank
- The setpoint for flow 1 is given by the operator.
- The control scheme should set flow 2 so that the mixing proportions is the desired one.

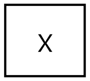


Solution: The SP for C_2 is a factor of y_1

The simplest solution is to set the setpoint for loop 2 as $r_2 = \alpha y_1$

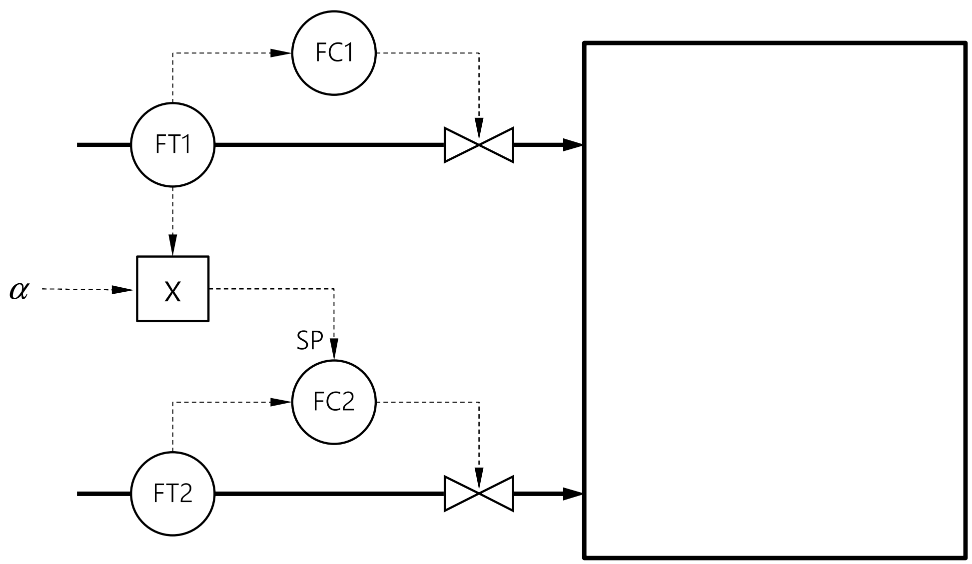


NB: Even though this is called "ratio control" there is no feedback from the ratio.



= multiplication

Ratio control for the example above



”True” ratio control

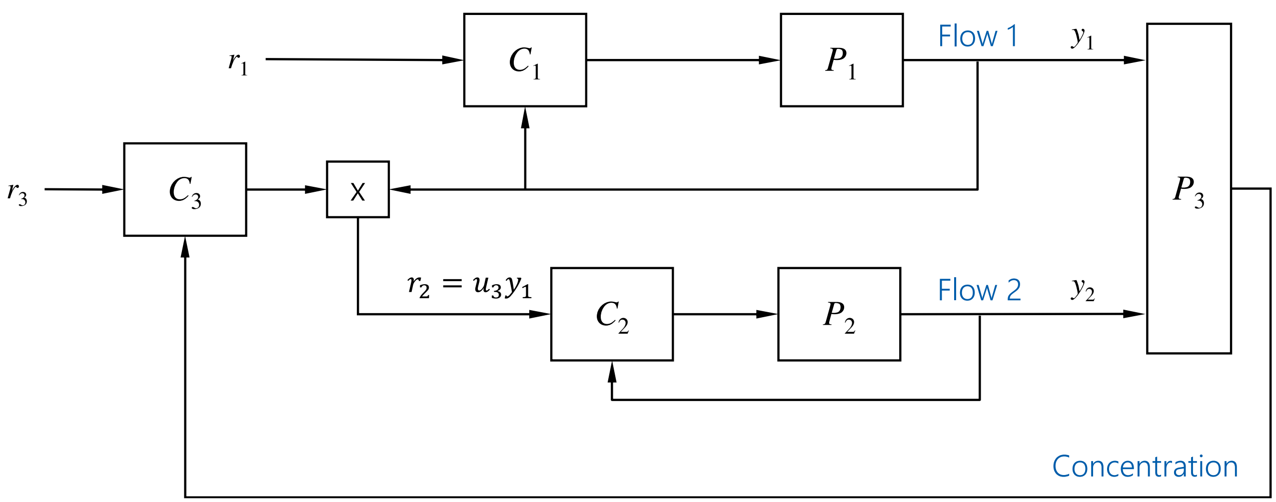
- In some applications we want to manipulate the flow ratio in order to control something, e.g. concentration.

- In this case we get one additional controller that becomes the master in a cascade.

- Example: A continuous dissolving process in a tank.
  Feed solids and water, and measure concentration in the tank:
  - Control the concentration by manipulating the ratio solids to water.
  - The level controller manipulates water flow.

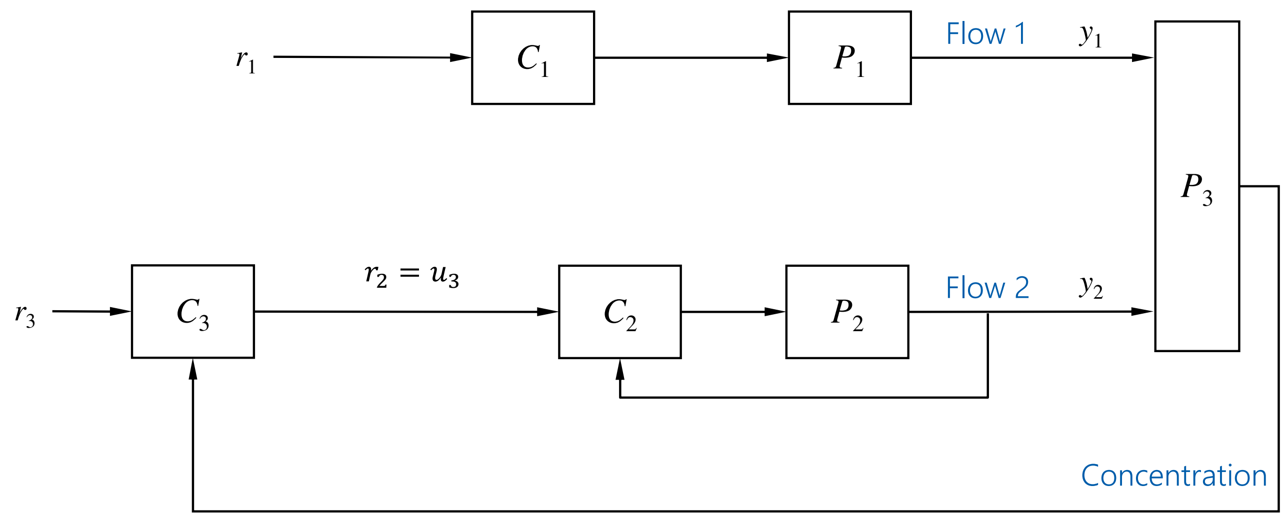
Ratio in cascade

Typical examples: reactor, mixing, dilution
This is an important and useful structure that is not well known by practitioners.

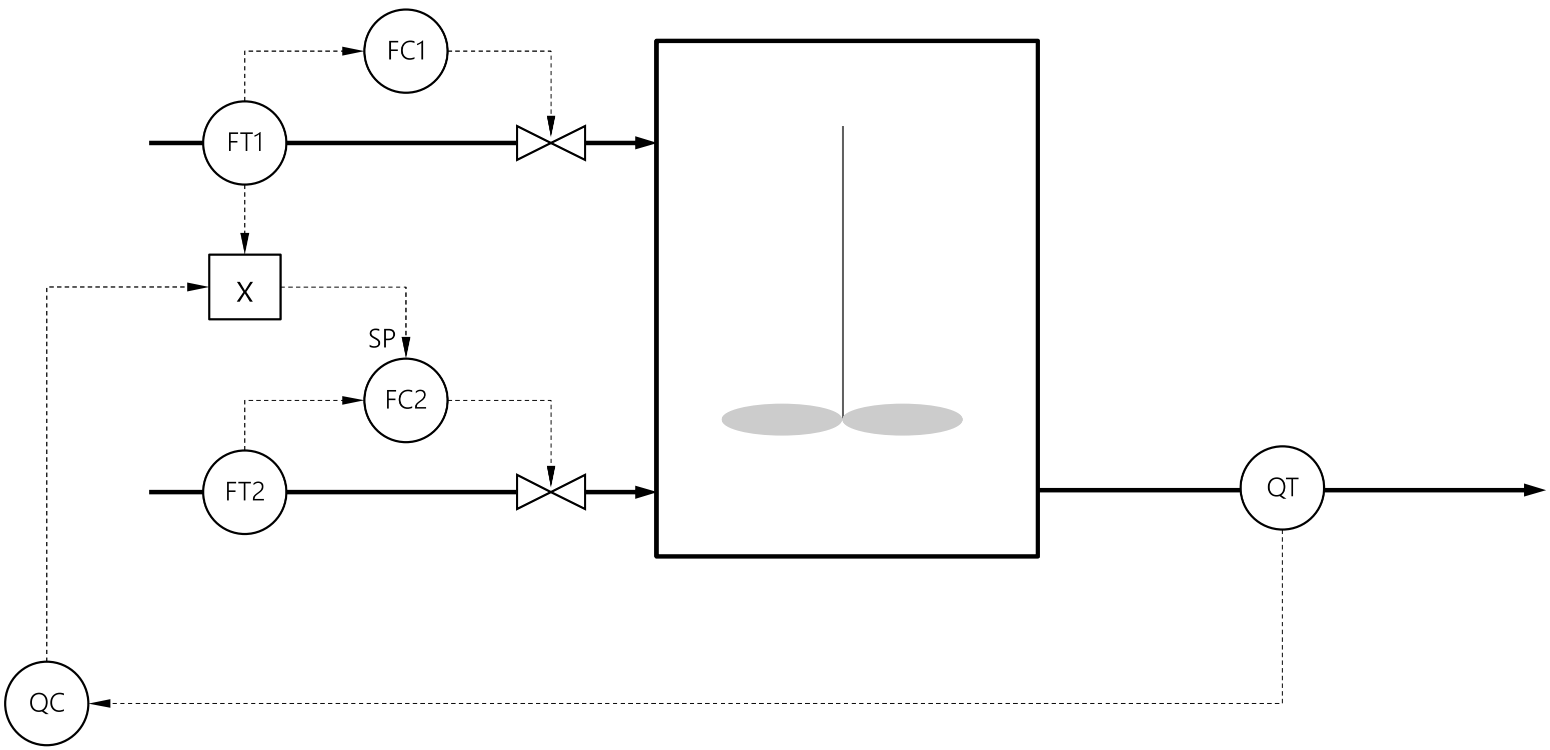


Cascade control, for comparison

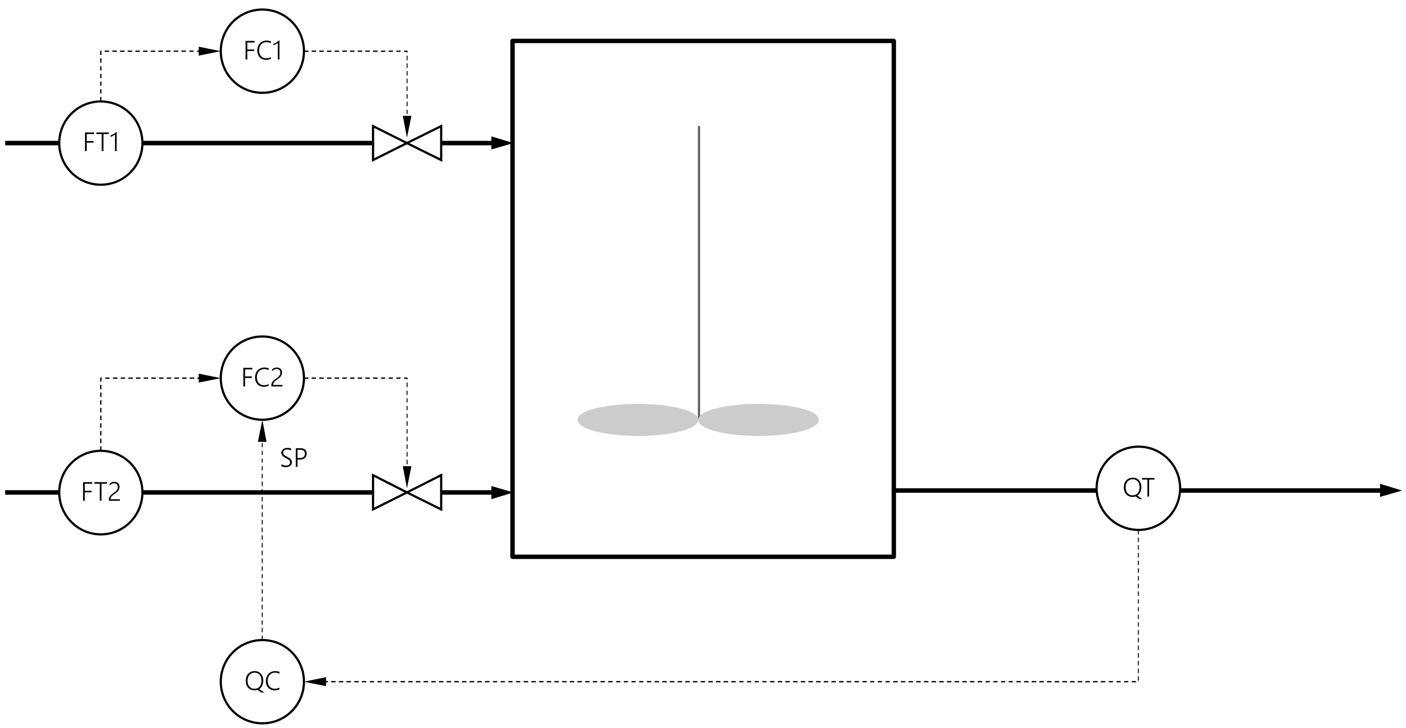
This structure is an alternative solution to the same problem.
Exercise: In which way is this structure inferior to ”ratio in cascade”?



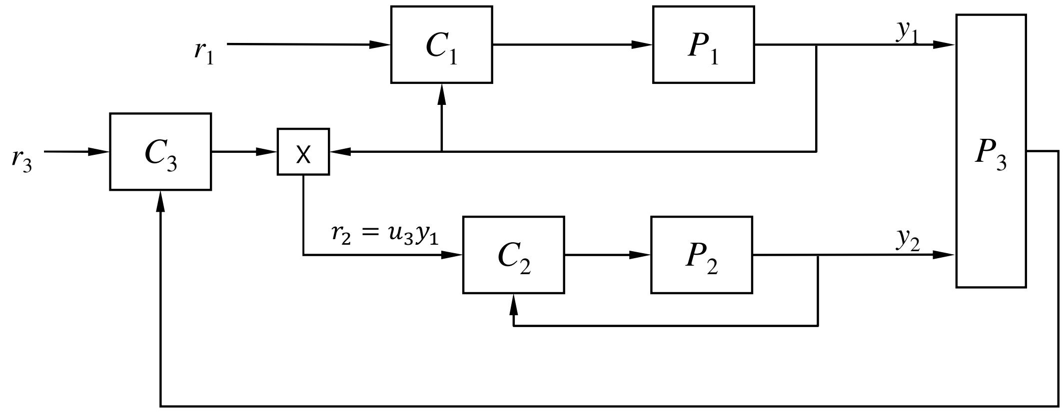
Application example: Ratio w feedback



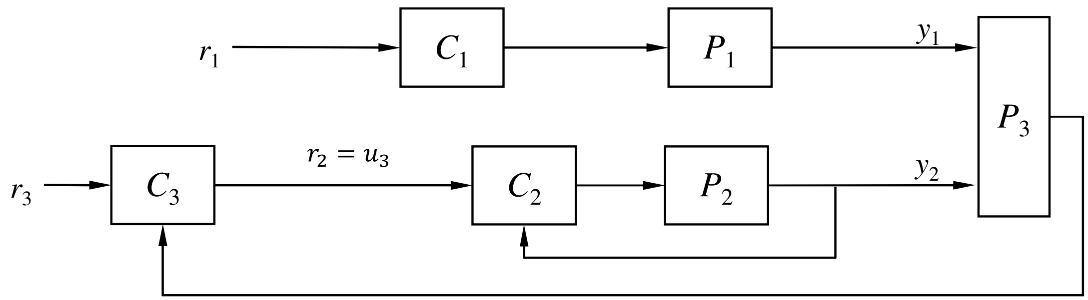
Application example: Cascade control



Compare structures



Exercise: In which way is cascade control inferior to "ratio in cascade"?



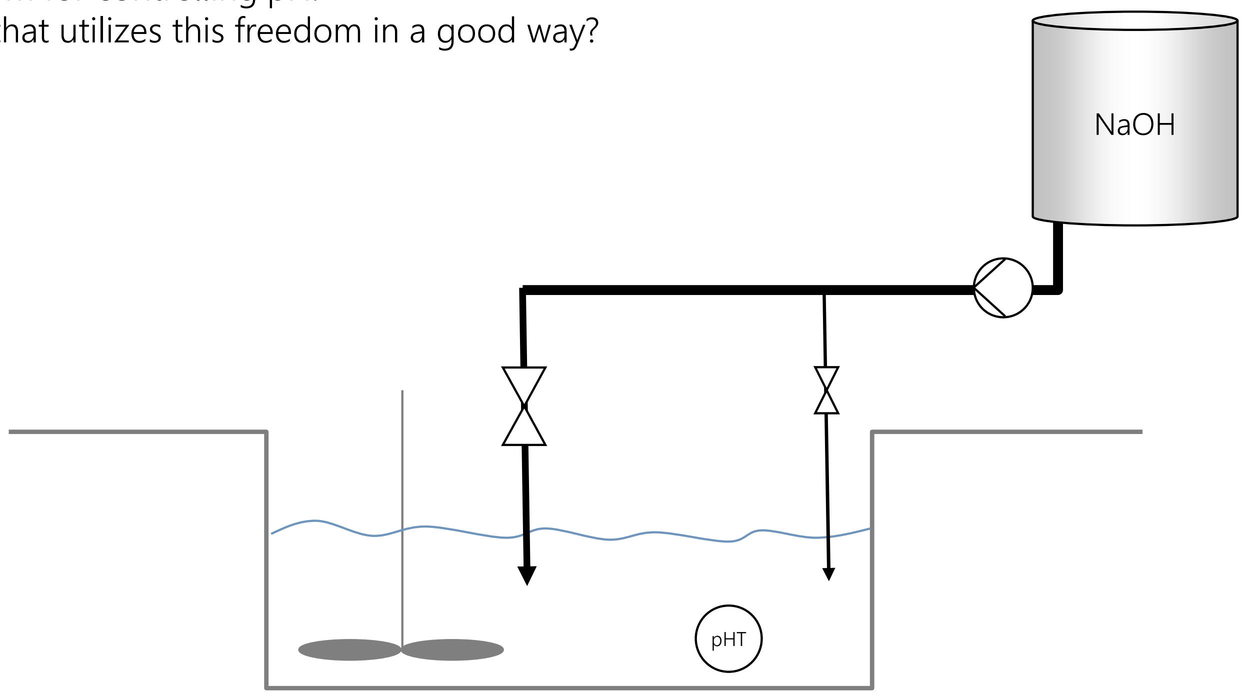
Answer: With ratio control any change in the master flow immediately changes the secondary flow SP, without going through P_3.

New case

Sewer pH-control process

There are two valves for feeding caustic to the pit:
a small, accurate one, and a larger coarse valve.

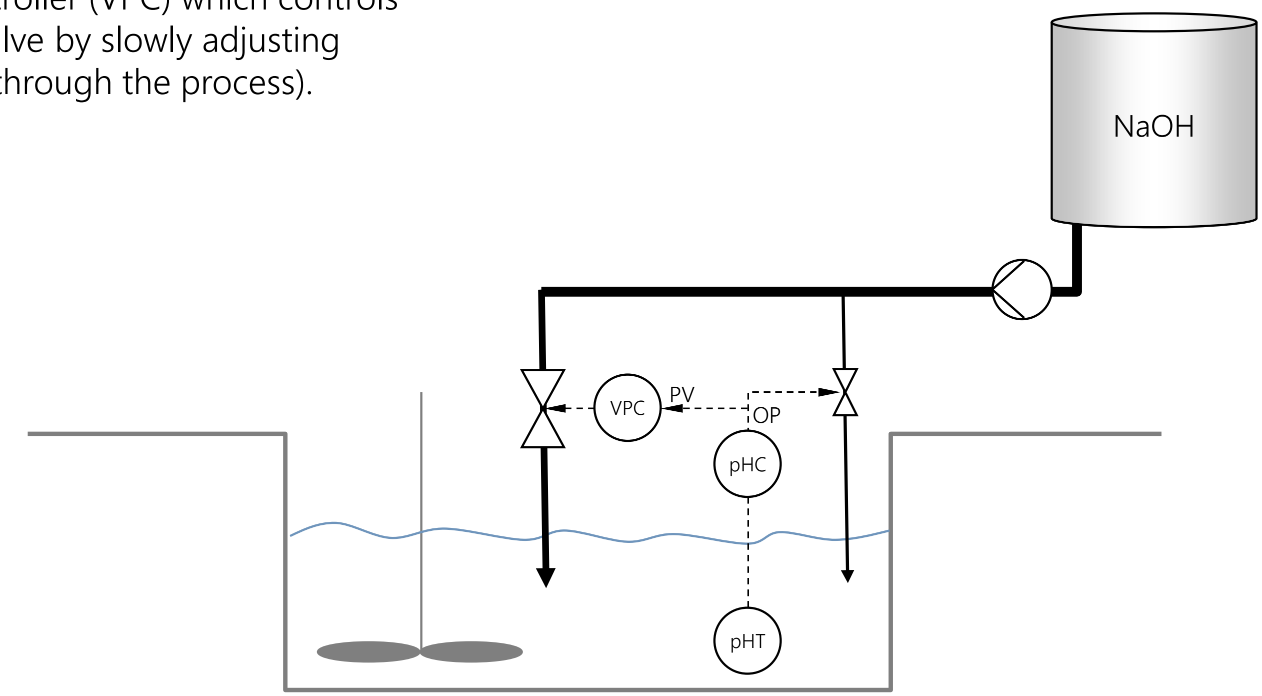
So we have one extra degree of freedom for controlling pH.
How can we design a control scheme that utilizes this freedom in a good way?



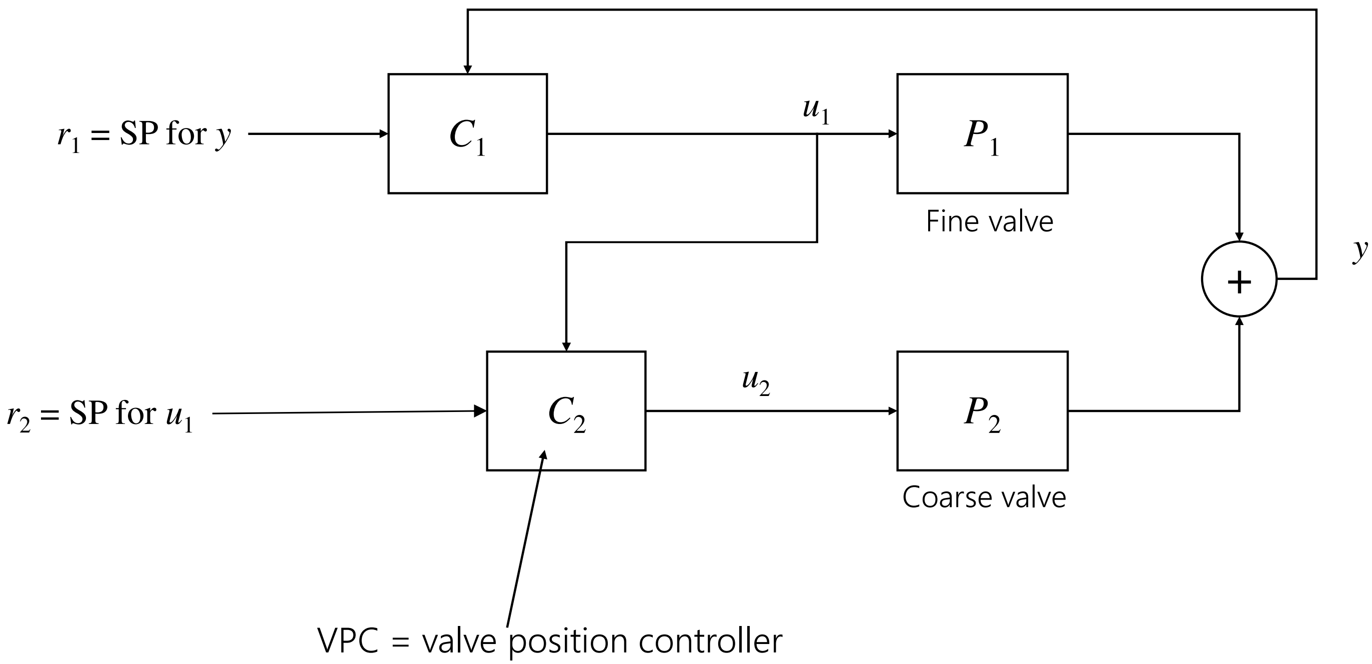
Solution: Mid-ranging (valve position control)

Let a pH-controller manipulate the small valve.

Introduce a valve position controller (VPC) which controls the position of the small valve by slowly adjusting the large valve (working through the process).

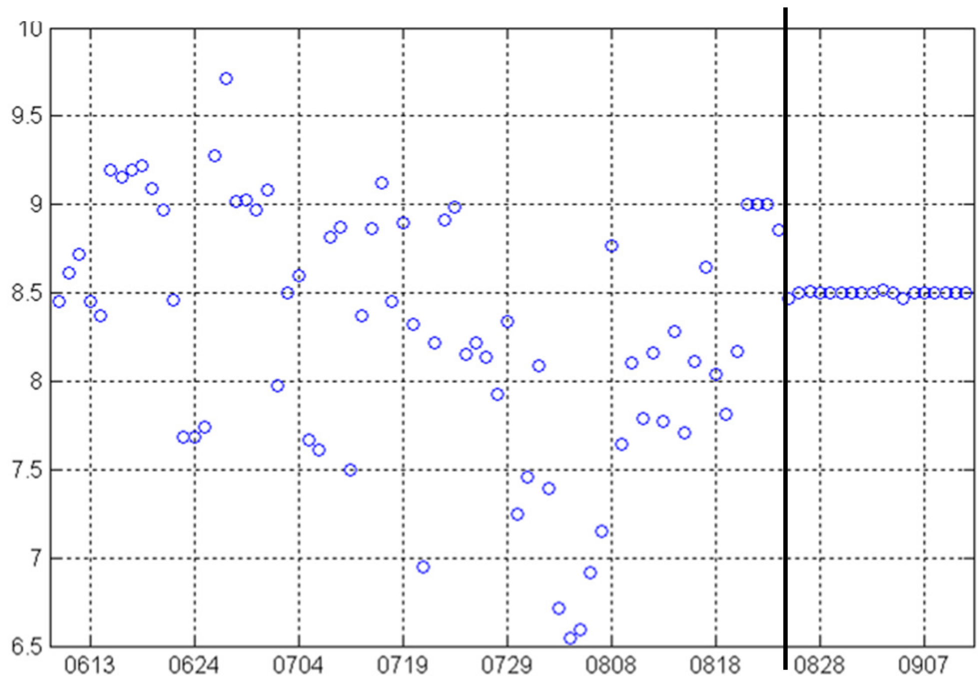


Block diagram for VPC: Give setpoint for u_1



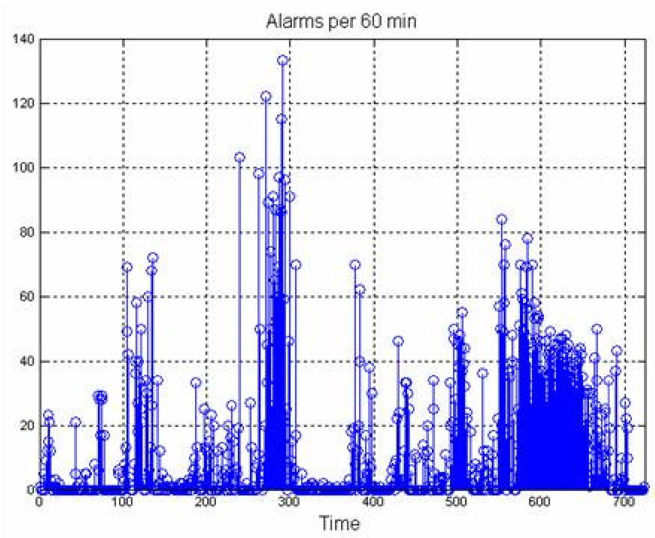
pH control; Results

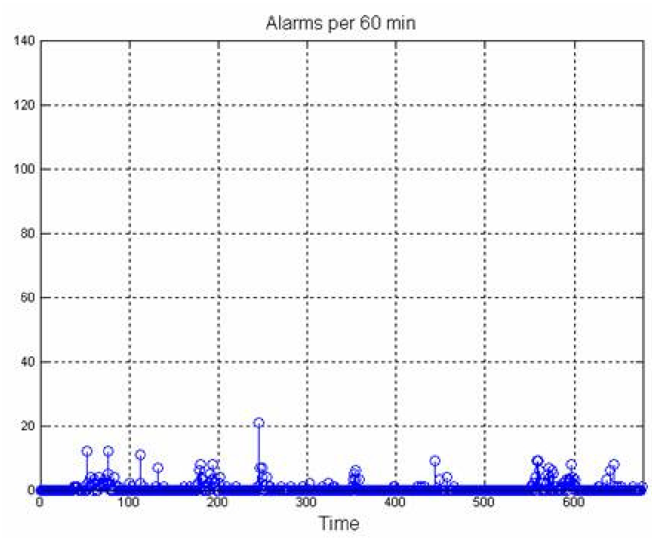
pH: Daily averages before and after new control structure



Improved pH-control gives fewer alarms

Perstorp
A Subsidiary of PETRONAS Chemicals Group





Before: 10 488 alarms in one month

After: 418 alarms in one month

96% fewer alarms from this object.

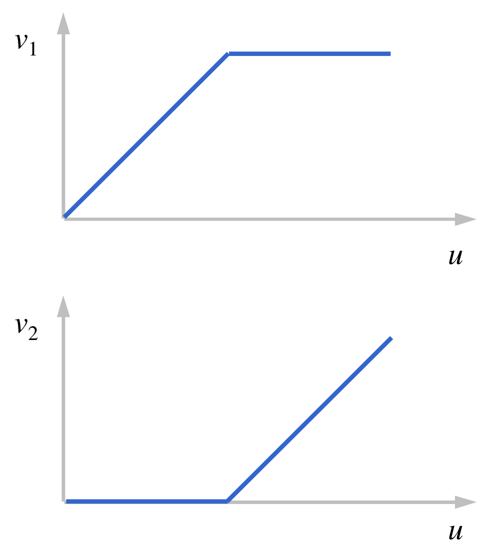
Split-range

(SRC: Split-range control)

Split-range: two valve – one controller

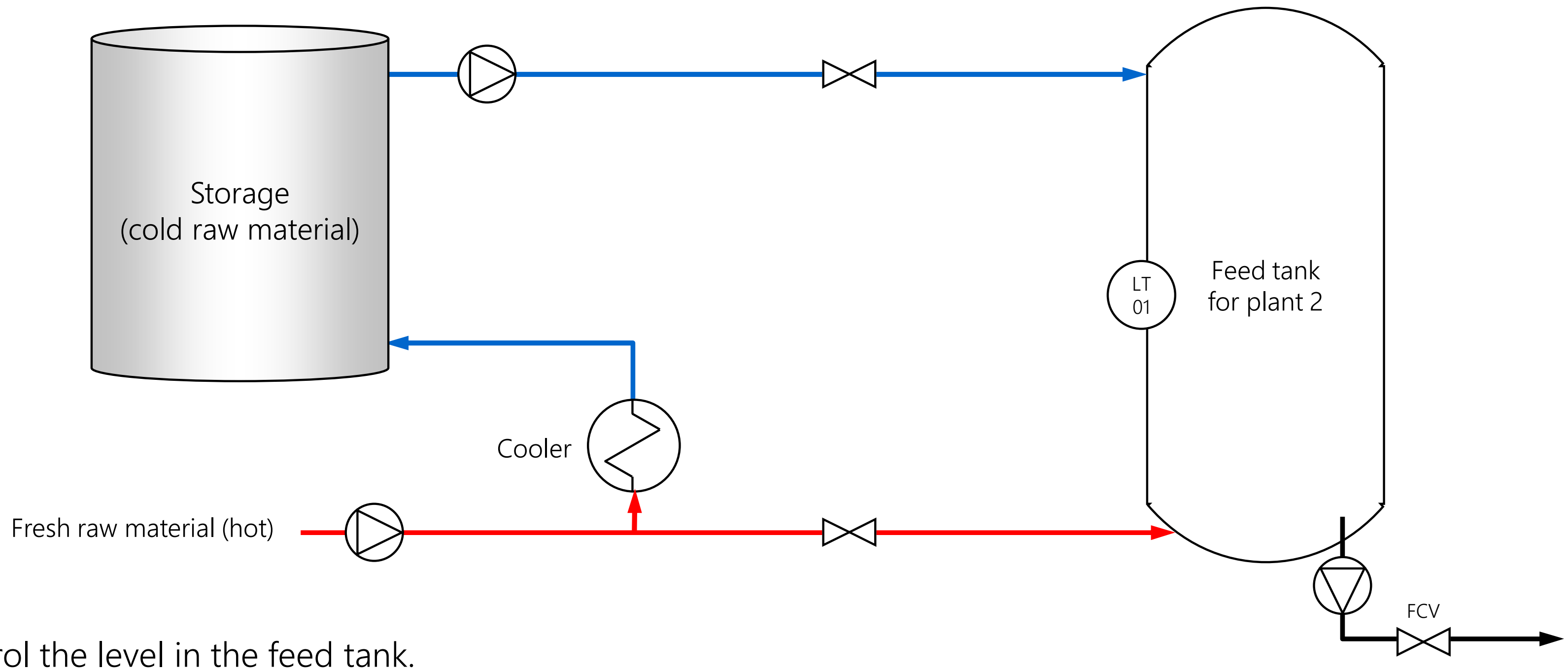
- In some applications we have two MVs and want the controller to use one ”first” and the other one next.
- The most common solution is to send the controller output to two tables; one per valve.
  For example:

OP	v_1	v_2
0	0	0
50	100	0
100	100	100



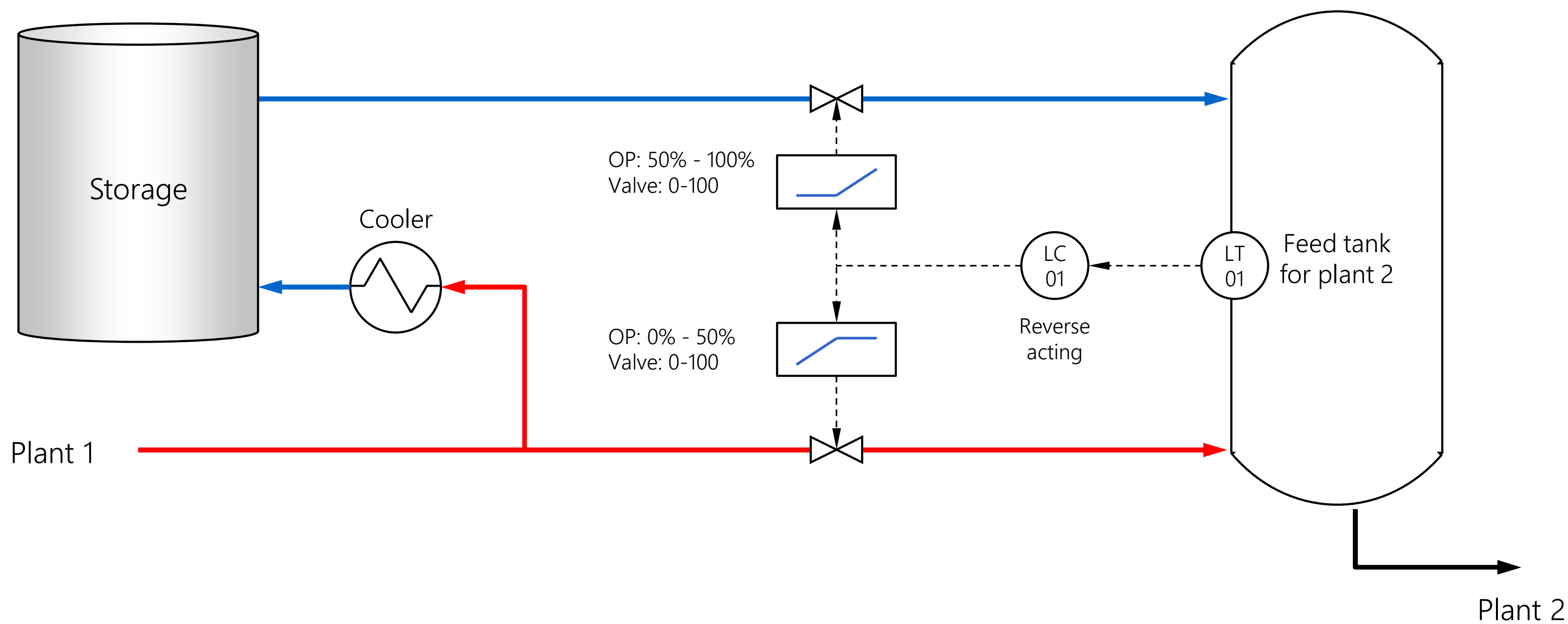
Level control with two manipulated flows

Perstorp
A Subsidiary of PETRONAS Chemicals Group



Main task: Control the level in the feed tank.
Use the extra degree of freedom for energy optimization: Primarily take fresh, hot, raw material.
If that doesn't suffice, take from storage.
If we don't have optimizing control we may cool unnecessarily, and then re-heat.

SRC application: level control with optimization

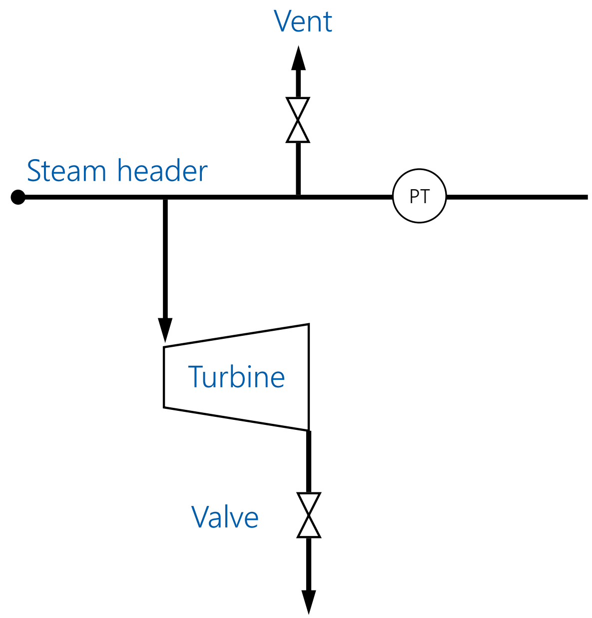


Parallel controllers

Control with several MVs

Perstorp
A Subsidiary of PETRONAS Chemicals Group

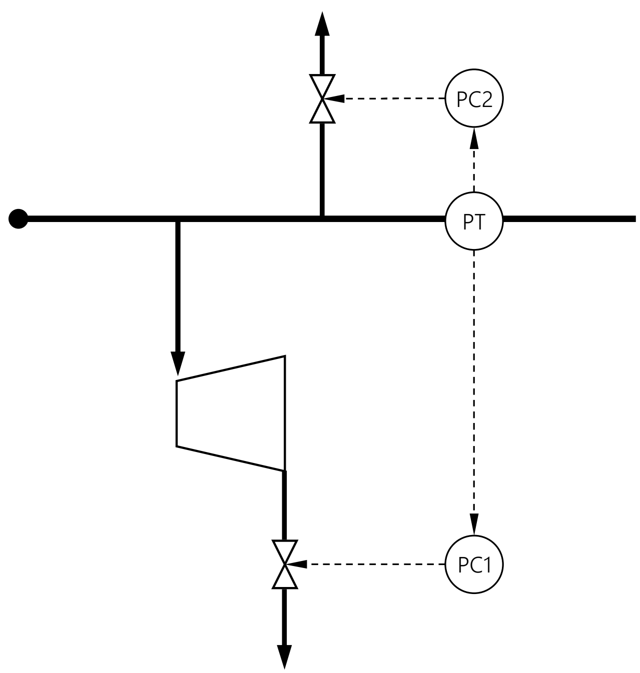
- Task: Control the pressure in the high pressure header by manipulating flow through the turbine.
- If the HP header pressure gets too high, open the vent valve.
  - But only in that case.



Solution: Two controllers with different SP

Perstorp
A Subsidiary of PETRONAS Chemicals Group

"Parallel controllers"



The two controllers have the same PV, but different MVs.
They should have different setpoints, and can be tuned differently.

In this application PC2 could even be a P-controller:
It doesn't really need to enforce setpoint adherence.

If we use P control the valve position for the vent valve will be simple function of the header pressure.

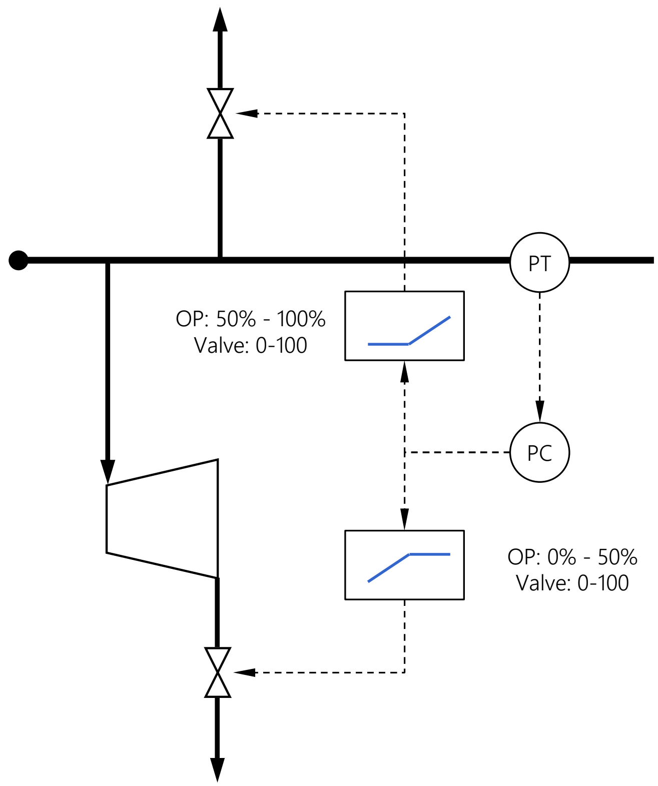
Test question: Which of PC1 and PC2 should have the highest SP?

Answer: PC2. Its OP should be 0% almost always.

A different solution: Split-range

A split-range could also solve the problem.

Does parallel control have advantages compared to SRC?



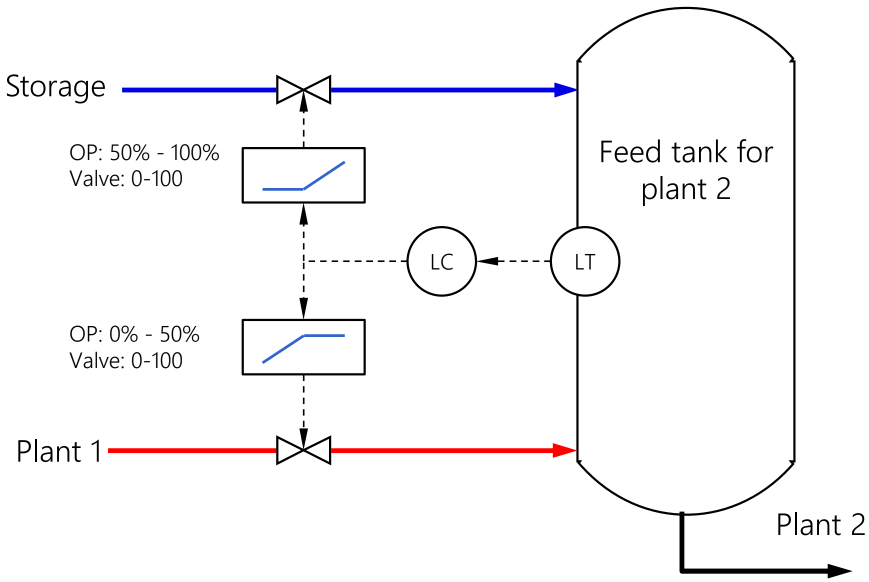
Answer:

1. With parallel controllers you can have different tuning parameters if the processes have different dynamics.
2. With parallel controllers the operator can set the valves manually, independently of each other, if they wish to.
3. Parallel controllers allow disturbances of short duration without immediately switching MV. "Grace period"
4. In some cases it is optimal to have two different steady state levels.

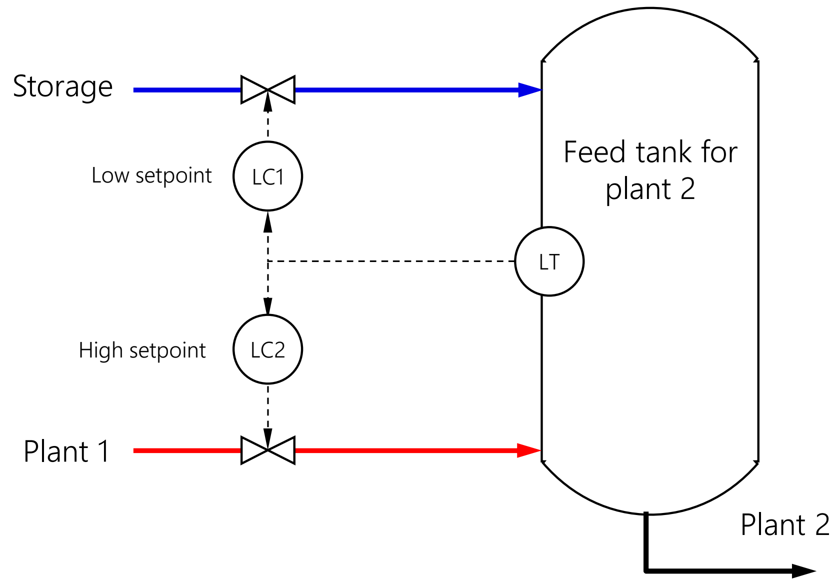
Level control with two feed streams

- In the example of a feed tank with two feed stream, we could have used parallel control as well.

Split-range control



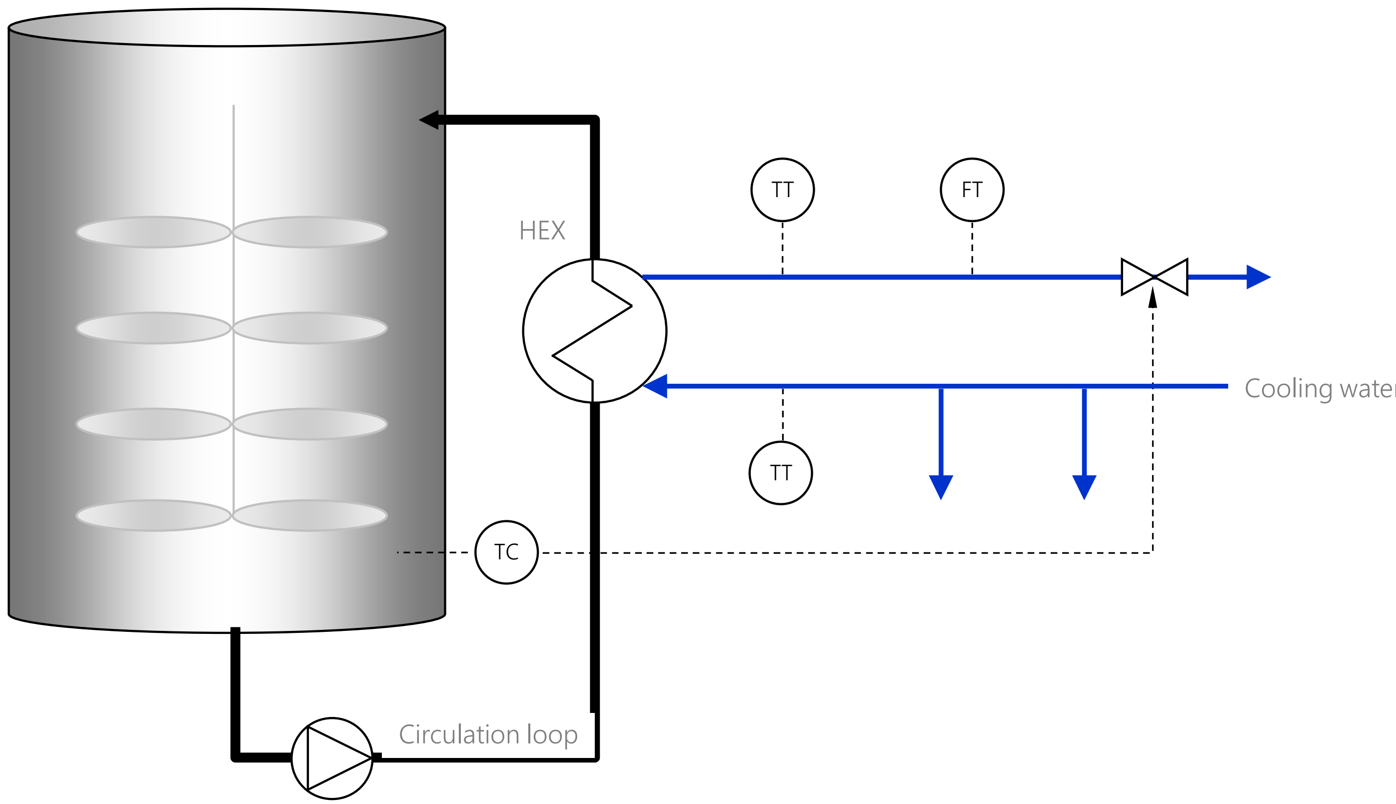
Parallel control



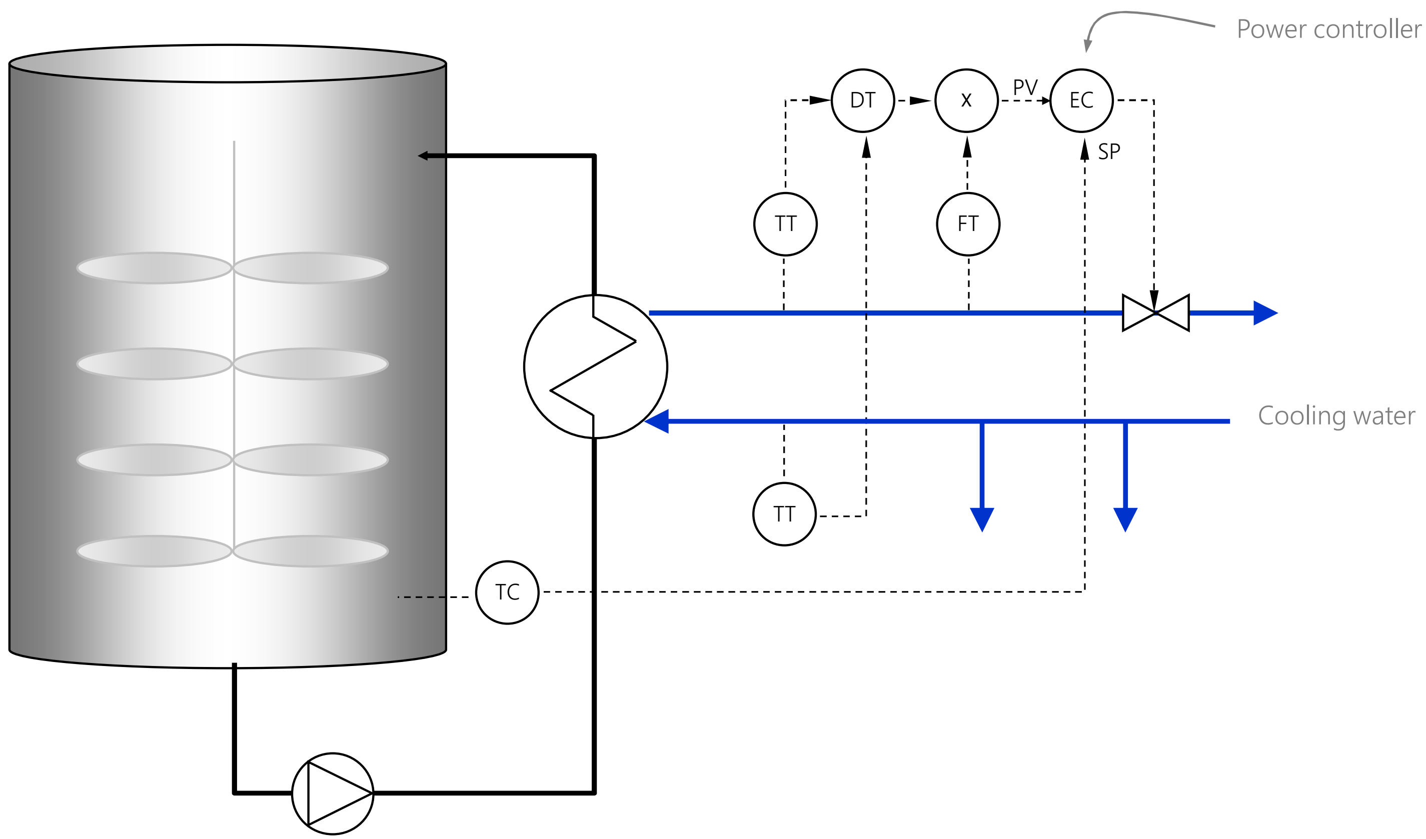
Heat exchanger control: exothermic reactor

Exothermic reactor temperature control

The reactor solution is circulated through a heat exchanger (cooler).
The reaction is very exothermic: it is important to control the temperature.
Typical variations/disturbances: Cooling water header pressure, CW temperature

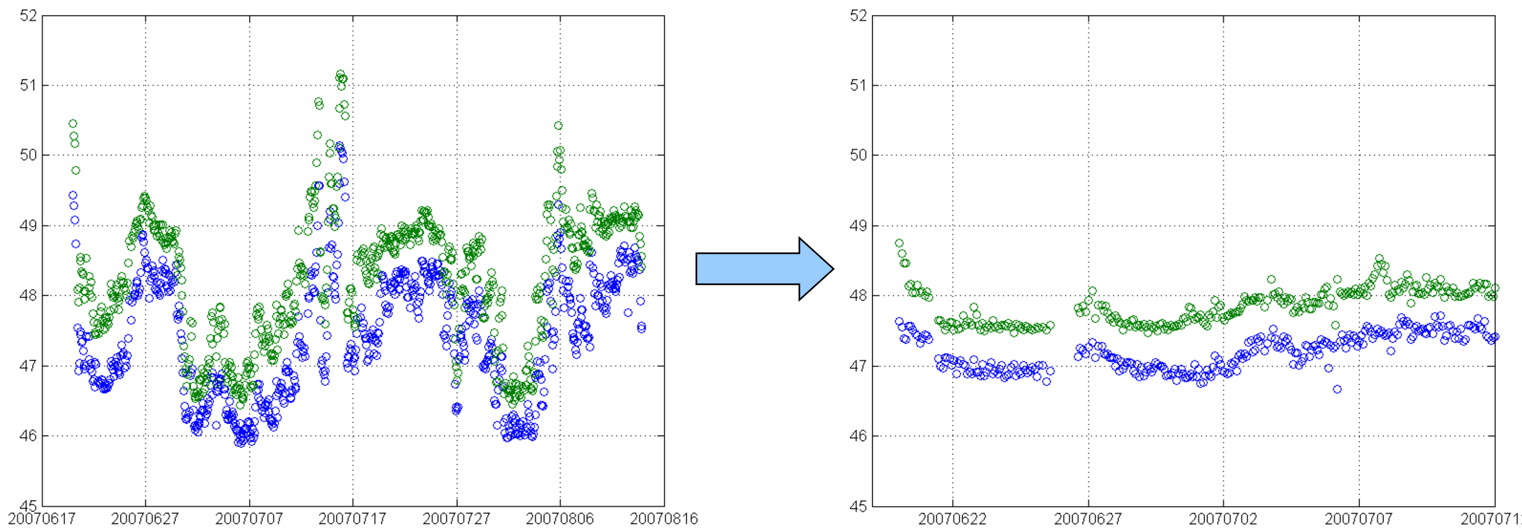


New control structure: Power control



HEX power control reduces variations between batches

Perstorp
A Subsidiary of PETRONAS Chemicals Group

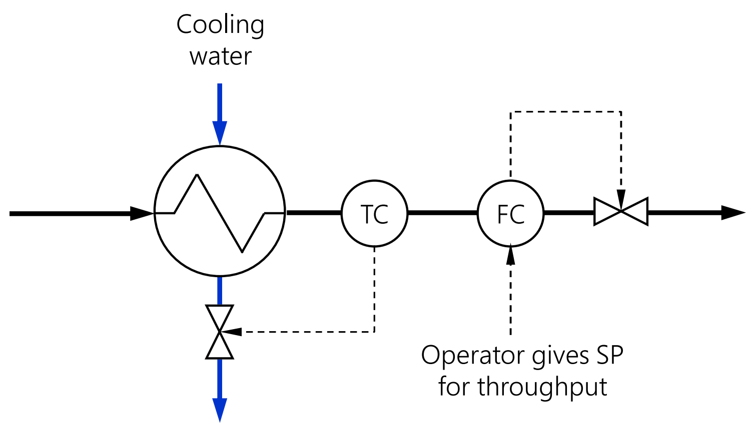


Heat exchanger control: Maximizing throughput

Maximizing throughput in a HEX (cooler)

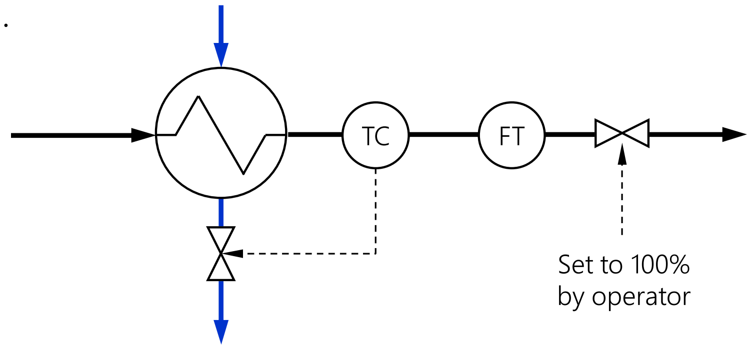
Temperature must be held at a given setpoint, e.g. 45 degrees.

"Traditional" structure:

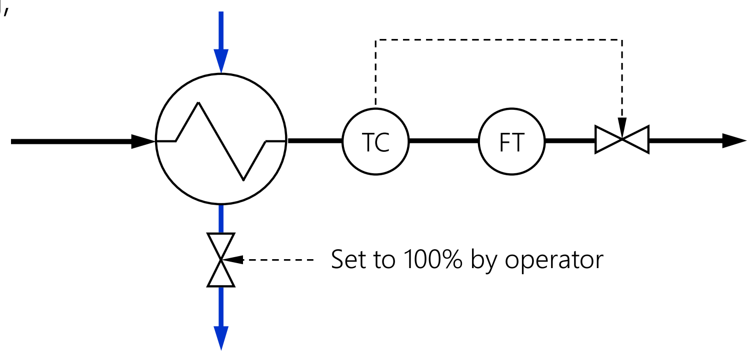


Maximizing throughput in a cooler; cont'd

If the flow valve is the limiting factor,
then this structure should be used.

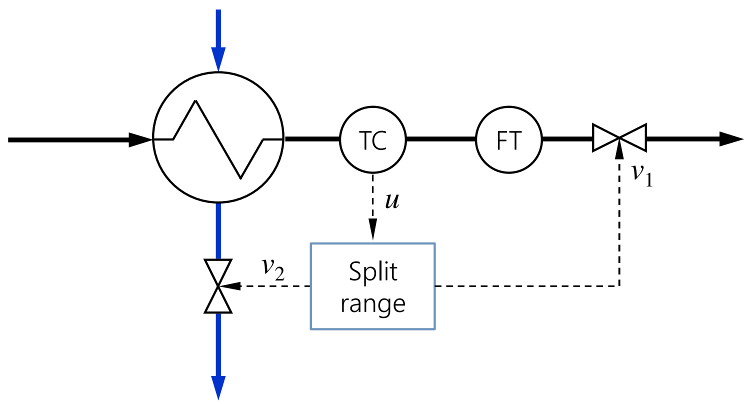


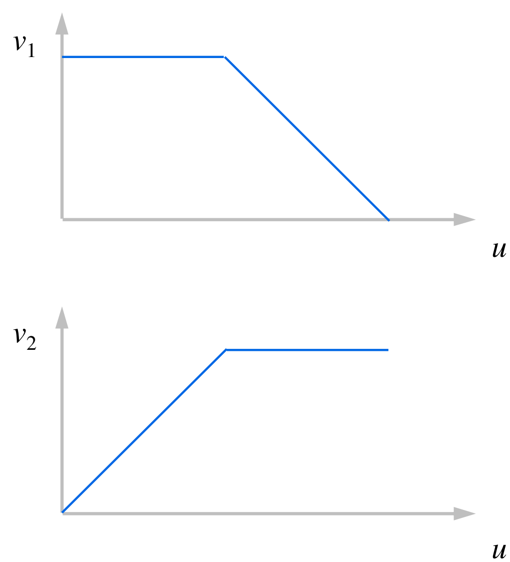
If the cooling water valve is limiting,
then use this structure.



Maximizing throughput in a cooler; cont'd

- It is not uncommon that sometimes the flow valve and sometimes the cw valve is limiting, e.g. due to cooling water temperature variations.
- There is a structure that handles both cases…





Bidirectional control

An application example

Application background

Perstorp
A Subsidiary of PETRONAS Chemicals Group

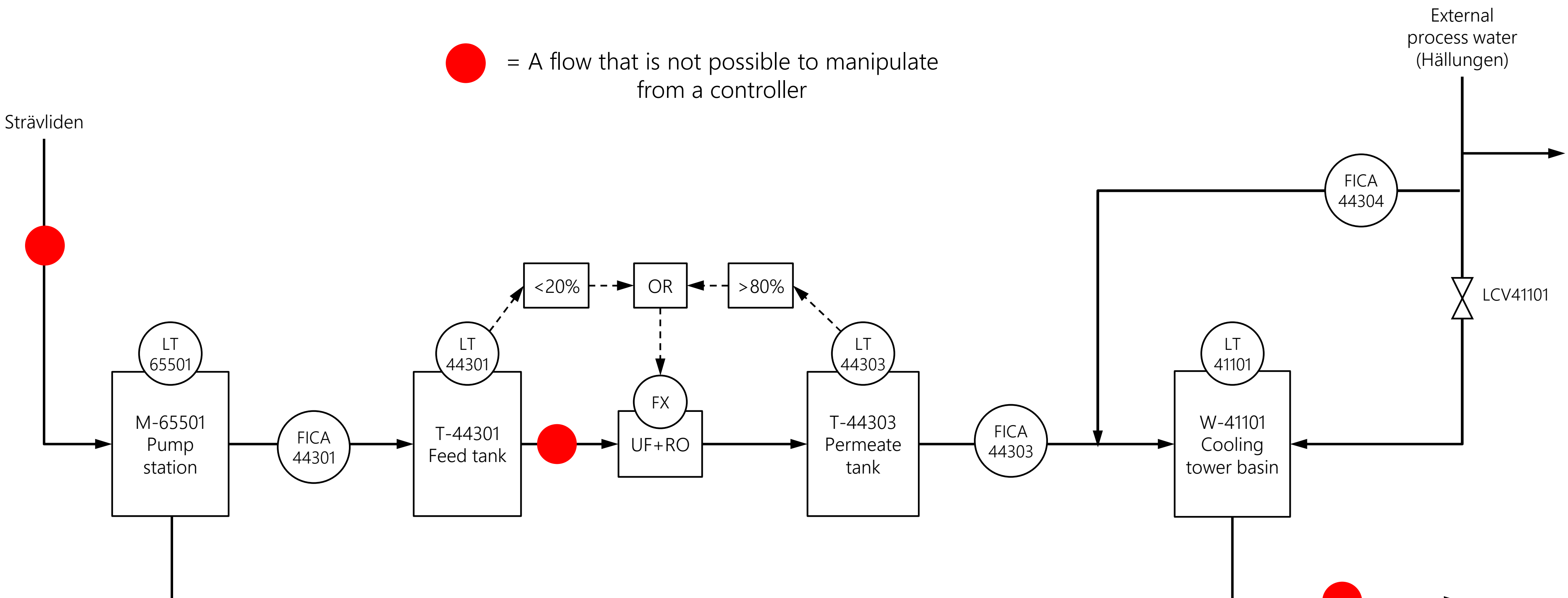
- We will connect to a new source for process water, in addition to the existing one. (Site: Stenungsund)
  - Motivated by sustainability: re-use waste water
- Control challenge: Buffer management
  - The bottle neck of the entire system is sometimes in waster water supply, sometimes in plant consumption and sometimes in purification (membrane unit).
  - How do we control buffer levels?
  - It is out of the question to let operators control the levels manually, because that would be too much work.

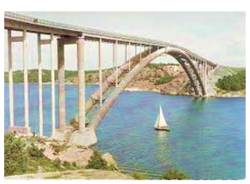
New source: Strävliden

Plant cooling towers

Existing source: Hällungen

Process, without controls

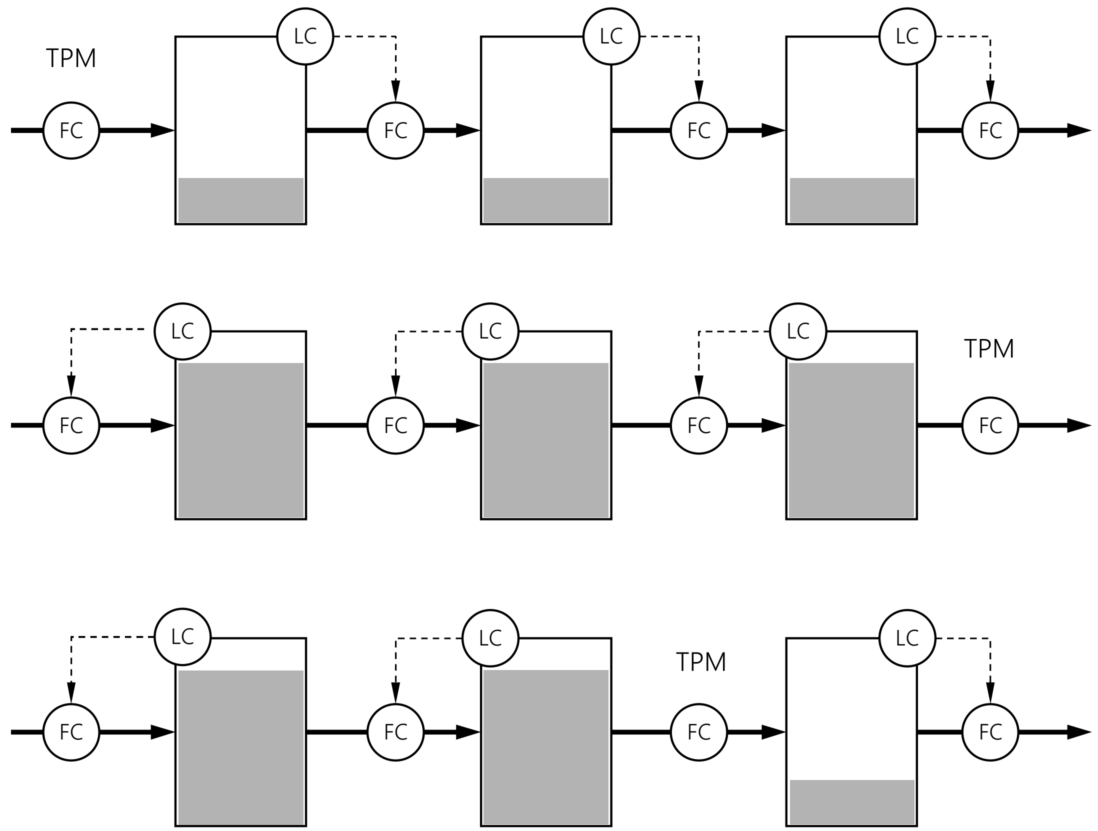




Askeröfjorden

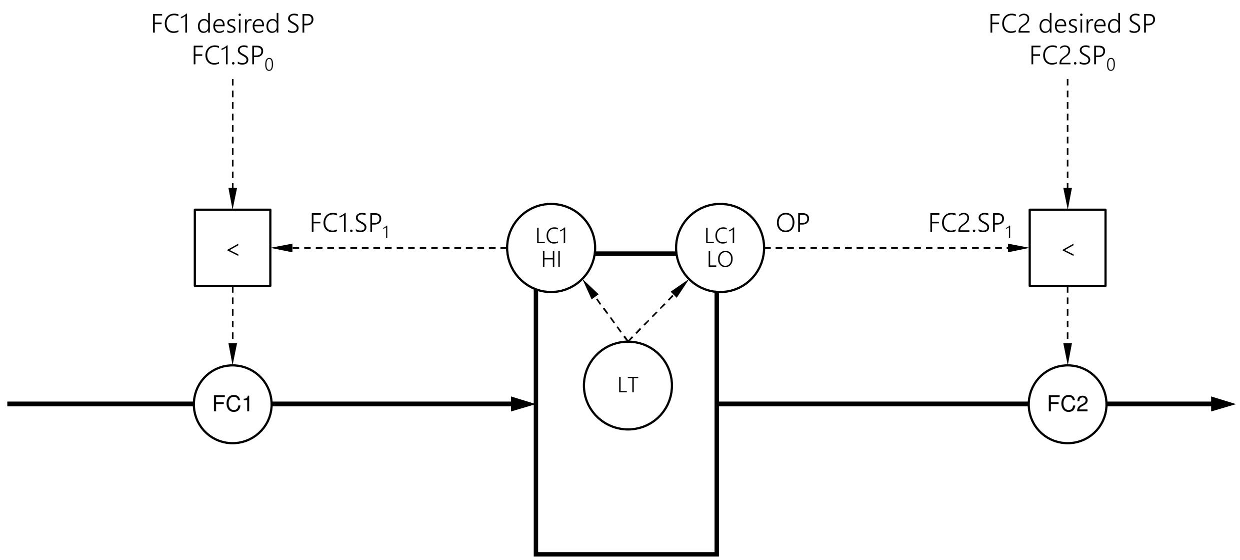
Recap: Bidirectional control

In a chain of inventories you may need different directionality of the level controllers depending on where the bottle neck (or throughput manipulator) is.



Basic element of bidirectional control

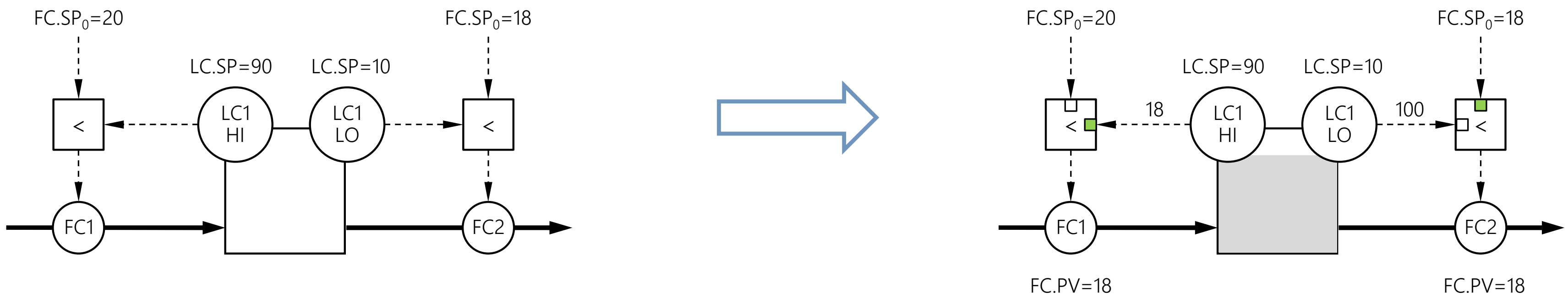
- A system of bidirectional controllers is made up from the following basic building block.



HI-controller: reverse acting
LO-controller: direct acting

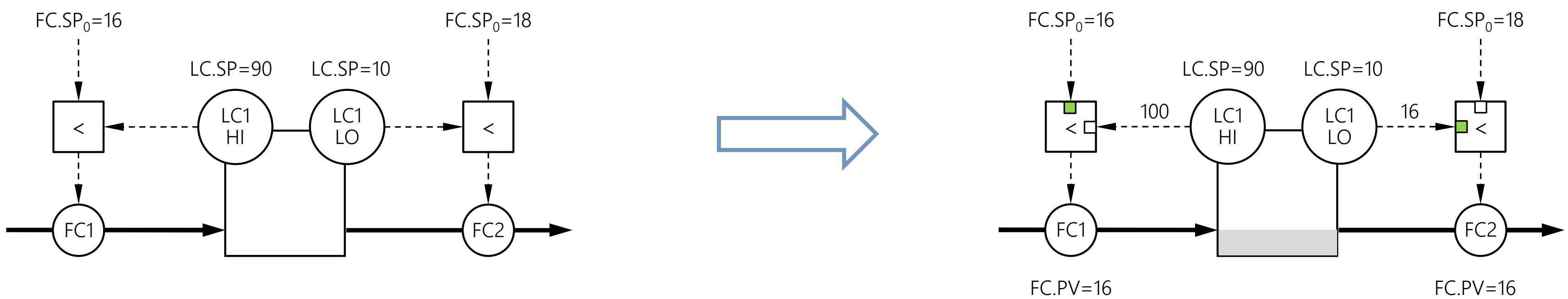
Examples

1



FC.SP$_0$=20
FC.SP$_0$=18
LC.SP=90
LC.SP=10
LC1 HI
LC1 LO
<
<
FC1
FC2
FC.SP$_0$=20
FC.SP$_0$=18
LC.SP=90
LC.SP=10
18
100
LC1 HI
LC1 LO
<
<
FC1
FC2
FC.PV=18
FC.PV=18

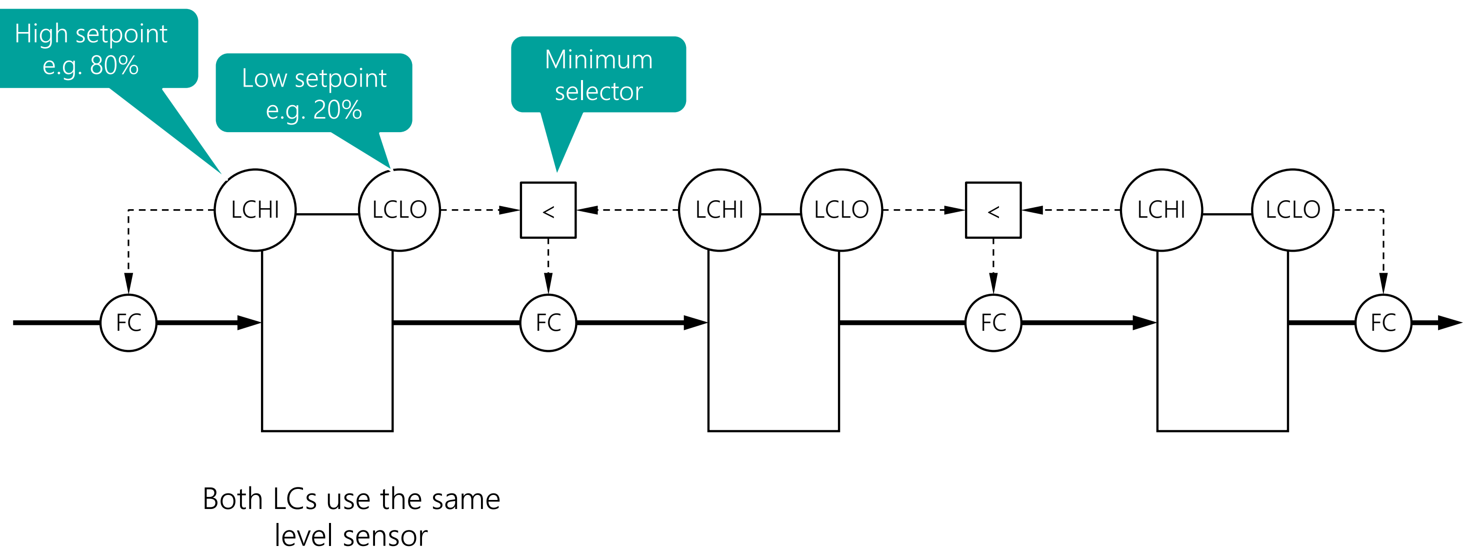
2



FC.SP$_0$=16
FC.SP$_0$=18
LC.SP=90
LC.SP=10
LC1 HI
LC1 LO
<
<
FC1
FC2
FC.SP$_0$=16
FC.SP$_0$=18
LC.SP=90
LC.SP=10
100
16
LC1 HI
LC1 LO
<
<
FC1
FC2
FC.PV=16
FC.PV=16

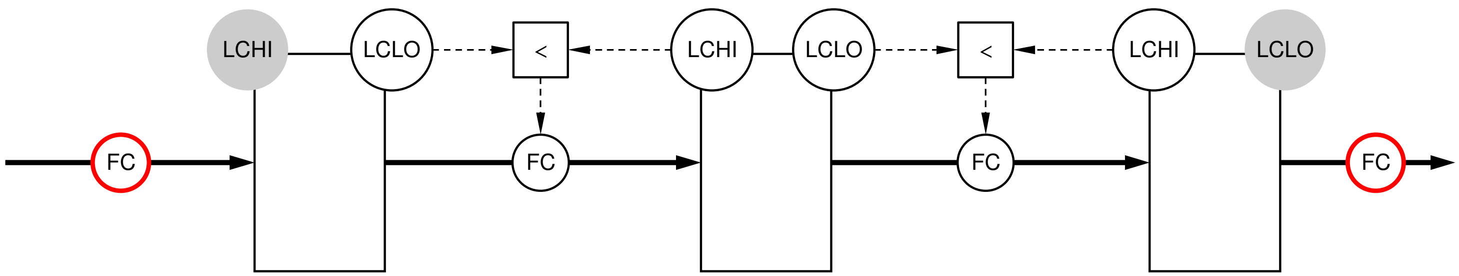
Continued recap

- A bidirectional control scheme handles all the cases automatically.
- The control structure reconfigures itself based on the position of the bottle neck.

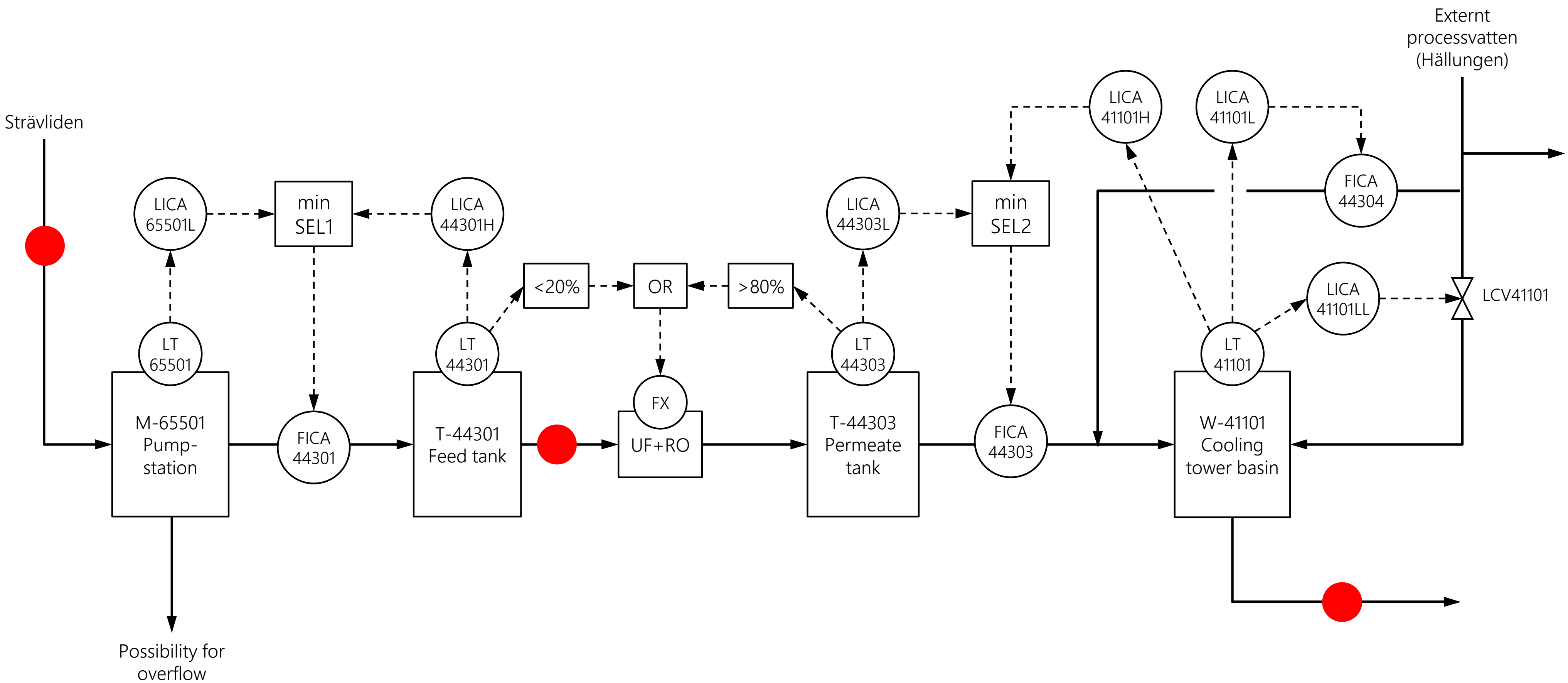


Comparison to simplified topology

- In this application, the level controllers cannot manipulate enough flows to control all levels.
- We need an overflow, and additional feed flow



Control solution implemented: Bidirectional control



Perstorp

A Subsidiary of PETRONAS Chemicals Group