IFAC World Congress 2020

Active Constraint Switching with the Generalized Split Range Control Structure using the *Baton Strategy*

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Norwegian University of Science and Technology

Agenda

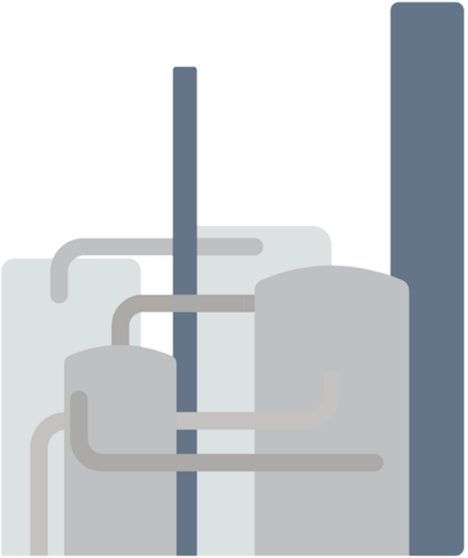
- Design of the control structure of a process plant
  - Active constraint switching with advanced control structures

- Constraint switching with advanced control structures
  - Split range control
    - Standard split range controllers
    - **Generalized split range controller**

- Case study: mixing of methanol and air

- Final comments

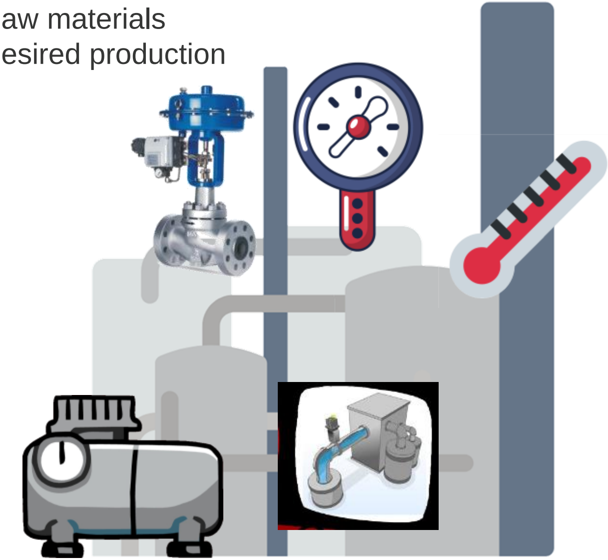
Design of the control structure of a process plant



Design of the control structure of a process plant

DV: disturbance variable (*d*)

- Ambient temperature
- Raw materials
- Desired production



CV: controlled variable (output, *y*)

- Temperature
- Pressure
- Concentration

MV: manipulated variable (input, *u*)

- Valve opening
- Compressor rotational speed

Design of the control structure of a process plant

DV: disturbance variable (*d*)

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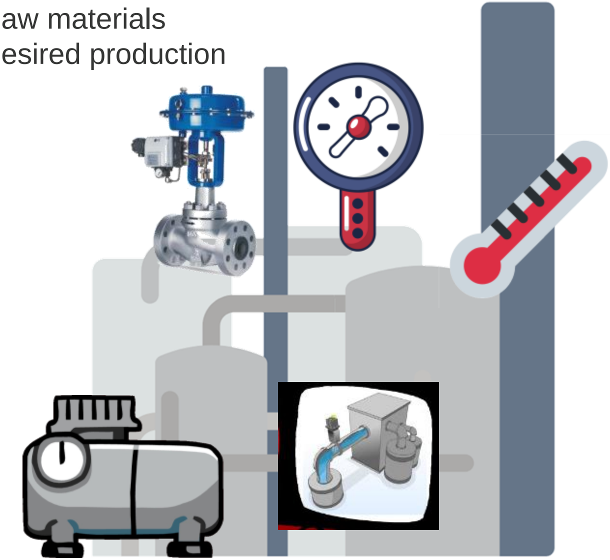

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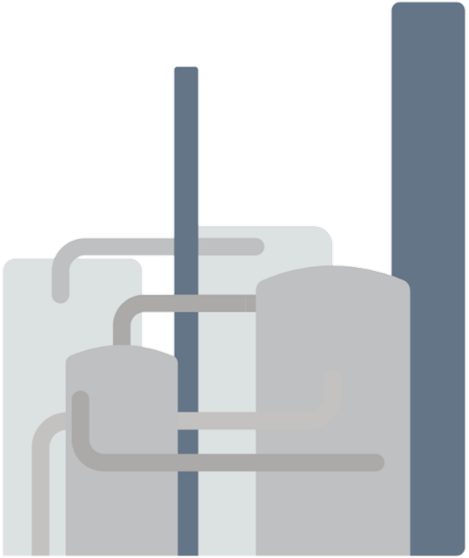
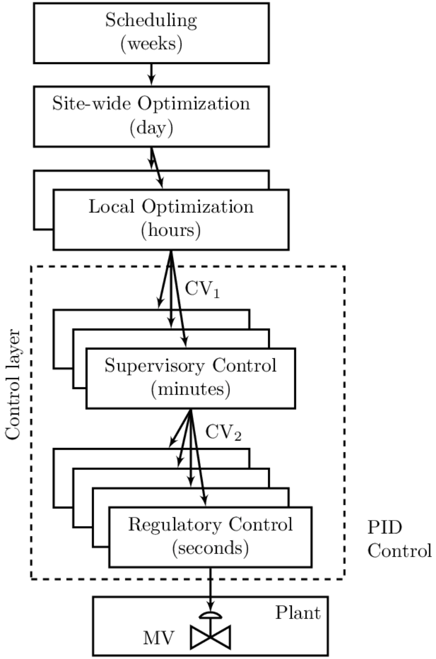
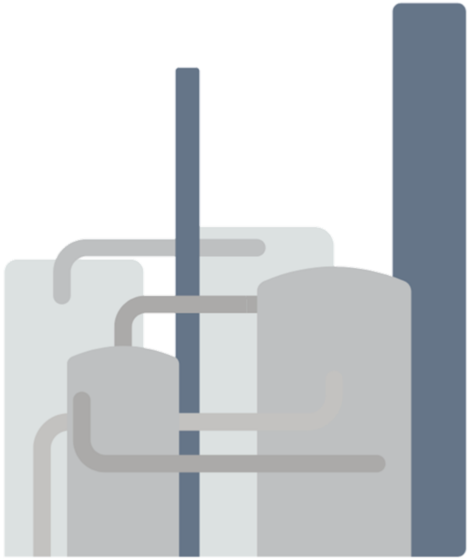
Design of the control structure of a process plant

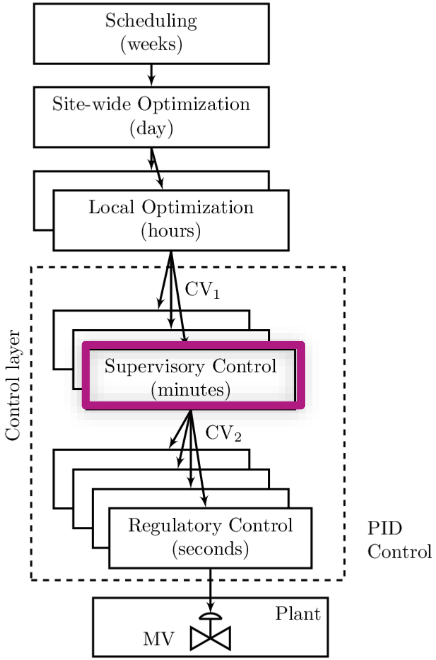




S. Skogestad, ``Control structure design for complete chemical plants'', Computers and Chemical Engineering, 28 (1-2), 219-234 (2004)

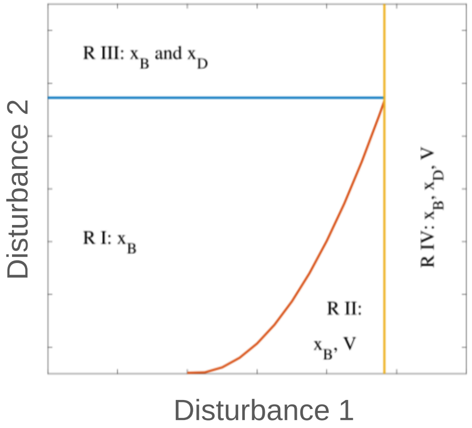
Design of the control structure of a process plant





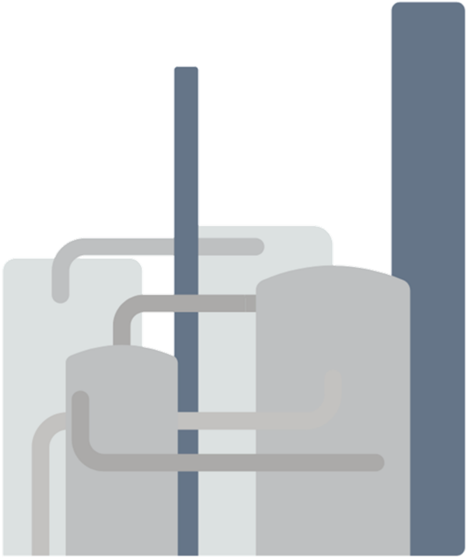
Constraint region

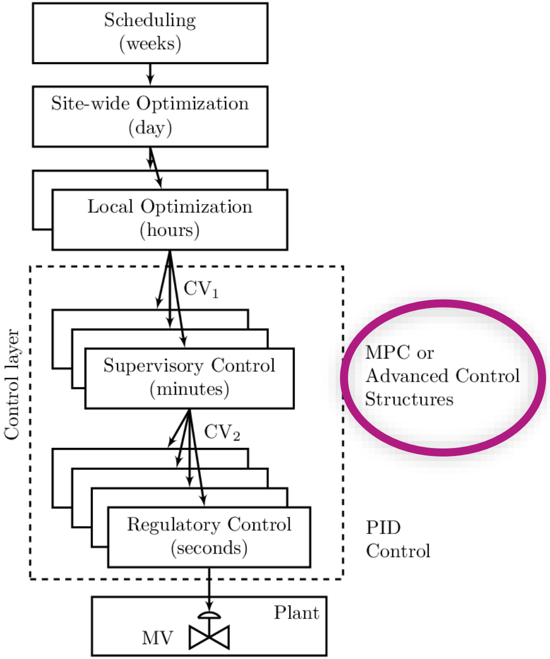
«region in the disturbance space defined by which constraints are active within it»



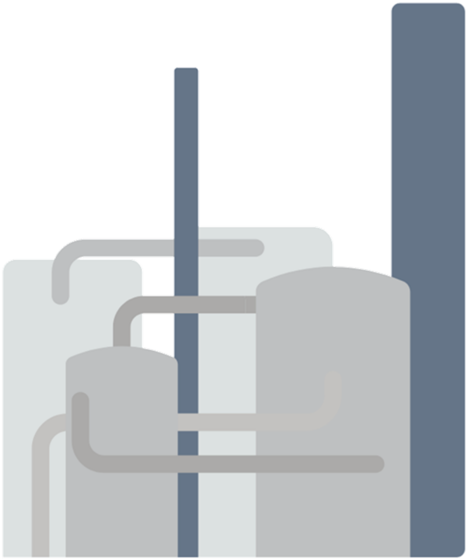
Jacobsen and Skogestad (2011) Active constraint regions for optimal operation of chemical processes. Industrial & Engineering Chemistry Research.

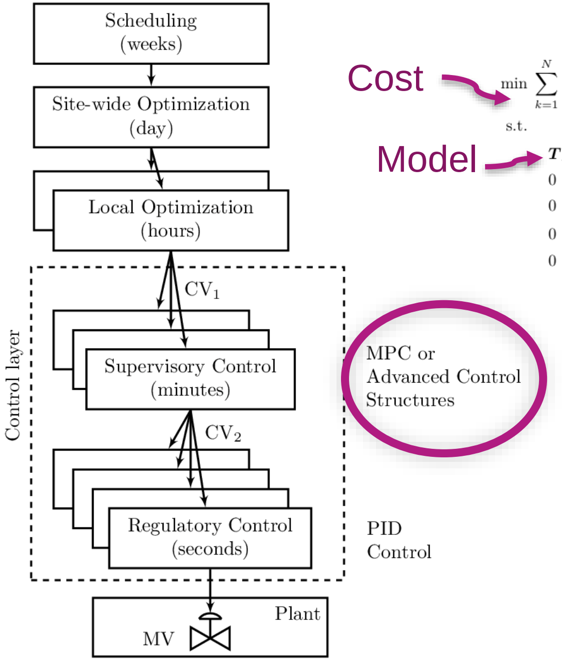
Design of the control structure of a process plant





Design of the control structure of a process plant





Model predictive control

Cost

$$\min \sum_{k=1}^{N} \left(\omega_1 \left\|(T_{H_k} - T_H^{sp})\right\|^2 + \omega_2 \left\|(F_{H_k}^{max} - F_{H_k})\right\|^2 \right)$$

s.t.

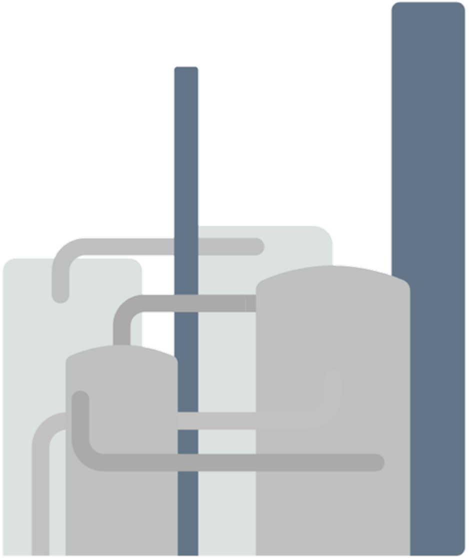
Model

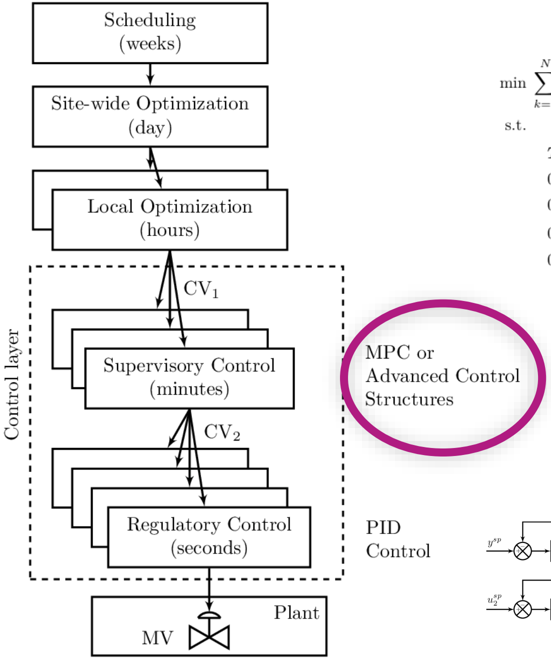
$$\left.\begin{aligned} &\boldsymbol{T}_{k,i} = f(T_{H_k,i}, T_{H_k,i-1}, T_{C_k,i}, T_{C_k,i+1}, F_{H_k}, F_{C_k}) \\ &0 \le F_{H_k} \le F_H^{max} \\ &0 \le F_{C_k} \le F_C^{max} \end{aligned}\right\} \quad \forall k \in \{1, \dots, N\}$$

$$\left.\begin{aligned} &0 \le \Delta F_{H_k} \le 0.1 F_H^{max} \\ &0 \le \Delta F_{C_k} \le 0.1 F_C^{max} \end{aligned}\right\} \quad \forall k \in \{1, \dots, N-1\}$$

Constraints

Design of the control structure of a process plant





MPC or
Advanced Control
Structures

PID
Control

Model predictive control

$$\min \sum_{k=1}^{N} \left(\omega_1 \left\| (T_{H_k} - T_H^{sp}) \right\|^2 + \omega_2 \left\| (F_{H_k}^{max} - F_{H_k}) \right\|^2 \right)$$

s.t.

$$\left.\begin{array}{l} \boldsymbol{T}_{k,i} = f(T_{H_k,i}, T_{H_k,i-1}, T_{C_k,i}, T_{C_k,i+1}, F_{H_k}, F_{C_k}) \\ 0 \leq F_{H_k} \leq F_H^{max} \\ 0 \leq F_{C_k} \leq F_C^{max} \end{array}\right\} \qquad \forall k \in \{1, \dots, N\}$$

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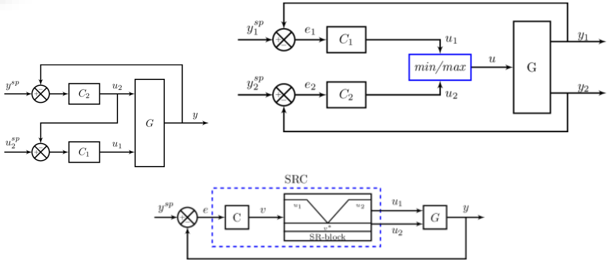
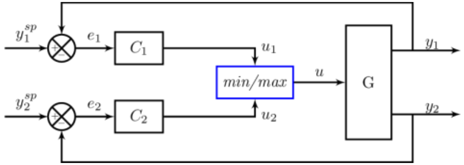
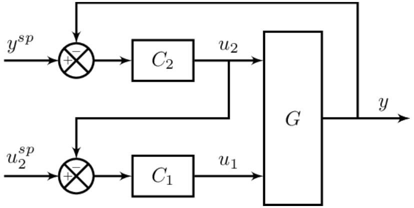
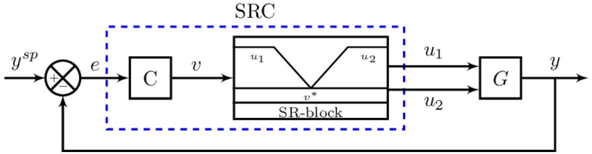
Advanced control structures



Active constraint switching with classical advanced control structures







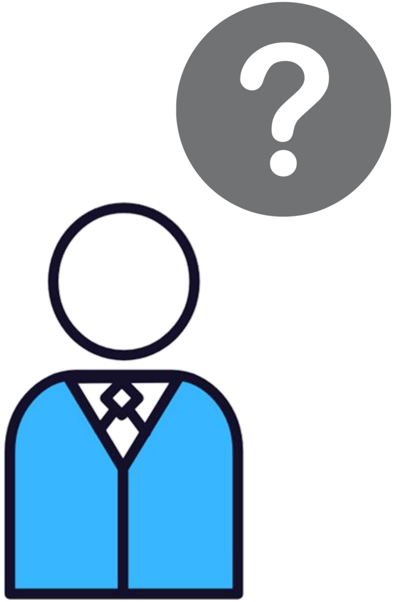
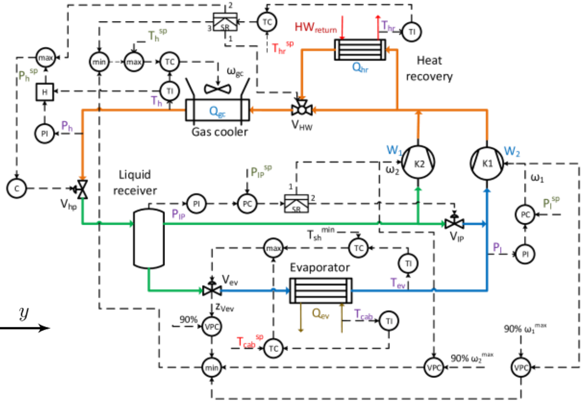
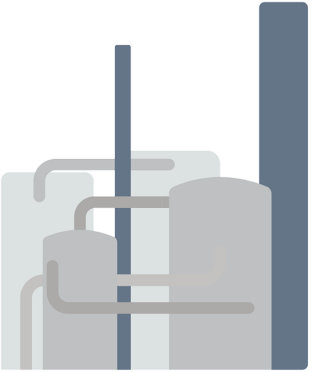
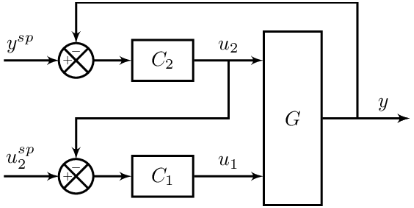


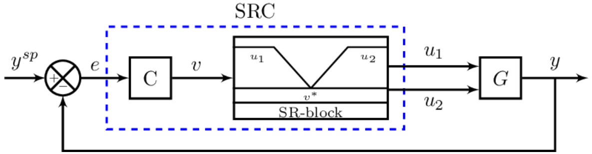
Figure taken from www.transmittershop.com/blog/causes-solutions-annoying-noise-control-valves

Active constraint switching with classical advanced control structures









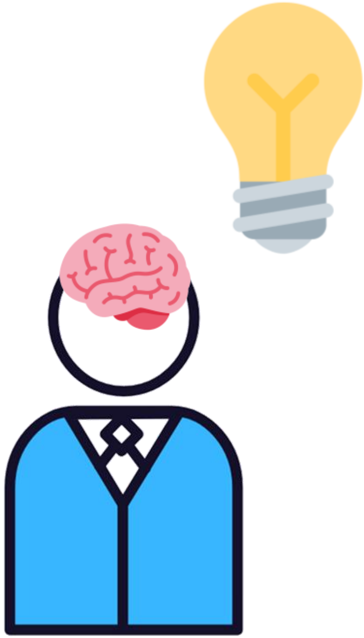
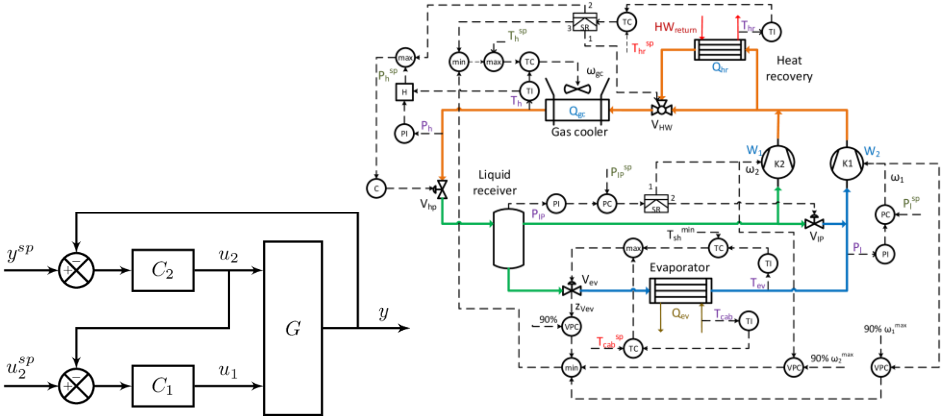
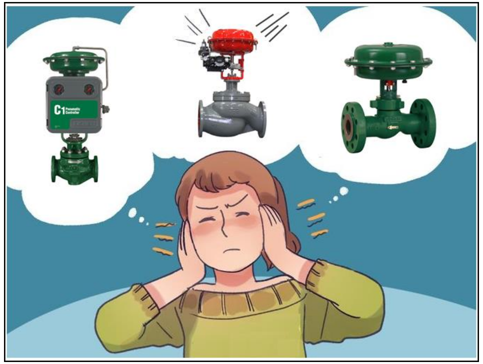


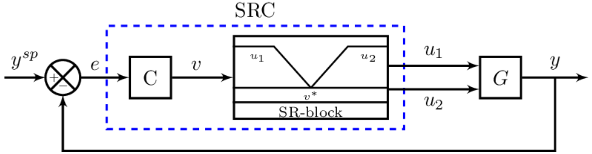
Figure taken from www.transmittershop.com/blog/causes-solutions-annoying-noise-control-valves

A. Reyes-Lúa, S. Skogestad. "Generalized Split Range Control Structure using the Baton Strategy"

Active constraint switching with classical advanced control structures





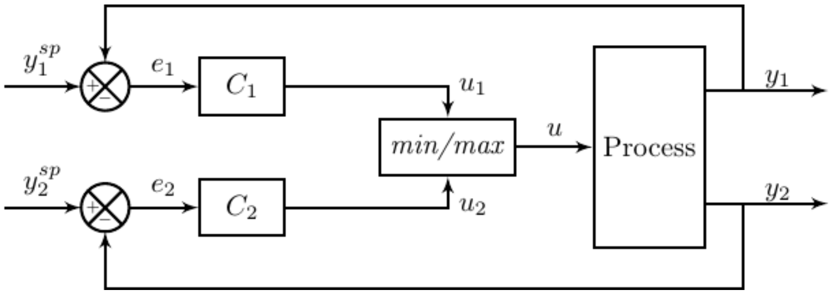


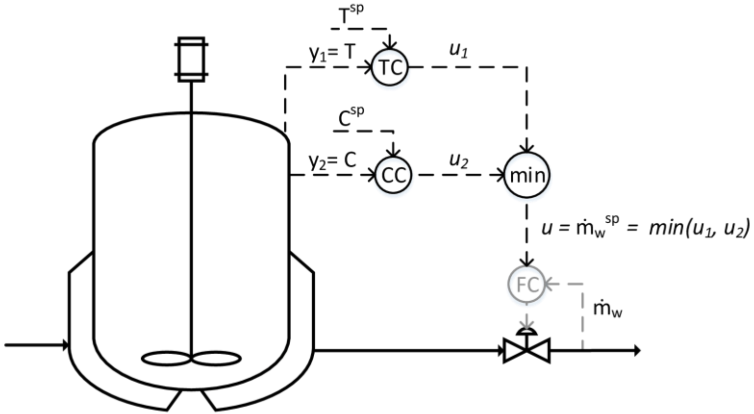
Reyes-Lúa, Adriana; Skogestad, Sigurd. (2019) Systematic Design of Active Constraint Switching Using Classical Advanced Control Structures. Industrial & Engineering Chemistry Research. vol. 56 (6).
Reyes-Lúa, Adriana; Andreasen, Glenn; Larsen, Lars F.S.; Stoustrup, Jakob; Skogestad, Sigurd. (2019) Control structure design for a CO_2-refrigeration system with heat recovery. Computer-aided chemical engineering. vol. 46.

Figure taken from www.transmittershop.com/blog/causes-solutions-annoying-noise-control-valves

Active constraint switches

- **Case 1: CV to CV constraint switching**
  One MV switching between two alternative CVs.

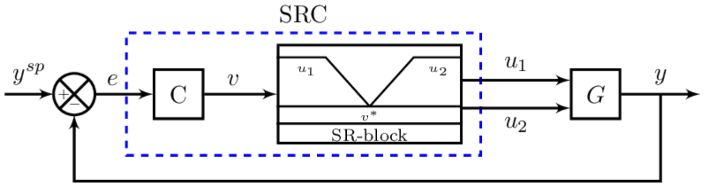




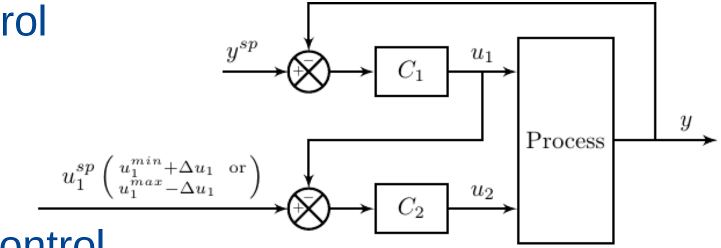
RReyes-Lúa, Adriana; Skogestad, Sigurd. (2019) Systematic Design of Active Constraint Switching Using Classical Advanced Control Structures. Industrial & Engineering Chemistry Research. vol. 56 (6).
Krishnamoorthy, Dinesh; Skogestad, Sigurd. (2019) Online Process Optimization with Active Constraint Set Changes using Simple Control Structures. Industrial & Engineering Chemistry Research. vol. 58 (30).

Active constraint switches

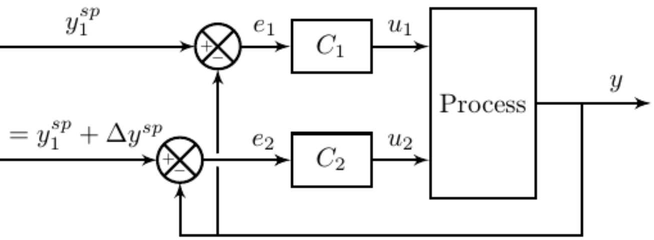
- **Case 2: MV to MV constraint switching**
  More than one MV for one CV.



Split range control



Valve position control



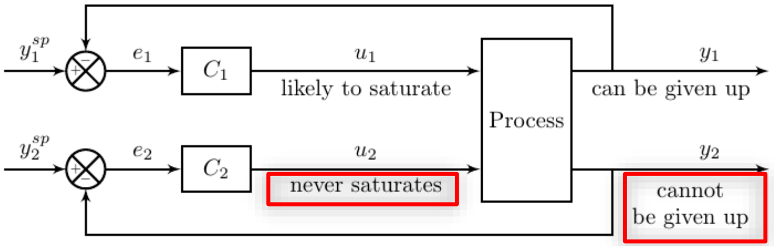
Different controllers with different setpoints

Reyes-Lúa, Adriana; Skogestad, Sigurd. (2019) Systematic Design of Active Constraint Switching Using Classical Advanced Control Structures. Industrial & Engineering Chemistry Research. vol. 56 (6).
Reyes-Lúa and Skogestad (2019) Multiple-Input Single-Output Control for Extending the Steady-State Operating Range—Use of Controllers with Different Setpoints. Processes 7 (12), 941

Active constraint switches

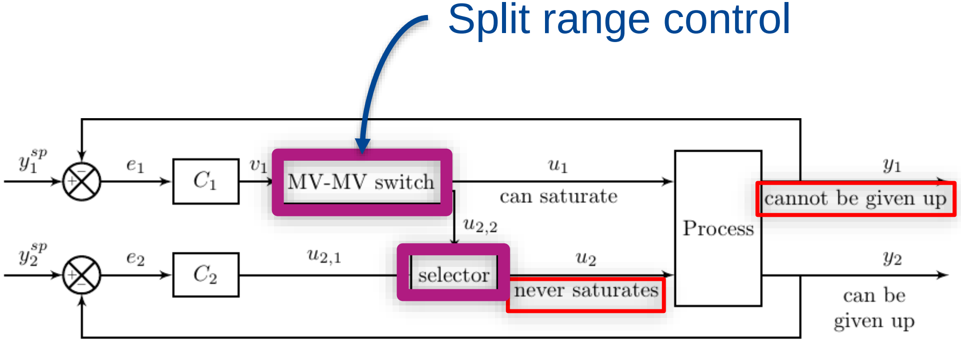
- **Case 3: MV to CV constraint switching**

  MV controlling a CV that may saturate; no extra MVs



Following the *input saturation pairing rule*

Split range control

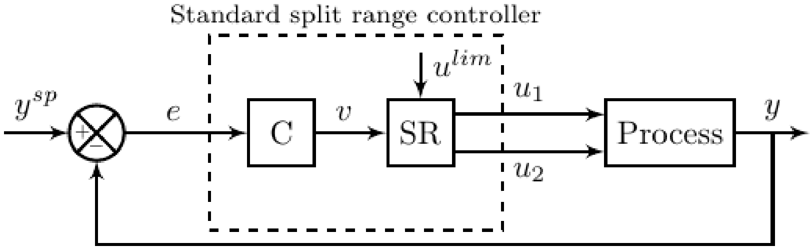


NOT following the *input saturation pairing rule*

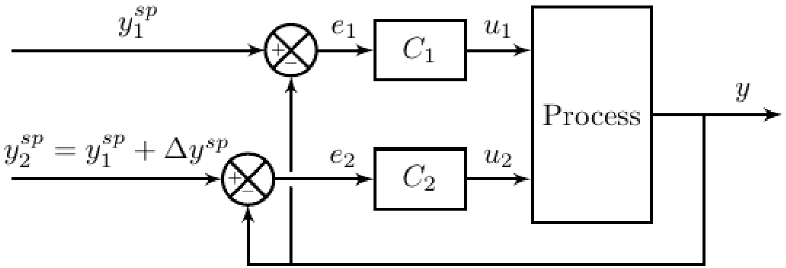
Reyes-Lúa, Adriana; Skogestad, Sigurd. (2019) Systematic Design of Active Constraint Switching Using Classical Advanced Control Structures. Industrial & Engineering Chemistry Research. vol. 56 (6).
A Reyes-Lúa, C Zotică, S Skogestad (2018) Optimal operation with changing active constraint regions using classical advanced control. IFAC-PapersOnLine 51 (18), 440-445

MV to MV constraint switching

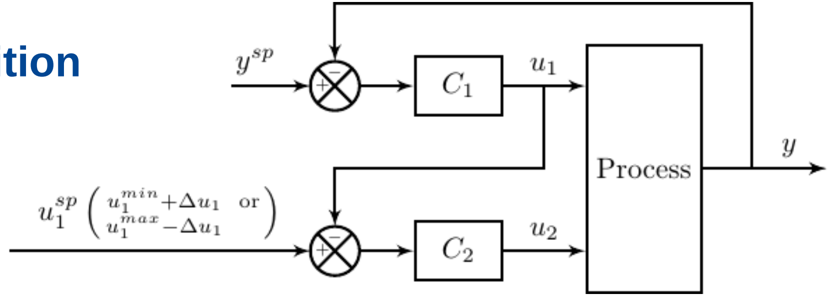
Split range control



Different controllers with different setpoints



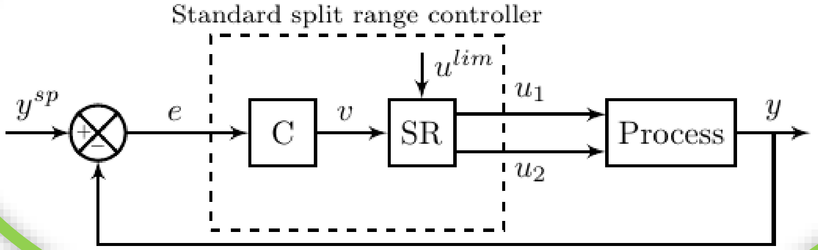
Valve position control



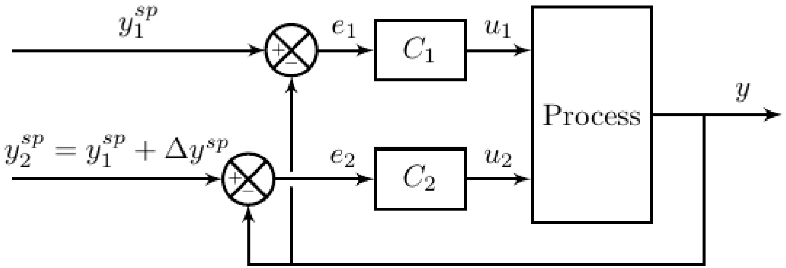
A. Reyes-Lúa, S. Skogestad. "Generalized Split Range Control Structure using the Baton Strategy"

MV to MV constraint switching

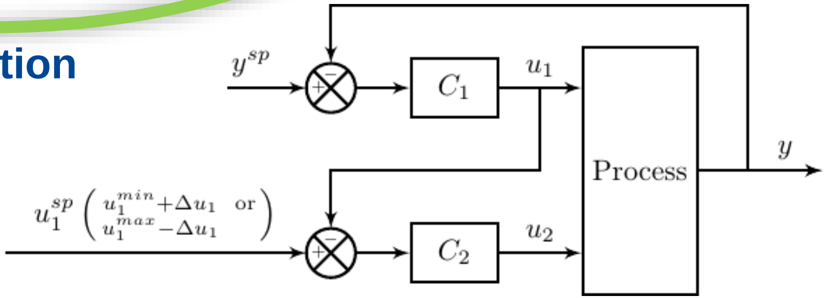
Split range control



Different controllers with different setpoints



Valve position control



Classical split range control

INSTRUMENTS AND PROCESS CONTROL

Information Sheet 9

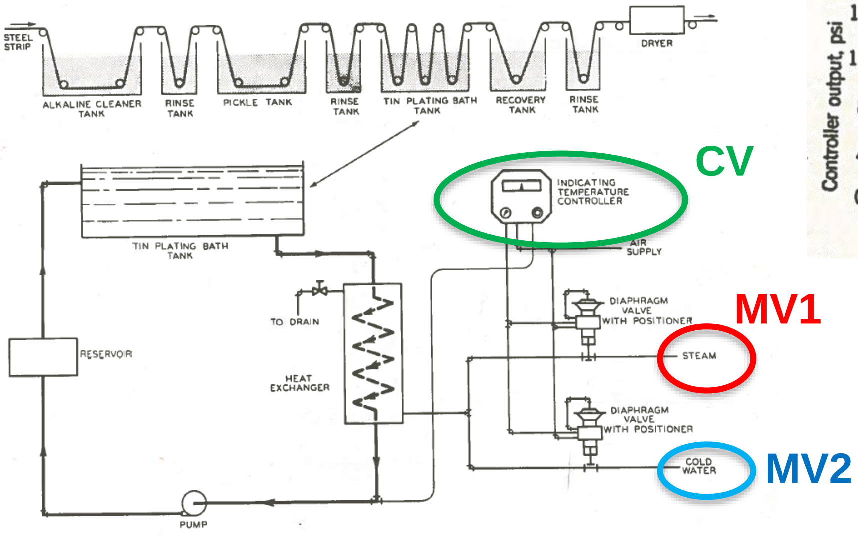
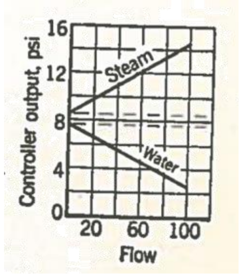
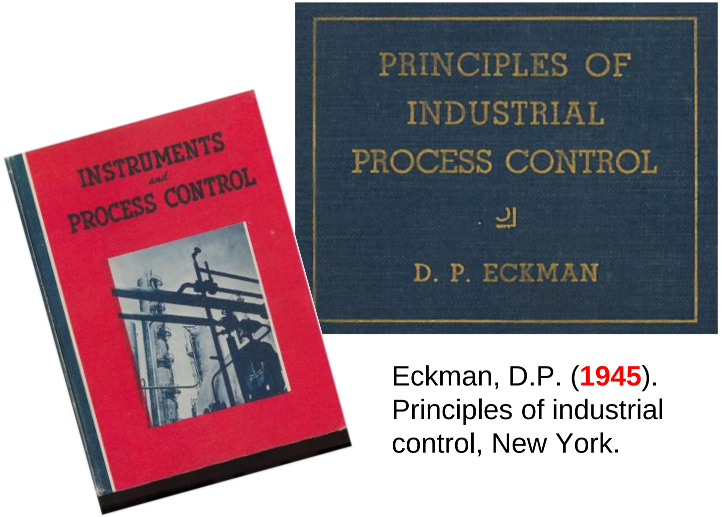


Fig. 125 - Temperature Control for a Tin Plating Bath

Courtesy of Taylor Instrument Companies

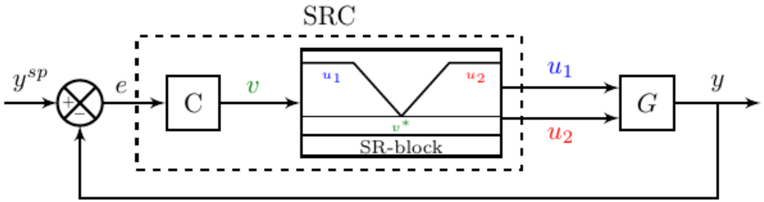


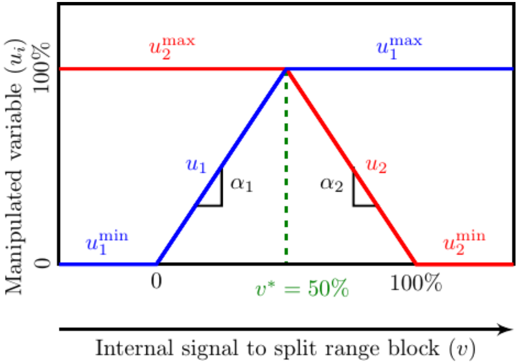


Eckman, D.P. (**1945**). Principles of industrial control, New York.

Monogram of Instruments and Process Control prepared at Cornell, NY, in **1945**

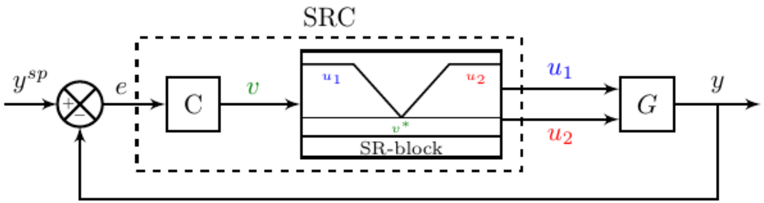
Classical split range control

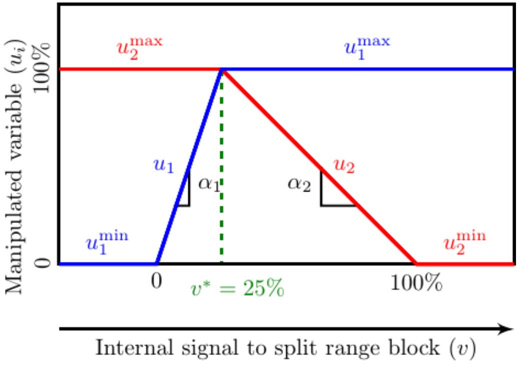




Reyes-Lúa, Adriana; Zotica, Cristina Florina; Forsman, Leif Krister; Skogestad, Sigurd. (2019) Systematic Design of Split Range Controllers. IFAC-PapersOnLine. vol. 52 (1).

Classical split range control





v	internal signal to split range block→ limited physical meaning
v^*	split value → degree of freedom
u_i	controller output (input to process) → physical meaning
α_i	gain from v to u_i → slope

$$u_i = u_{i,0} + \alpha_i \ v \quad \forall i \in \{1, \ldots, N\}$$

Reyes-Lúa, Adriana; Zotica, Cristina Florina; Forsman, Leif Krister; Skogestad, Sigurd. (2019) Systematic Design of Split Range Controllers. IFAC-PapersOnLine. vol. 52 (1).

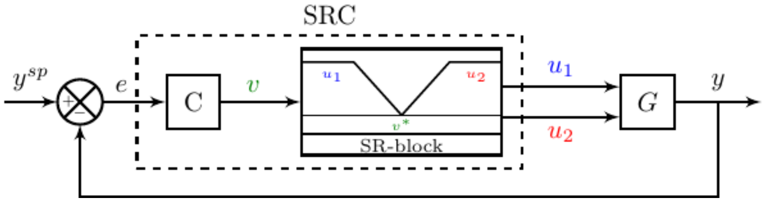
Classical split range control: a compromise

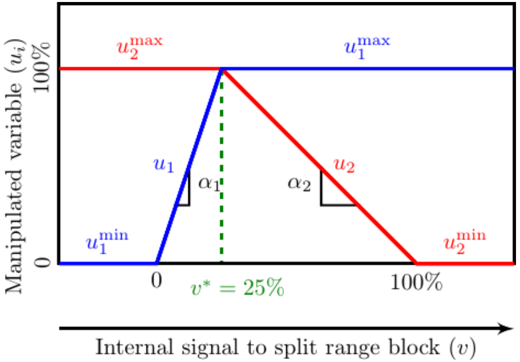
$$C(s) = K_C\left(1 + \frac{1}{\tau_I s}\right)$$

2 tuning parameters

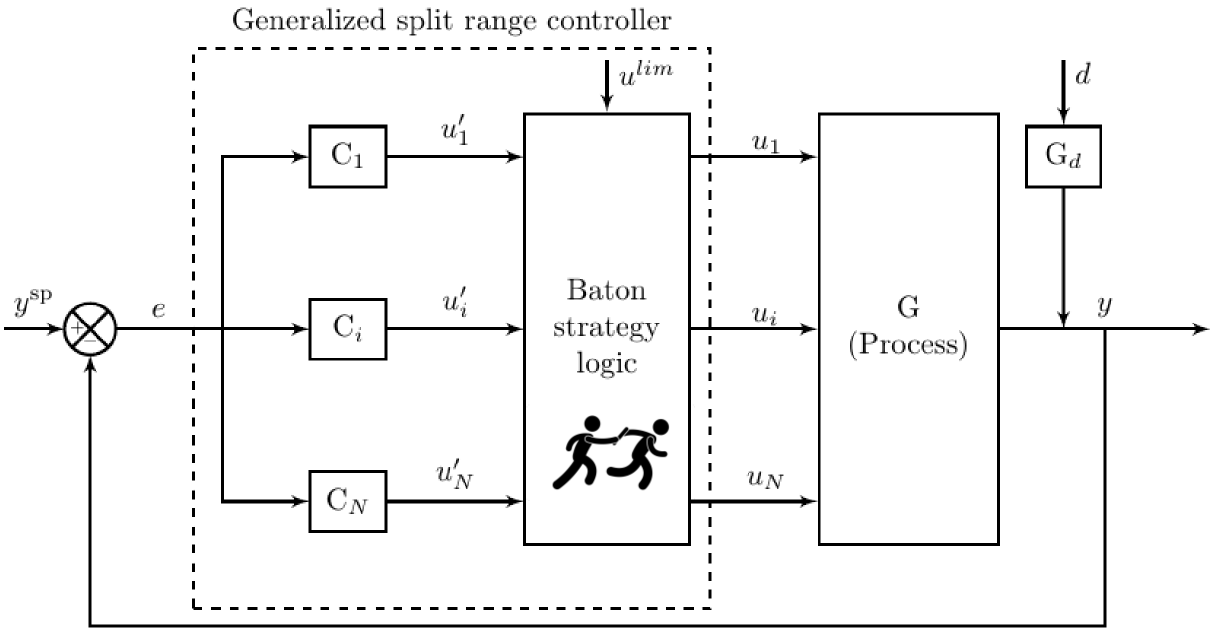
$$K_{C,i} = \alpha_i K_C$$

1 DOF



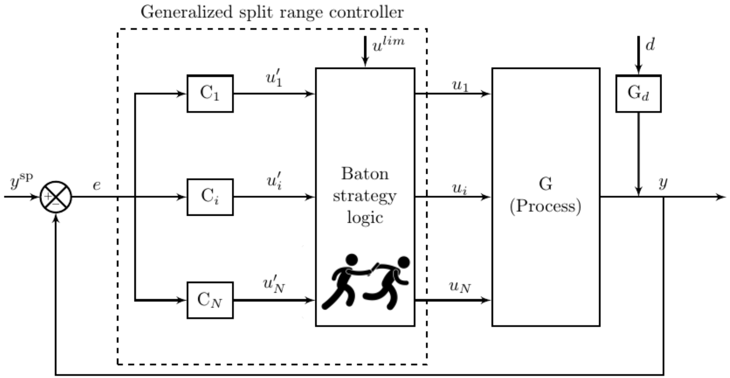


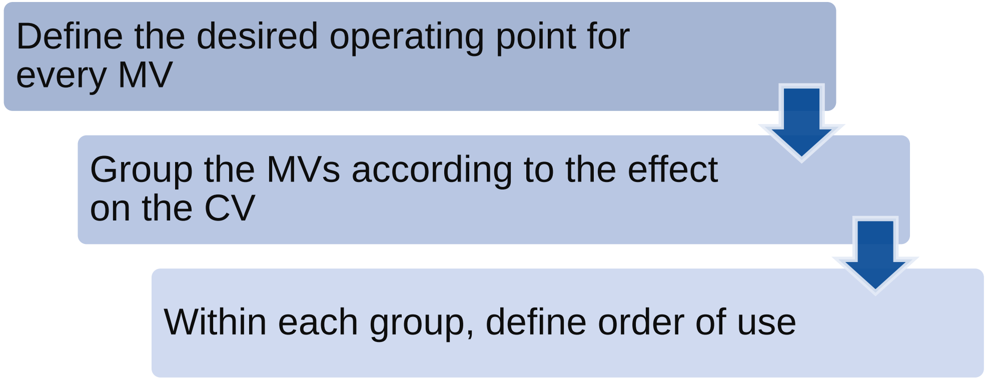
Generalized split range controller



Reyes-Lúa, Adriana; Skogestad, Sigurd. (2020) Multi-input single-output control for extending the operating range: Generalized split range control using the baton strategy. Journal of Process Control. vol. 91.

Generalized split range controller





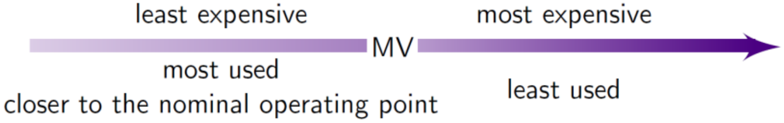
Define the desired operating point for every MV

Group the MVs according to the effect on the CV

Within each group, define order of use

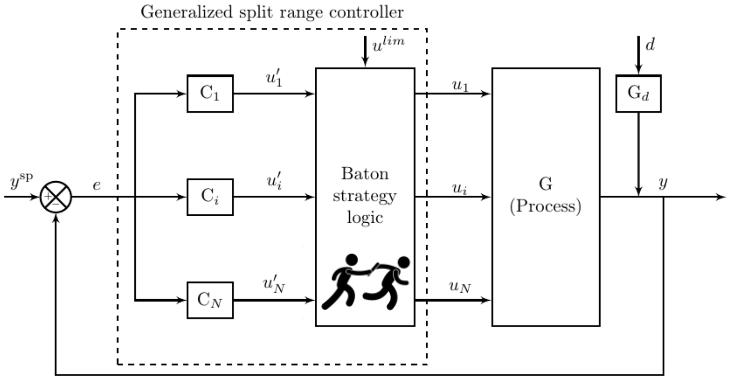
Preliminary step:

- Define order of use of MVs (*j*=1,…,N)
- Tune controllers



Reyes-Lúa, Adriana; Zotica, Cristina Florina; Forsman, Leif Krister; Skogestad, Sigurd. (2019) Systematic Design of Split Range Controllers. IFAC-PapersOnLine. vol. 52 (1).
Reyes-Lúa, Adriana; Skogestad, Sigurd. (2020) Multi-input single-output control for extending the operating range: Generalized split range control using the baton strategy. Journal of Process Control. vol. 91.

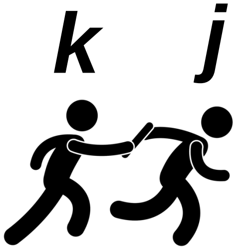
Generalized split range controller



Preliminary step:

- Define order of use of MVs (*j*=1,…,N)
- Tune controllers

«Baton strategy» logic

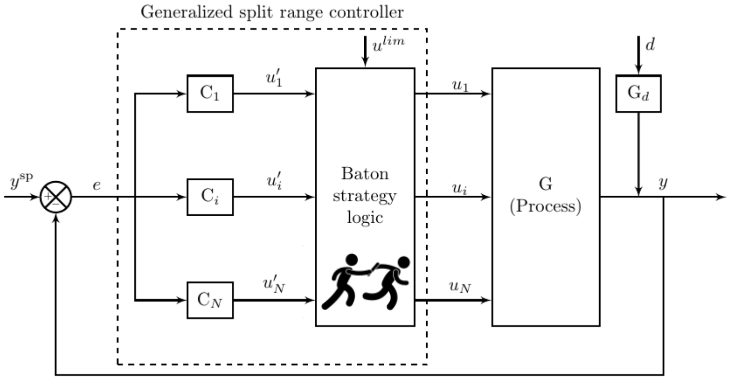


k is the active input

- C_k computes u_k' (suggested value for u_k)
- If $u_k^{min} < u_k' < u_k^{max}$
  - Keep u_k active and $u_k \leftarrow u_k'$
  - Keep remaining u_i at limiting value
- else
  - Set $u_k = u_k^{min}$ or $u_k < u_k^{max}$, depending on the reached limit
  - New active input selected according to predefined sequence (*j*= *k*-1 or *j*=*k*+1)

Reyes-Lúa, Adriana; Skogestad, Sigurd. (2020) Multi-input single-output control for extending the operating range: Generalized split range control using the baton strategy. Journal of Process Control. vol. 91.

Generalized split range controller



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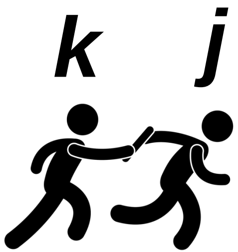

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  - Set $u_k = u_k^{min}$ or $u_k < u_k^{max}$, depending on the reached limit
  - New active input selected according to predefined sequence (*j*= *k*-1 or *j*=*k*+1)

The active input will *decide* when to switch and will remain active as long as it is not saturated.

Reyes-Lúa, Adriana; Skogestad, Sigurd. (2020) Multi-input single-output control for extending the operating range: Generalized split range control using the baton strategy. Journal of Process Control. vol. 91.

Generalized split range controller: initialization

"I'm the new *k*"

Reyes-Lúa, Adriana; Skogestad, Sigurd. (2020) Multi-input single-output control for extending the operating range: Generalized split range control using the baton strategy. Journal of Process Control. vol. 91.

Generalized split range controller: initialization

"I'm the new *k*"

$$\boxed{u'_k(t)} = u_k^0 + K_{C,k}\left(e(t) + \frac{1}{\tau_{I,k}} \underbrace{\int_{t_b}^{t} e(t)}\right)$$

This suggested input was not being applied while (new) input *k* was not in use

This accumulated error is not due to the previous actions of (new) input *k*

Reyes-Lúa, Adriana; Skogestad, Sigurd. (2020) Multi-input single-output control for extending the operating range: Generalized split range control using the baton strategy. Journal of Process Control. vol. 91.

Generalized split range controller: initialization

"I'm the new *k*"

Resetting:

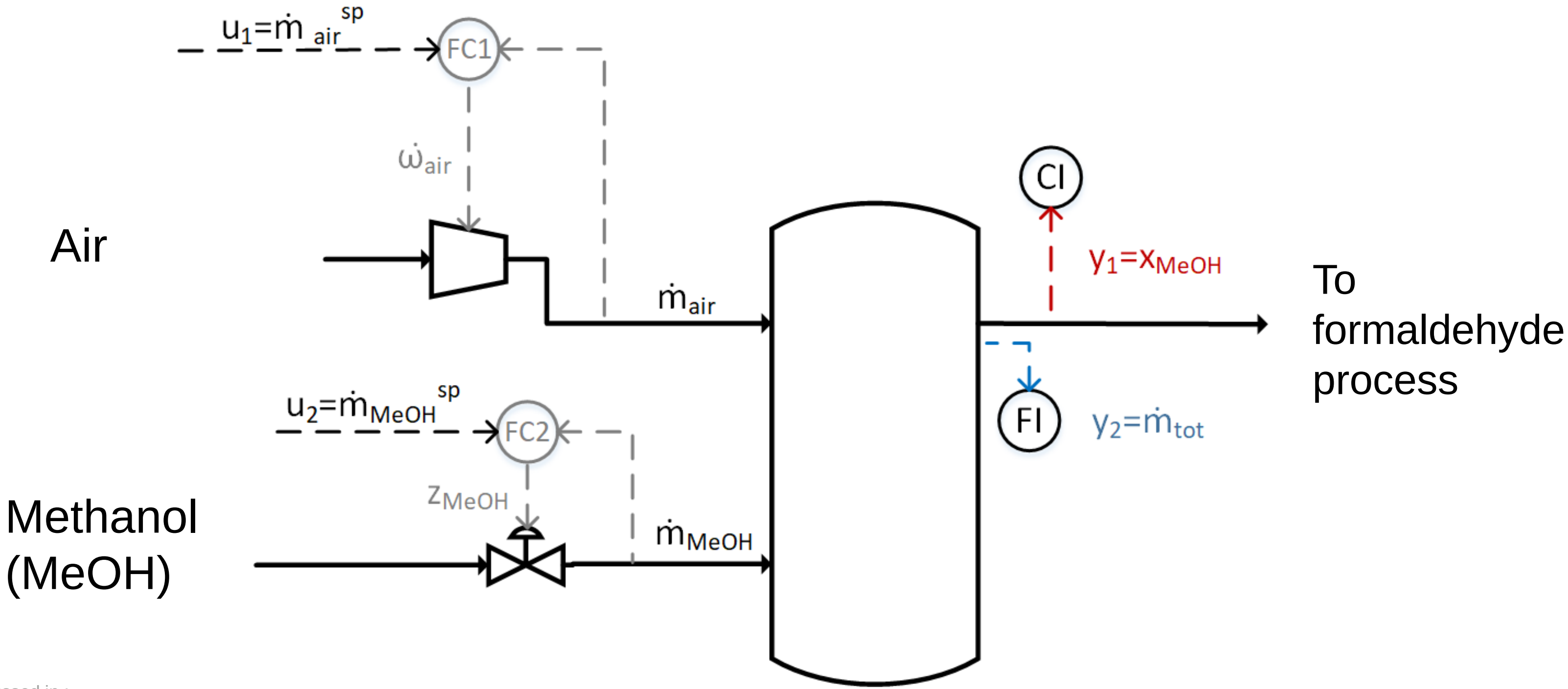
$$u'_k(t) = u_k^0 + K_{C,k}\left(e(t) + \xcancel{\frac{1}{\tau_{I,k}}\int_{t_b}^{t}} e(t)\right)$$

$$u_k(t_b) = u_k^0 + K_{C,k}e(t_b)$$

Initial action proportional to error at time of switch (t_b)

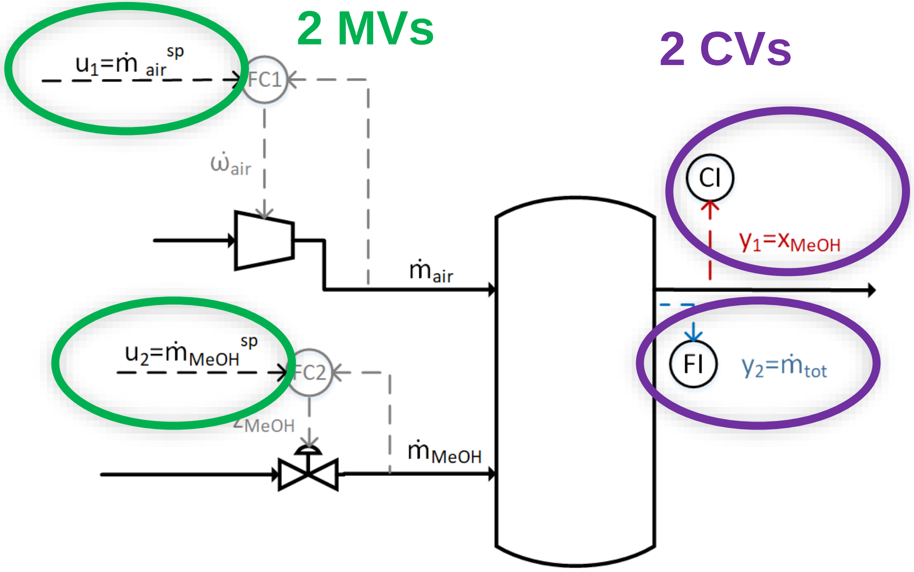
Reyes-Lúa, Adriana; Skogestad, Sigurd. (2020) Multi-input single-output control for extending the operating range: Generalized split range control using the baton strategy. Journal of Process Control. vol. 91.

Case study: Mixing of air and MeOH



This case study is also discussed in :
Reyes-Lúa, Adriana; Skogestad, Sigurd. (2019) Systematic Design of Active Constraint Switching Using Classical Advanced Control Structures. Industrial & Engineering Chemistry Research. vol. 56 (6).

Case study: Mixing of air and MeOH



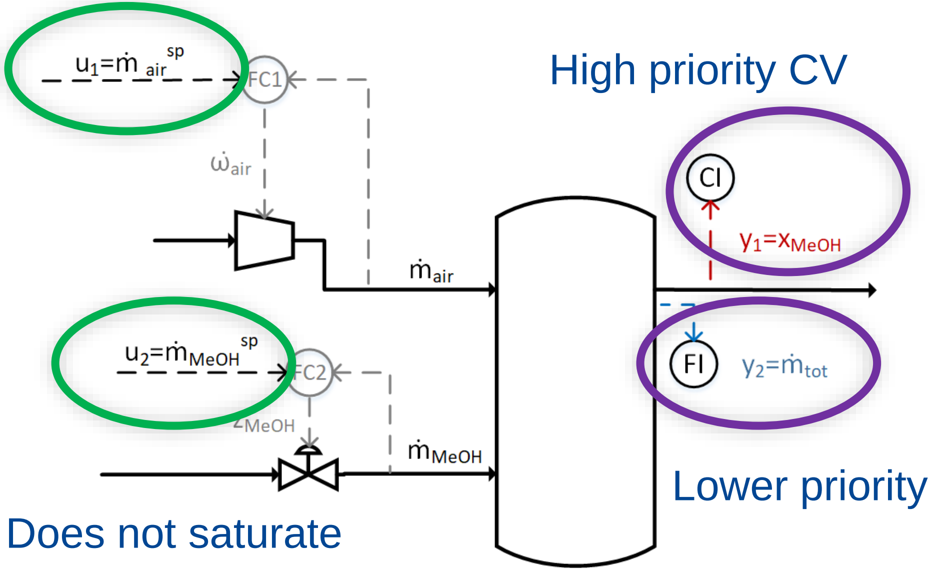
2 MVs

2 CVs

Case study: Mixing of air and MeOH

Likely to saturate

High priority CV

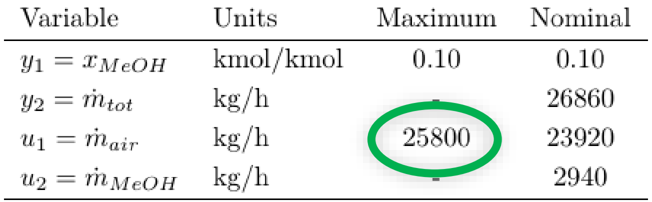


Lower priority CV

Does not saturate

Control objectives:

- Keep $y_1 = x_{MeOH} = 0.10$
- Keep $y_1 = x_{MeOH} > 0.08$
- Keep $y_2 = m_{tot}$

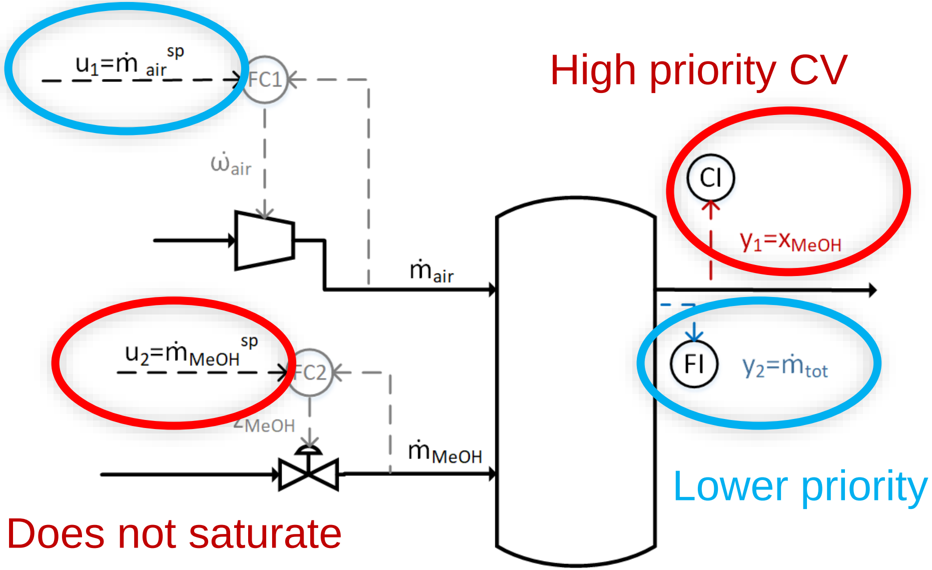


Variable	Units	Maximum	Nominal
$y_1 = x_{MeOH}$	kmol/kmol	0.10	0.10
$y_2 = \dot{m}_{tot}$	kg/h	-	26860
$u_1 = \dot{m}_{air}$	kg/h	25800	23920
$u_2 = \dot{m}_{MeOH}$	kg/h	-	2940

u_1 is has a maximum value

Case study: Mixing of air and MeOH

Likely to saturate

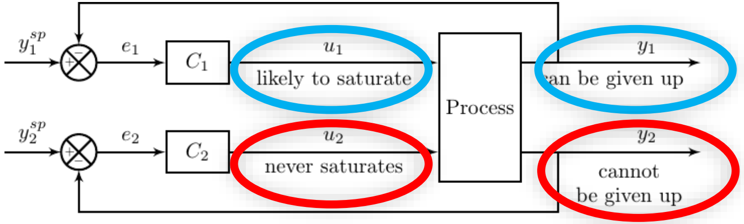


High priority CV

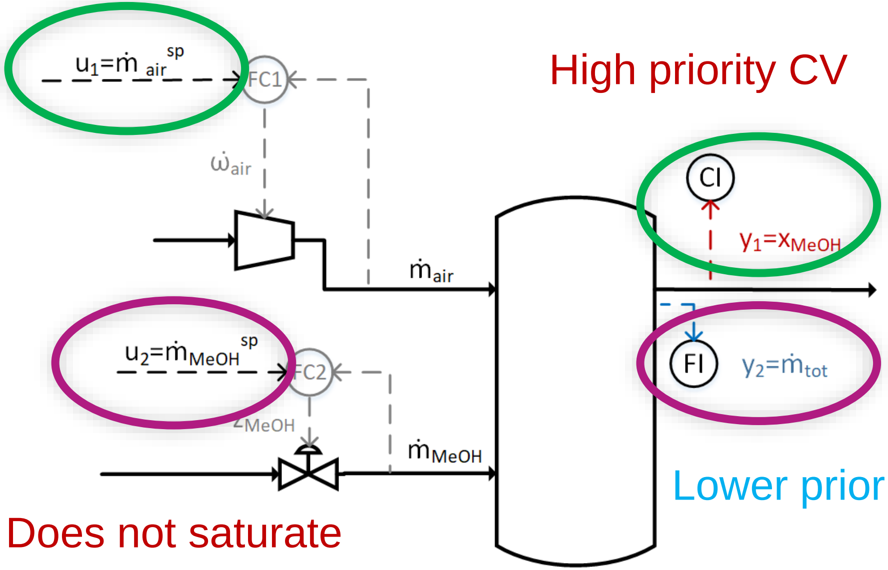
Lower priority CV

Does not saturate

Following input saturation pairing rule



Case study: Mixing of air and MeOH



Likely to saturate

High priority CV

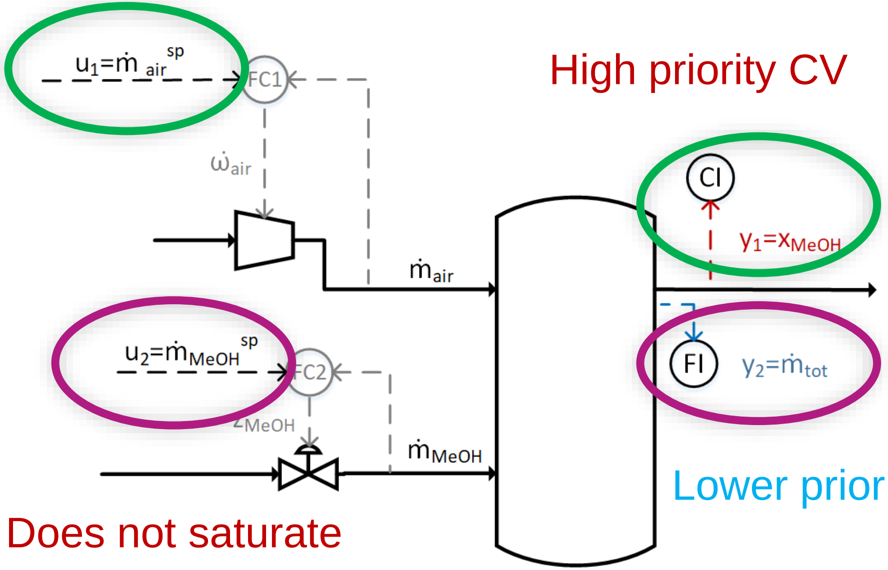
Lower priority CV

Does not saturate

NOT following input saturation pairing rule

Case study: Mixing of air and MeOH

Likely to saturate

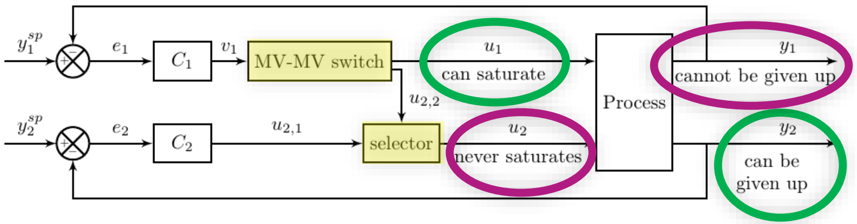


High priority CV

Lower priority CV

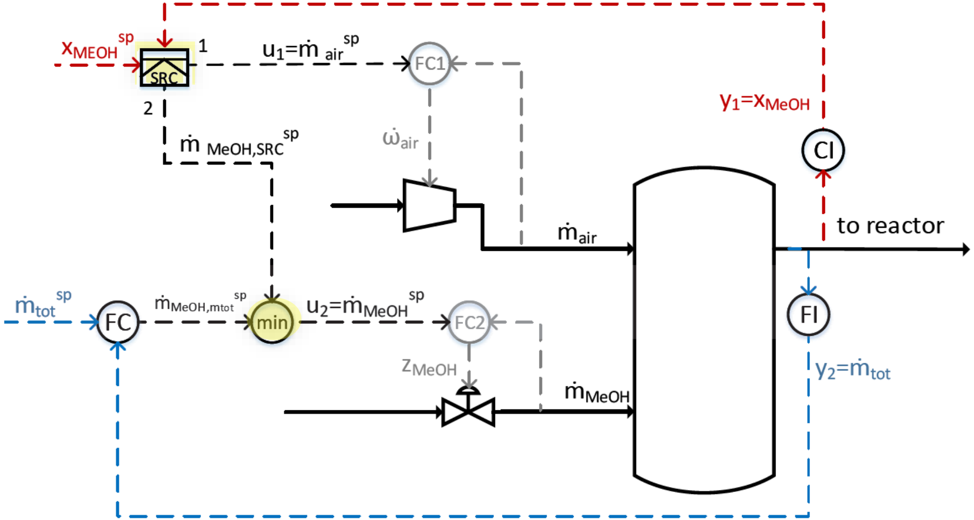
Does not saturate

NOT following input saturation pairing rule

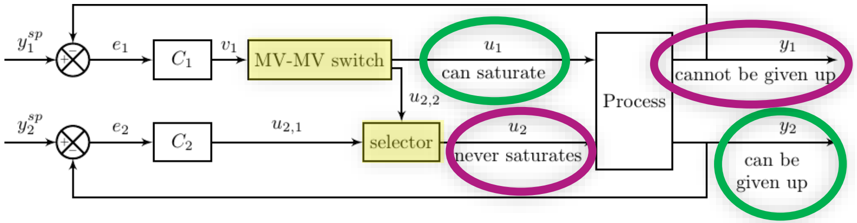


A. Reyes-Lúa, S. Skogestad. "Generalized Split Range Control Structure using the Baton Strategy"

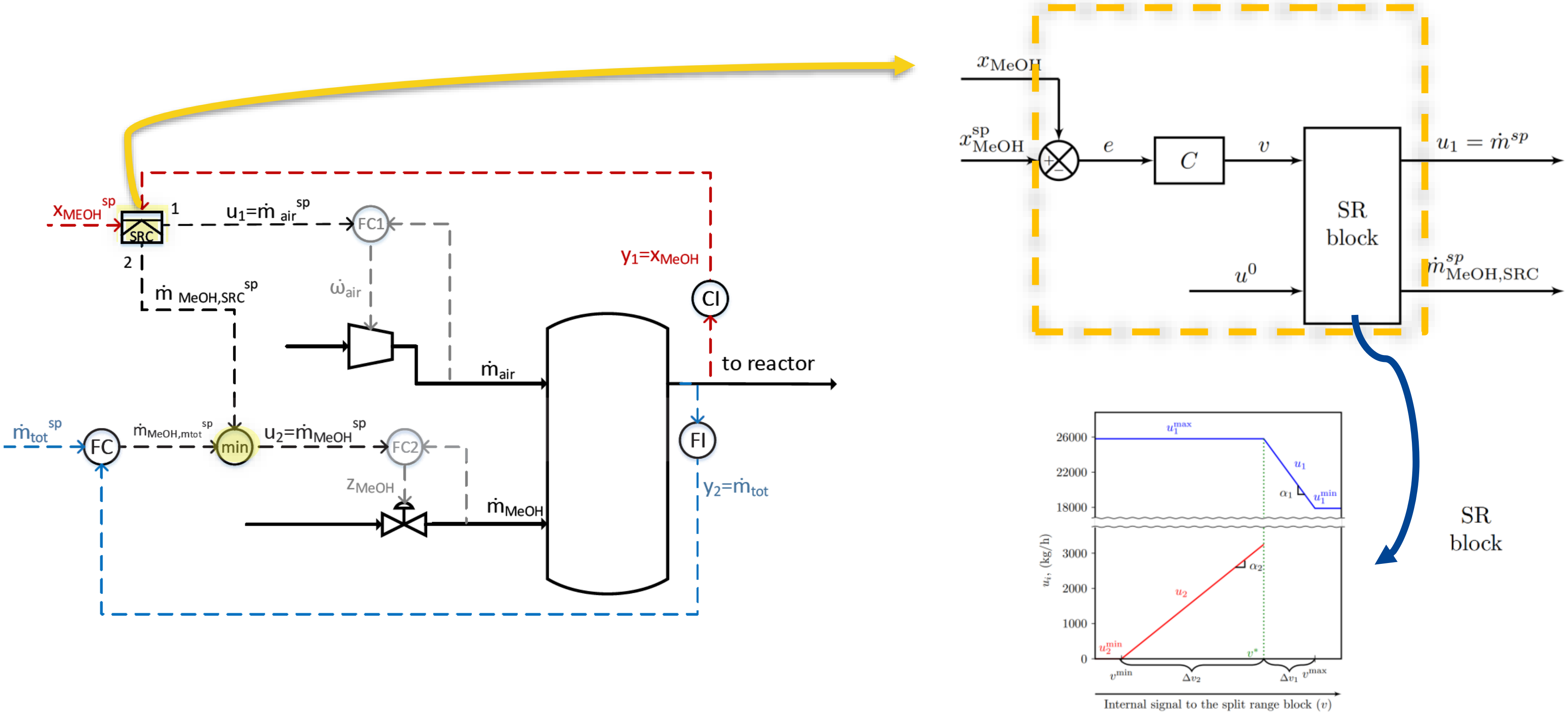
Case study: Mixing of air and MeOH



NOT following input saturation pairing rule



Case study: Mixing of air and MeOH



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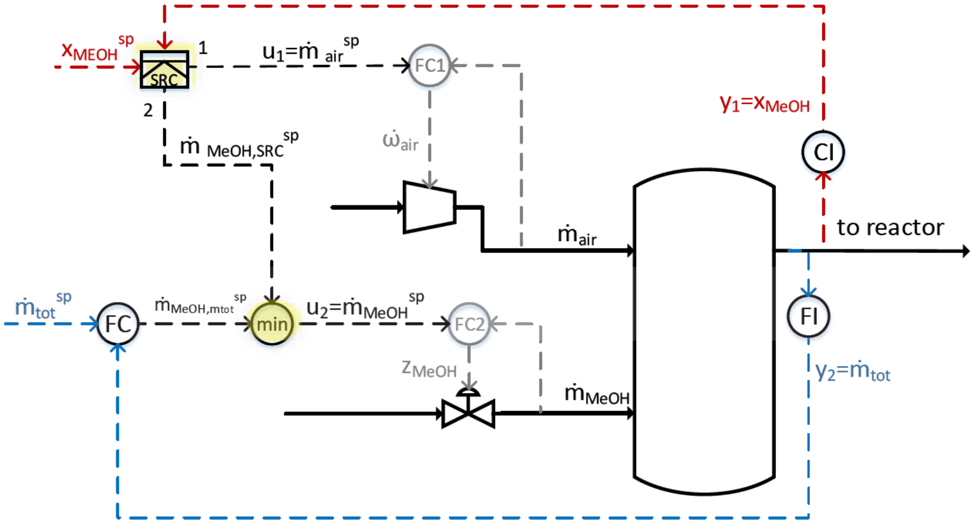
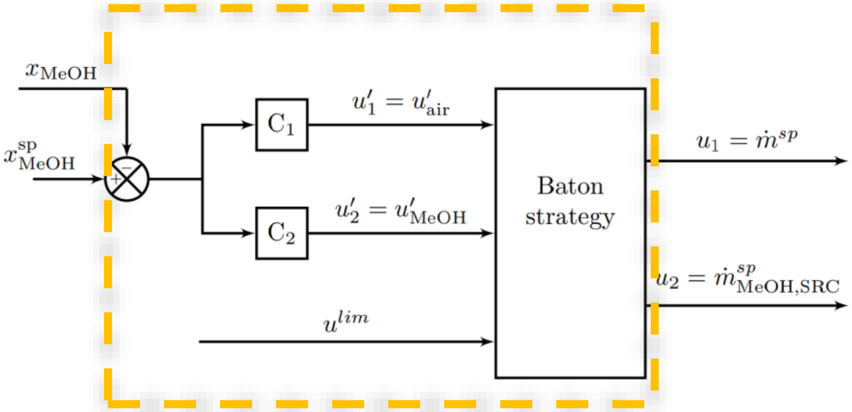
Case study: Mixing of air and MeOH



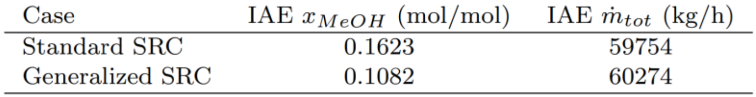
Value of u_k	$u_k = u_1 = \dot{m}_{air}$	$u_k = u_2 = \dot{m}_{MeOH}$
$u'_k \geq u_k^{max}$	baton to u_2 $u_1 \leftarrow u_1^{max}$ $u_2^0 = u_2^{max}$	baton to u_1 $u_1^0 = u_1^{max}$ $u_2 \leftarrow u_2^{max}$
$u_k^{min} < u'_k < u_k^{max}$	Keep u_1 active $u_1 \leftarrow u'_1$ $u_2 \leftarrow u_2^{max}$	Keep u_2 active $u_2 \leftarrow u'_2$ $u_1 \leftarrow u_1^{max}$



:

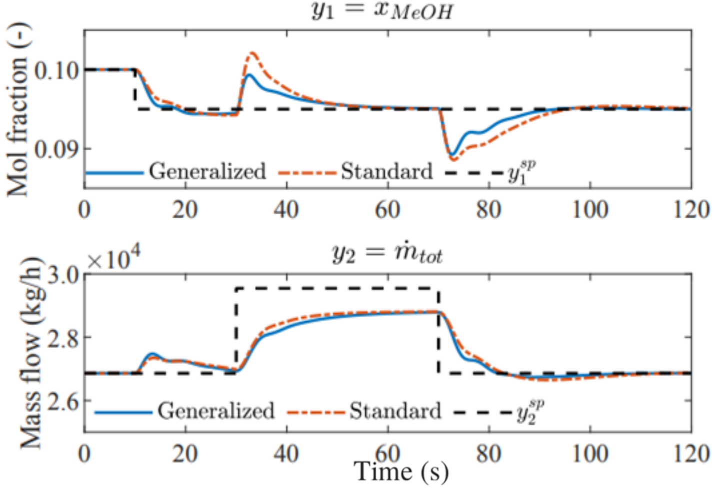
In this case study, Ci are PI controllers tuned with the SIMC tuning rules:
Skogestad, S. (2003). Simple analytic rules for model reduction and PID controller tuning. J. Process Control 13, 291–309.

Case study: Mixing of air and MeOH

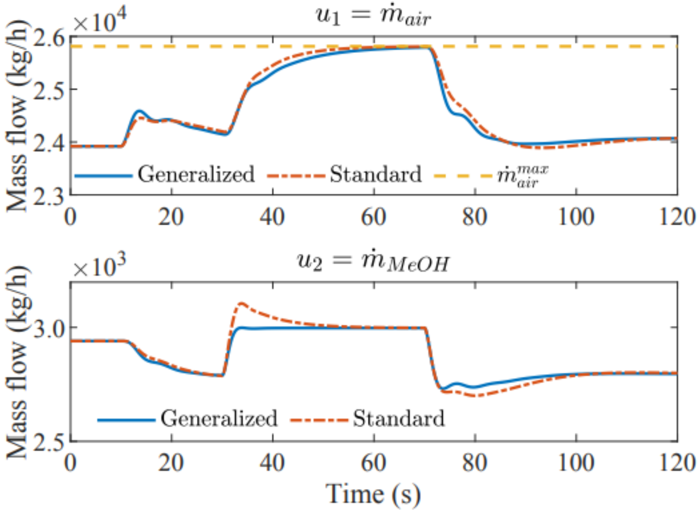


Case	IAE x_{MeOH} (mol/mol)	IAE $\dot{m}_{tot}$ (kg/h)
Standard SRC	0.1623	59754
Generalized SRC	0.1082	60274

High priority CV: concentration



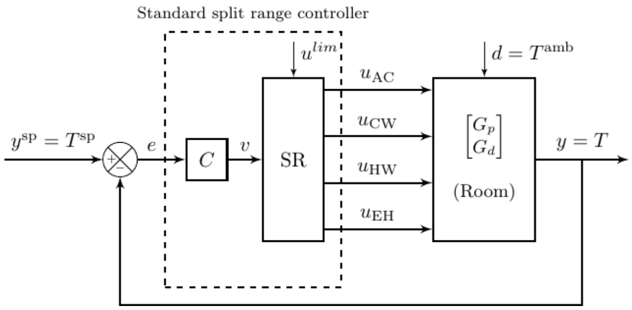
Low priority CV: throughput

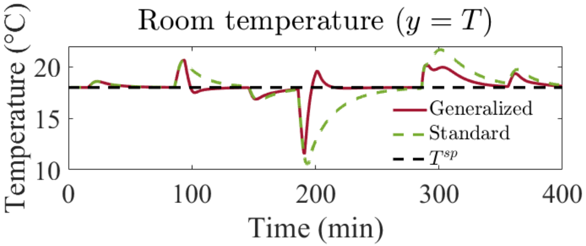


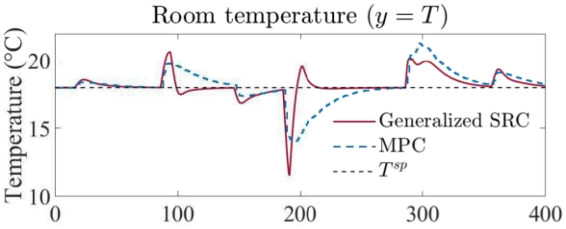
Better transient with generalized SRC (baton strategy)

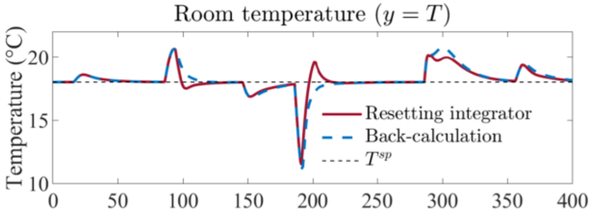
A. Reyes-Lúa, S. Skogestad. "Generalized Split Range Control Structure using the Baton Strategy"

More about the *baton strategy* for split range control









Adriana Reyes-Lúa and Sigurd Skogestad (2020).
Multi-input single-output control for extending the operating range: Generalized split range control using the baton strategy
Journal of Process Control 91, 1-11
https://doi.org/10.1016/j.jprocont.2020.05.001

Final comments

- With the generalized SRC with the baton strategy, each MV has its own controller, but only one MV is active at the time.

- This structure can be used in the same applications as standard SRC.
  - We presented a mixing study (2 MVs)
  - We have also implemented it in other case studies (4 MVs).

- For active constraint switching, SRC can be used for *MV to MV constraint switching* on its own, or for *MV to CV constraint switching*, in combination with a selector.

IFAC World Congress 2020

Active Constraint Switching with the Generalized Split Range Control Structure using the Baton Strategy

Thank you for your attention!

Adriana Reyes-Lúa[1], Sigurd Skogestad[2]

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