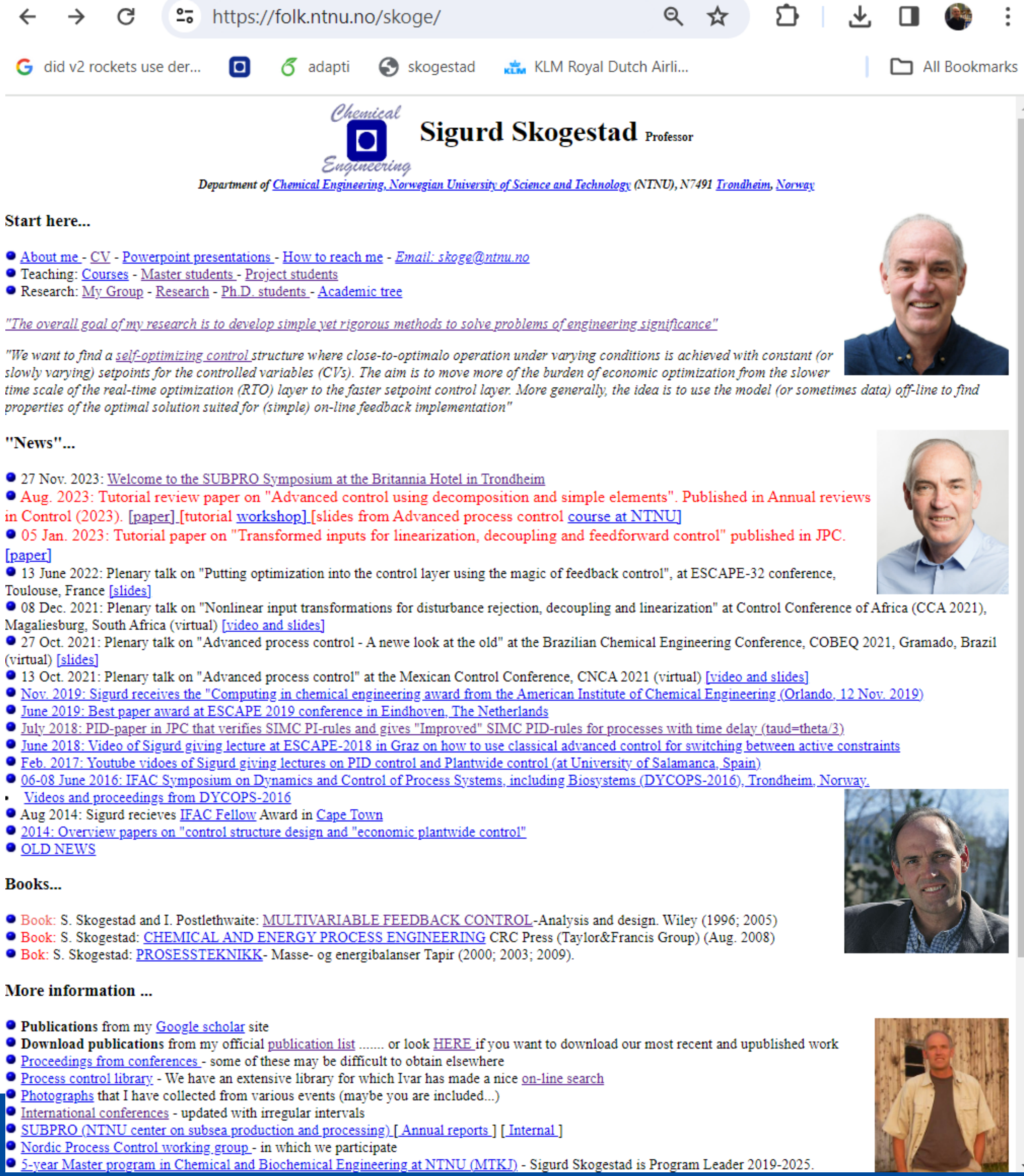
Advanced PID architectures for tracking changing active constraints

Sigurd Skogestad
NTNU

NPC Workshop, Lyngby, 17 August 2026

IFAC World Congress, Busan, Korea, August 2026

“The goal of my research is to develop simple yet rigorous methods to solve problems of engineering significance”



https://folk.ntnu.no/skoge/

did v2 rockets use der... adapti skogestad KLM Royal Dutch Airli... All Bookmarks

Chemical Engineering

Sigurd Skogestad Professor

Department of Chemical Engineering, Norwegian University of Science and Technology (NTNU), N7491 Trondheim, Norway

Start here...

- About me - CV - Powerpoint presentations - How to reach me - *Email: skoge@ntnu.no*
- Teaching: Courses - Master students - Project students
- Research: My Group - Research - Ph.D. students - Academic tree

"The overall goal of my research is to develop simple yet rigorous methods to solve problems of engineering significance"

"We want to find a self-optimizing control structure where close-to-optimalo operation under varying conditions is achieved with constant (or slowly varying) setpoints for the controlled variables (CVs). The aim is to move more of the burden of economic optimization from the slower time scale of the real-time optimization (RTO) layer to the faster setpoint control layer. More generally, the idea is to use the model (or sometimes data) off-line to find properties of the optimal solution suited for (simple) on-line feedback implementation"

"News"...

- 27 Nov. 2023: Welcome to the SUBPRO Symposium at the Britannia Hotel in Trondheim
- Aug. 2023: Tutorial review paper on "Advanced control using decomposition and simple elements". Published in Annual reviews in Control (2023). [paper] [tutorial workshop] [slides from Advanced process control course at NTNU]
- 05 Jan. 2023: Tutorial paper on "Transformed inputs for linearization, decoupling and feedforward control" published in JPC. [paper]
- 13 June 2022: Plenary talk on "Putting optimization into the control layer using the magic of feedback control", at ESCAPE-32 conference, Toulouse, France [slides]
- 08 Dec. 2021: Plenary talk on "Nonlinear input transformations for disturbance rejection, decoupling and linearization" at Control Conference of Africa (CCA 2021), Magaliesburg, South Africa (virtual) [video and slides]
- 27 Oct. 2021: Plenary talk on "Advanced process control - A newe look at the old" at the Brazilian Chemical Engineering Conference, COBEQ 2021, Gramado, Brazil (virtual) [slides]
- 13 Oct. 2021: Plenary talk on "Advanced process control" at the Mexican Control Conference, CNCA 2021 (virtual) [video and slides]
- Nov. 2019: Sigurd receives the "Computing in chemical engineering award from the American Institute of Chemical Engineering (Orlando, 12 Nov. 2019)
- June 2019: Best paper award at ESCAPE 2019 conference in Eindhoven, The Netherlands
- July 2018: PID-paper in JPC that verifies SIMC PI-rules and gives "Improved" SIMC PID-rules for processes with time delay (taud=theta/3)
- June 2018: Video of Sigurd giving lecture at ESCAPE-2018 in Graz on how to use classical advanced control for switching between active constraints
- Feb. 2017: Youtube videos of Sigurd giving lectures on PID control and Plantwide control (at University of Salamanca, Spain)
- 06-08 June 2016: IFAC Symposium on Dynamics and Control of Process Systems, including Biosystems (DYCOPS-2016), Trondheim, Norway.
- Videos and proceedings from DYCOPS-2016
- Aug 2014: Sigurd recieves IFAC Fellow Award in Cape Town
- 2014: Overview papers on "control structure design and "economic plantwide control"
- OLD NEWS

Books...

- Book: S. Skogestad and I. Postlethwaite: MULTIVARIABLE FEEDBACK CONTROL-Analysis and design. Wiley (1996; 2005)
- Book: S. Skogestad: CHEMICAL AND ENERGY PROCESS ENGINEERING CRC Press (Taylor&Francis Group) (Aug. 2008)
- Bok: S. Skogestad: PROSESSTEKNIKK- Masse- og energibalanser Tapir (2000; 2003; 2009).

More information ...

- **Publications** from my Google scholar site
- **Download publications** from my official publication list .... or look HERE if you want to download our most recent and upublished work
- Proceedings from conferences - some of these may be difficult to obtain elsewhere
- Process control library - We have an extensive library for which Ivar has made a nice on-line search
- Photographs that I have collected from various events (maybe you are included...)
- International conferences - updated with irregular intervals
- SUBPRO (NTNU center on subsea production and processing) [Annual reports] [Internal]
- Nordic Process Control working group - in which we participate
- 5-year Master program in Chemical and Biochemical Engineering at NTNU (MTKJ) - Sigurd Skogestad is Program Leader 2019-2025.

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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.

Paper (2023) is open access and is also available on my home page (search for "skogestad")

QUIZ
What are the three most important inventions of process control?

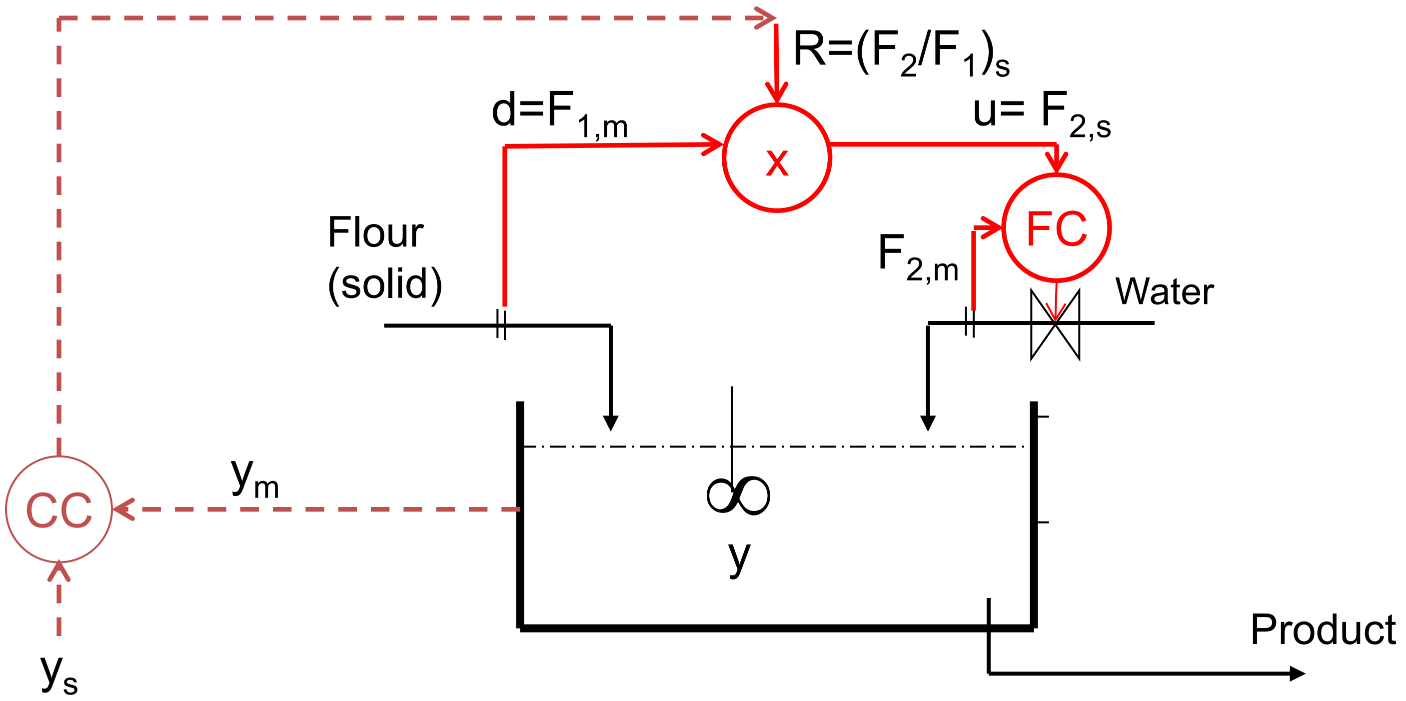
- Hint 1: According to Sigurd Skogestad
- Hint 2: All were in use around 1940

SOLUTION

1. PID controller, in particular, I-action
2. Cascade control
3. Ratio control

EXAMPLE: MIXING PROCESS

RATIO CONTROL with outer feedback (to adjust ratio setpoint)



Feedback correction («trim»)

Want to control: Composition y

(or any intensive quality variable, like viscicity, ρ or T*)

* S. Skogestad. *Ratio control: Theoretical basis and practical implementation*, Journal of process control, 2026.

Constraints

- **Active constraint**: Optimally at limiting value (max or min) in current situation.
  - current value of disturbances, parameters, and prices.
- Want to use Control to switch between changing active constraints
- *«OK, you may handle many things with PIDs - but for constraints you need MPC.»*
- No, this is an academic myth

QUIZ, part 2
Three more important inventions of process control?

- Hint: All related to constraints

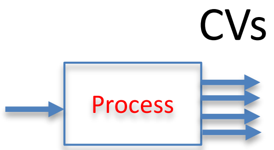
SOLUTION

1. Anti-windup on I-action *(MV constraint)*
2. A. Split-range/ B. Split-parallel control *(MV constraint switching)*
3. MAX/MIN-Selectors (“Override”) *(CV constraint switching)*

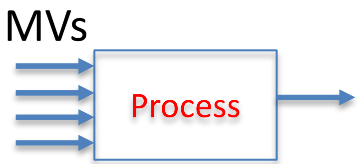
Fact: Most constraints can be handled nicely using PIDs plus these three inventions

Constraint switching cases

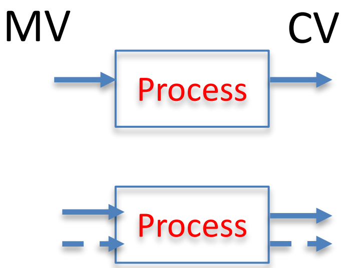
- CV-CV switching («override»)
  - Control one CV at a time



- MV-MV switching («split range»)
  - Use one MV at a time

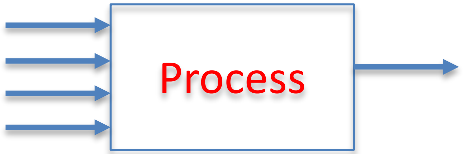


- MV-CV switching
  - MV saturates so must give up CV
  1. Simple («do nothing»)
  2. Complex (need another MV); Combine MV-MV and CV-CV



MV = manipulated variable
CV = controlled variable

MV-MV switching



- Need several MVs to cover whole steady-state range

Three solutions:

Alt.1 Split-range control (one controller)

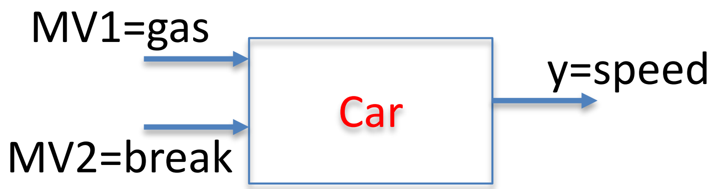
Alt.2 Several controllers with different setpoints = Split parallel control

Alt.3 Split VPC

Which is best? It depends on the case!

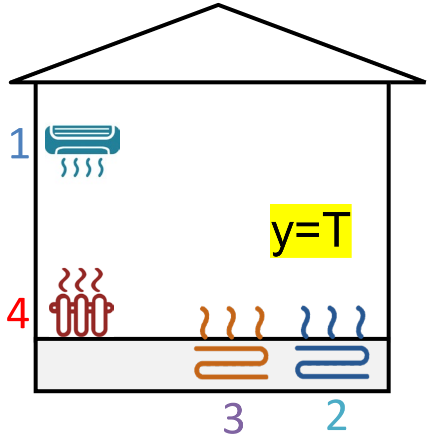
Optimal Operation with Changing Active Constraint Regions using Classical Advanced Control, Adriana Reyes-Lua Cristina Zotica, Sigurd Skogestad, Adchem Conference, Shenyang, China. July 2018 ,

Example MV-MV switching

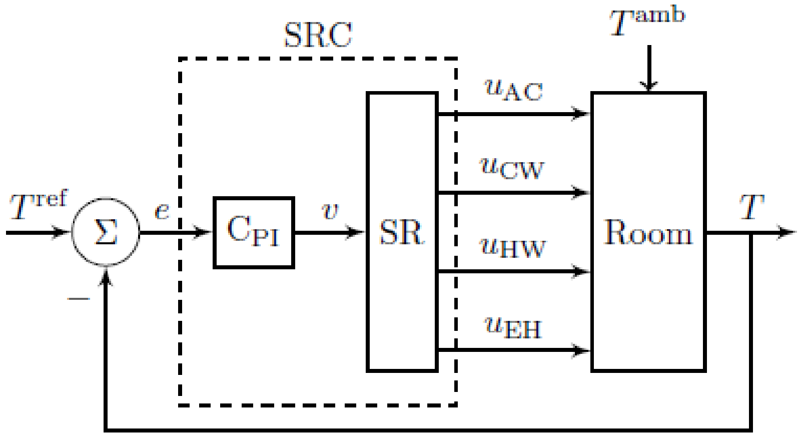


- Break and gas pedal in a car
- Use only one at a time,
- «manual split range control»

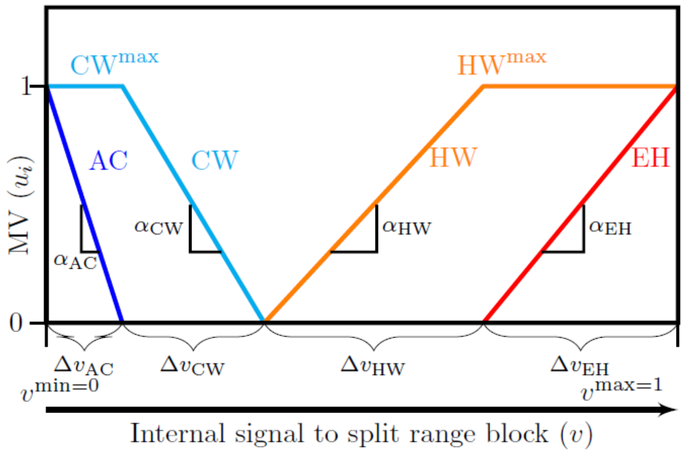
Example split range control (SRC): Room temperature with 4 MVs



MVs (two for summer and two for winter):
1. AC (expensive cooling)
2. CW (cooling water, cheap)
3. HW (hot water, quite cheap)
4. Electric heat, EH (expensive)

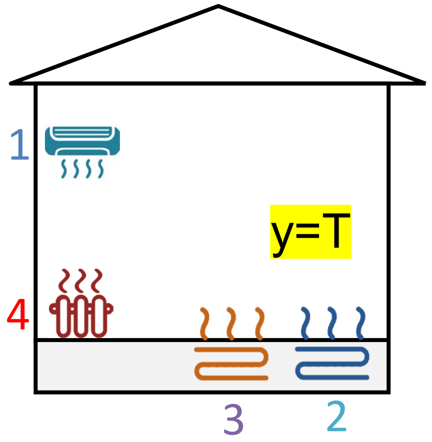


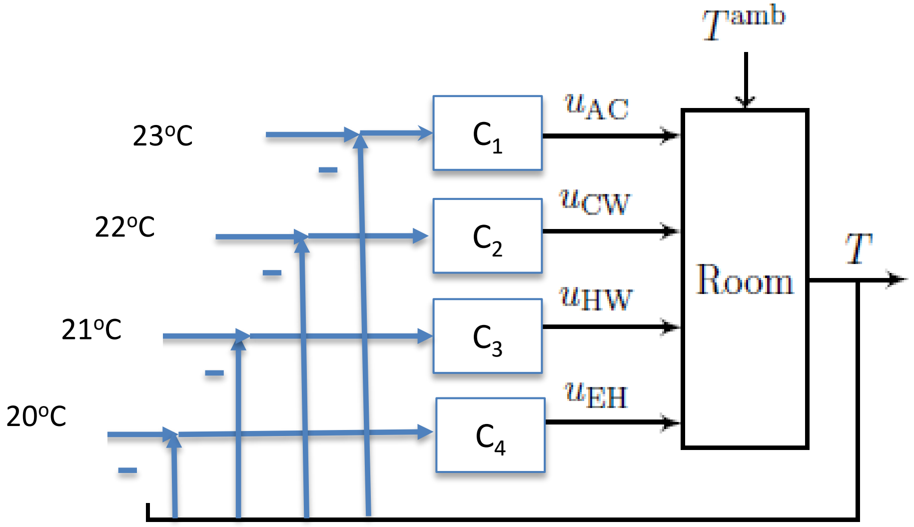
SR-block:



C_{PI} – same controller for all inputs (one integral time)
But get different gains by adjusting slopes α in SR-block

Alternative: Multiplple Controllers with different setpoints = Split parallel control (SPC)





Advantage SPC (relative to SRC):

- One controller for each MV
- Simple: Switching by feedback

Disadvantage SPC:

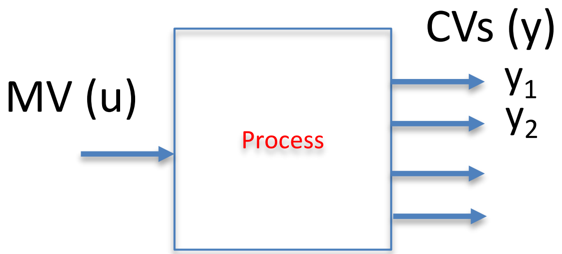
- Different setpoints
  - may fix with outer cascade
- May get fighting («limbo») with small setpoint separation

But Advantage:

- Different setpoints (energy savings)
- «Limbo» may improve control of y

«Split parallel control – A little known control structure», K. Forsman, M. Adlouni, S. Skogestad, IFAC Dycops conference, 2025 (and JPC 2026)

CV-CV switching ("override")



- Only one input (MV) controls many outputs (CVs)
  - Typically caused by change in active constraint
  - Example, Adaptive cruise control:
    - Control car speed (y_1) - but give up if too small distance (y_2) to car in front.

- Use max- or min-selectors (note: switching on controller outputs = inputs u!)

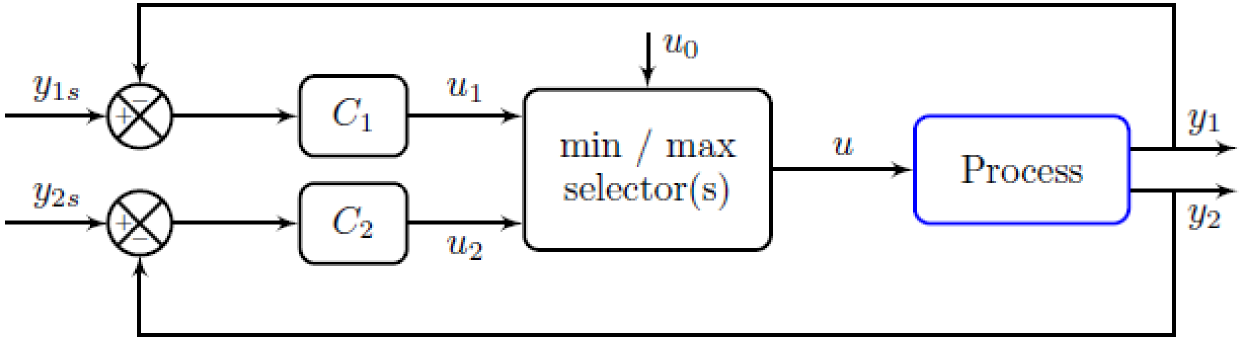


Figure 17: CV-CV switching with selector on MV (input u).

$>$ = MAX = HS

$<$ = MIN = LS

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)

IFAC in Korea , 26 Aug. 2026

Advanced PID architectures for tracking changing active constraints

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Extended version (with simulations) of paper at IFAC World Congress, August 2026, Korea. This version (with also separator case study I): 13 August 2026

Abstract: Advanced regulatory control (ARC), also known as advanced PID architectures, is a simple and robust way of controlling processes with changing and possibly conflicting constraints, where it previously was believed - at least in academia - that model-based solutions, such as MPC, were the only effective solution. To illustrate this, ARC is applied in two case studies. The first is a gas-liquid separation process, in which selectors and split-parallel control are combined to achieve bidirectional inventory control in which the throughput manipulator moves automatically to the most optimal position. The second case study is on keeping acceptable air quality (CO2-level) and temperature in a room (in this case, a barn for cows). The CO2 and temperature constraints can be conflicting, leading to a hierarchical switching network of PID controllers.

Keywords: process control, PID control, decentralized control, selectors, hybrid control

1. INTRODUCTION

An active constraint is a constraint which, in the current situation, should be kept at its limiting (maximum or minimum) value to achieve optimal (economic) operation at steady state. The "current situation" is defined by the current value of disturbances, parameters, and prices in the cost function. To achieve optimal economic operation, the most important is usually tracking and controlling active constraints (Maarleveld and Rijnsdorp, 1970).

For about 40 years, since the 1980s, there has been a myth, at least in the academic community, that this requires model-based schemes, such as model predictive control (MPC) and real-time optimization (RTO). Of course, academic researchers had some knowledge about industrial schemes for dealing with constraints, including selectors and split-range control, but such "override" schemes (e.g., as described in Maarleveld and Rijnsdorp (1970) for an industrial distillation column) were thought to be *ad hoc*, old-fashioned and not optimal, and not worth the effort of more detailed studies. Until about 10 years ago this was also my view.

Selectors. Consider the case where a single manipulated variable (MV) (input) should control more than one controlled variable (CV) (output). MAX- and MIN-selectors are simple logic elements (sometimes referred to as over-

used to control a single CV. Only one MV should be used at a time, which is known as *MV-MV switching.* The traditional solution is to use split-range control, but this requires the user to specify the MV values (say, 0% and 100% in the simple case of valve saturation) where switching should occur. This is avoided with split-parallel control where each MV has its own controller with a different CV setpoint. Here, the switching occurs by feedback when an MV saturates (or is taken over by another controller) and control of the CV is lost.

These and other ARC schemes were discussed in a recent paper (Skogestad, 2023). The objective of the present paper is to extend these findings (with some new rules) and show with two case studies, the power of selectors and split-parallel control.

2. CASE STUDY I: GAS-LIQUID SEPARATOR

2.1 General about inventory control and TPM

Maintaining throughput and managing and controlling inventories (e.g., levels) are of vital importance for process operation. An important concept is the throughput manipulator (TPM), which is the variable that sets the throughput (production rate) for the entire process. Most processes have only one TPM, which also sets the feed rate(s) and product rate(s). Additional feeds are usually

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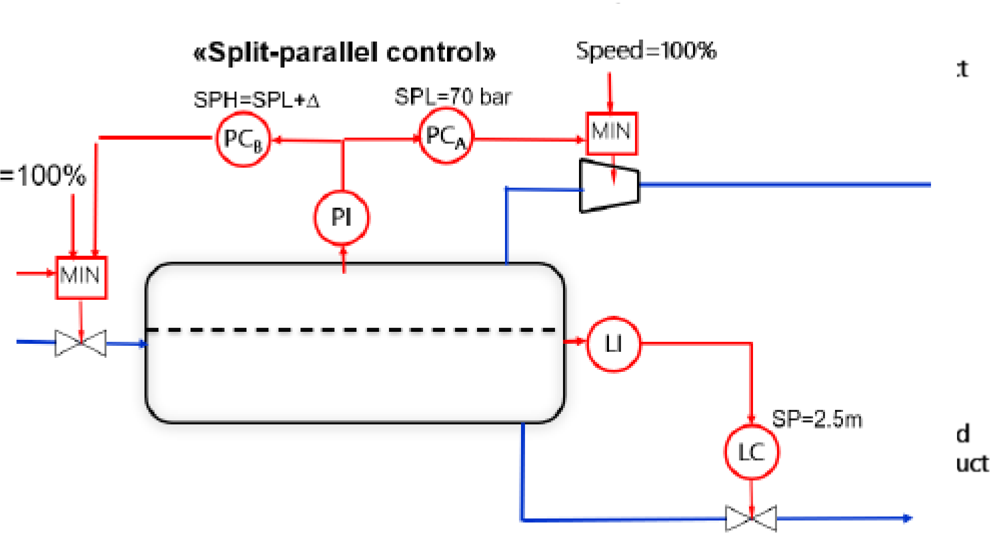
Separator case study I



z_s=47% -> 75%

Fig. 4. Bidirectional control scheme where TPM moves automatically to the bottleneck (feed valve or compressor) to maximize throughput.

$\Delta = 1$ bar (small setpoint separation)

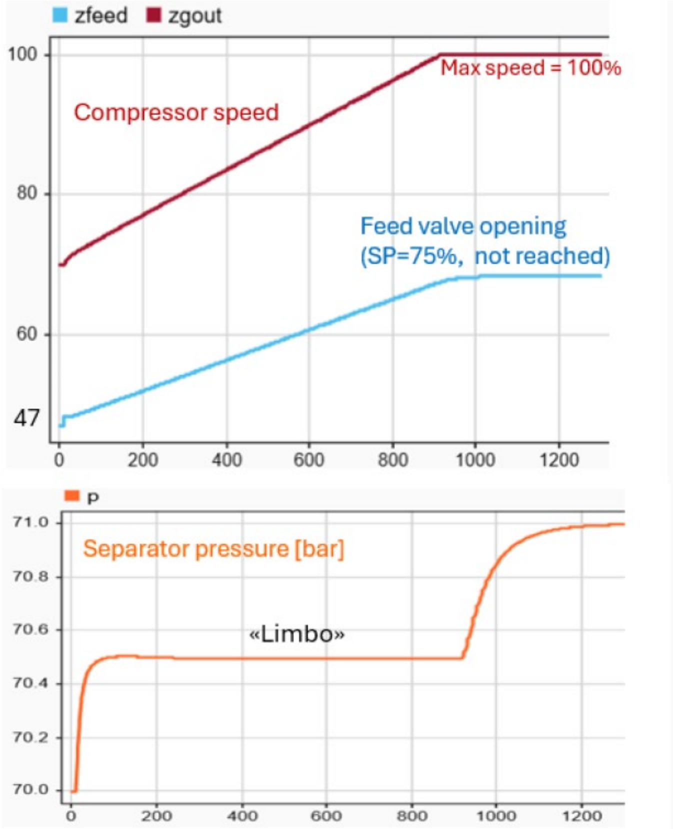


Fig. 14. Separator with SPC (Figure 4): Dynamic simulation of setpoint increase in feed valve opening from 47% to 75%.

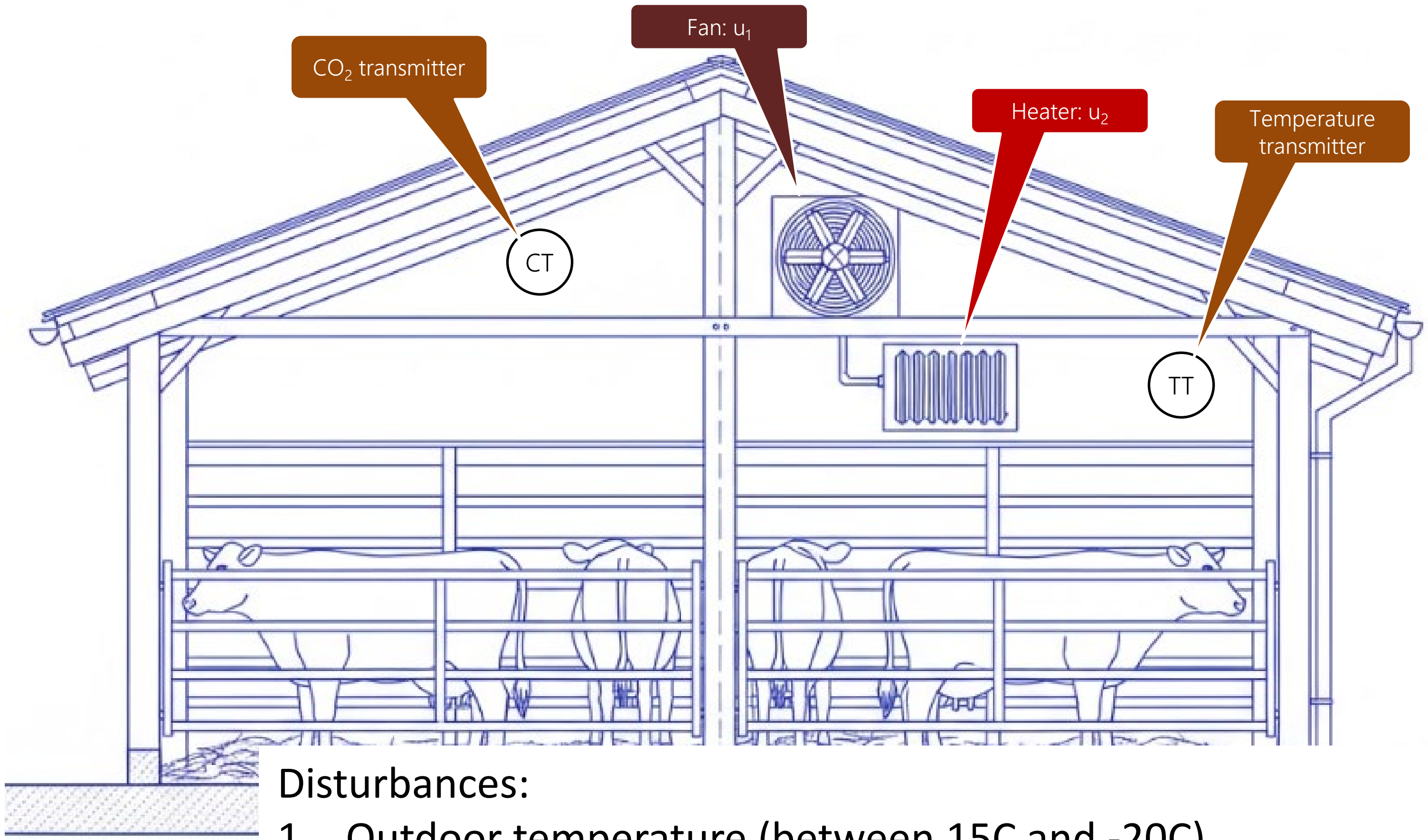
Cow case study II (Norway, outdoor 15C to -40C)

Happy cows
- y1=C (CO2) less than 1000 ppm
- y2=T between 5C and 20C
- Not too much draft or noise from fan
    - 50% fan speed is good

Unhappy (cold) cows
- y2=T less than 0C

Even more unhappy (sick) cows
- y1=C above 3000 ppm (poor air quality)

MVs
- u1=fan (cheap)
- u2=heater (expensive)



Disturbances:
1. Outdoor temperature (between 15C and -20C)
2. Number of cows (they generate CO2 and heat)
    - Because of heat from cows it’s always colder outside

NOMINAL CASE

Happy cows
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Unhappy cows
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Even more unhappy
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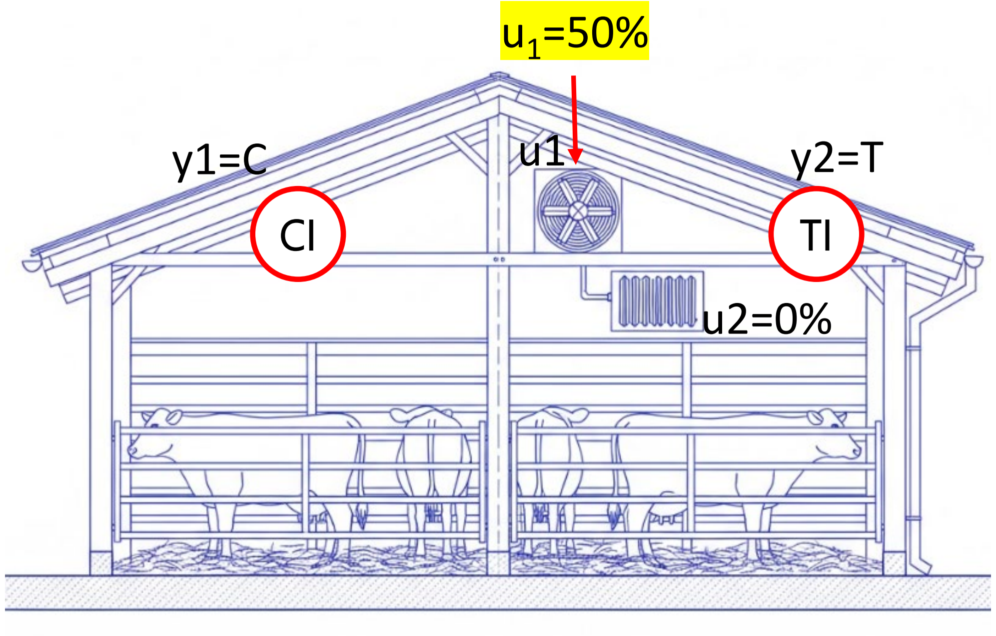

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Many cows: Lower CO_2 (less than 1000ppm) is satisfied by large fan speed ⇒ MAX-selector

Happy cows
- y1=C (CO_2) less than 1000 ppm
- y2=T between 5C and 20C
- Not too much draft or noise from fan
    - 50% fan speed is good

Unhappy cows
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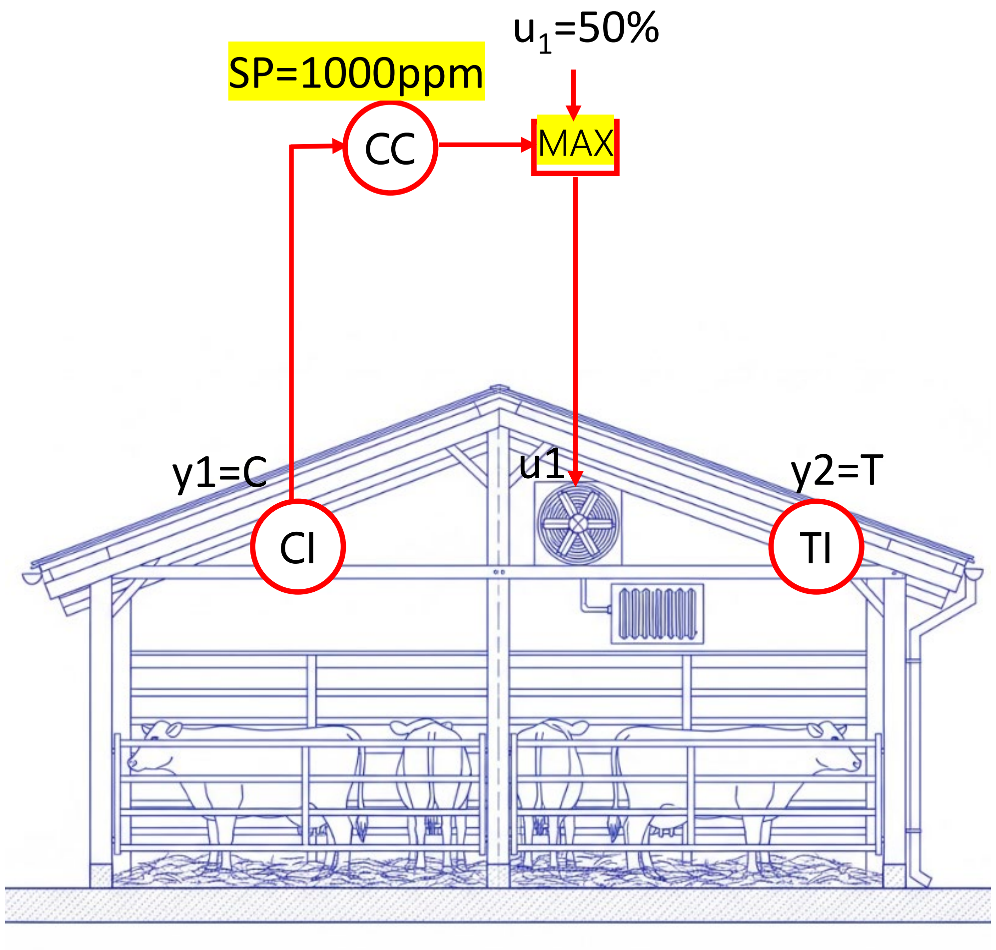


Winter: T (inside) may drop to 5C.

Control: Higher T (above 5C) is satisfied by small fan speed ⇒ MIN-selector

Happy cows

- y1=C (CO2) less than 1000 ppm
- y2=T between 5C and 20C
- Not too much draft or noise from fan
    - 50% fan speed is good

Unhappy cows

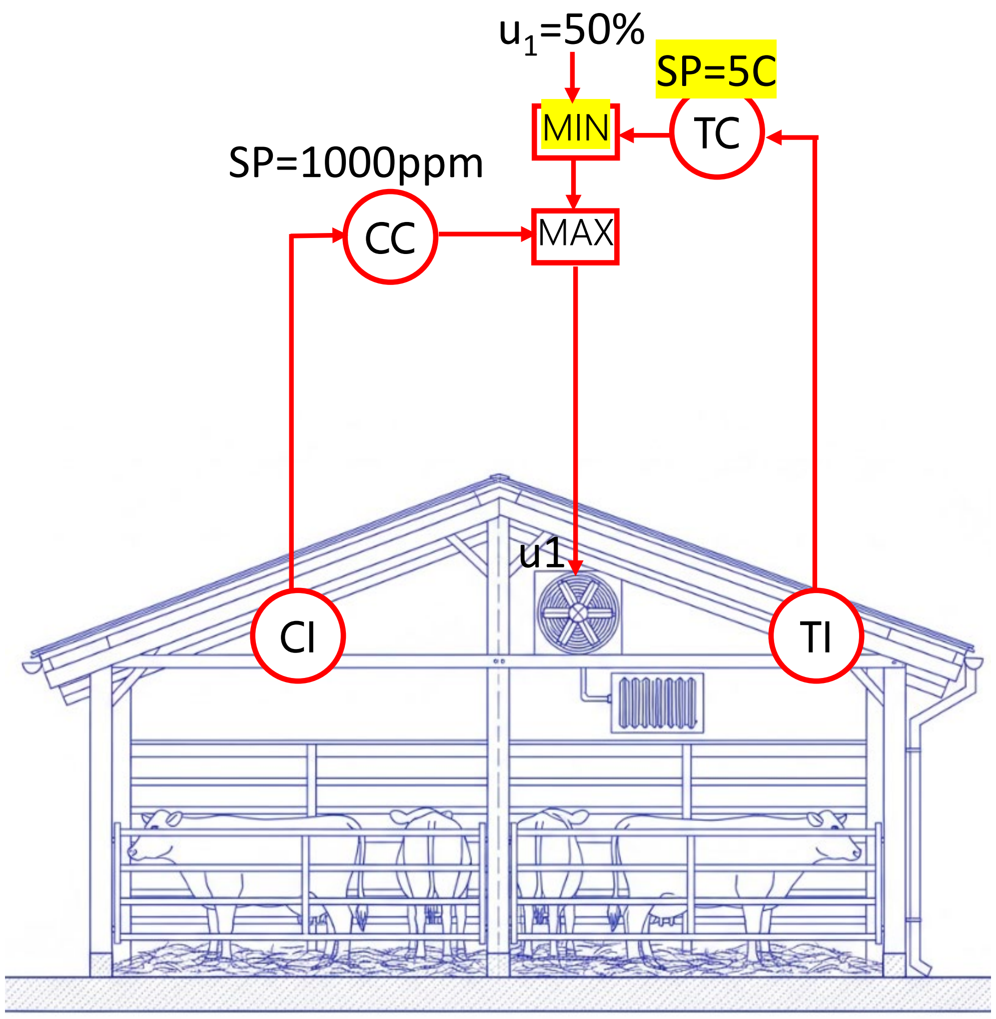
- y2=T less than 0C

Even more unhappy

- y1=C above 3000 ppm (poor air quality)

MVs

- u1=fan (cheap)
- u2=heater (expensive)



Winter (colder): Cannot reduce fan more because CO_2 > 1000 ppm.
Start heater. Use split parallell control (could use split range control instead)

Happy cows
- y1=C (CO_2) less than 1000 ppm
- y2=T between 5C and 20C
- Not too much draft or noise from fan
  - 50% fan speed is good

Unhappy cows
- y2=T less than 0C

Even more unhappy
- y1=C above 3000 ppm (poor air quality)

MVs
- u1=fan (cheap)
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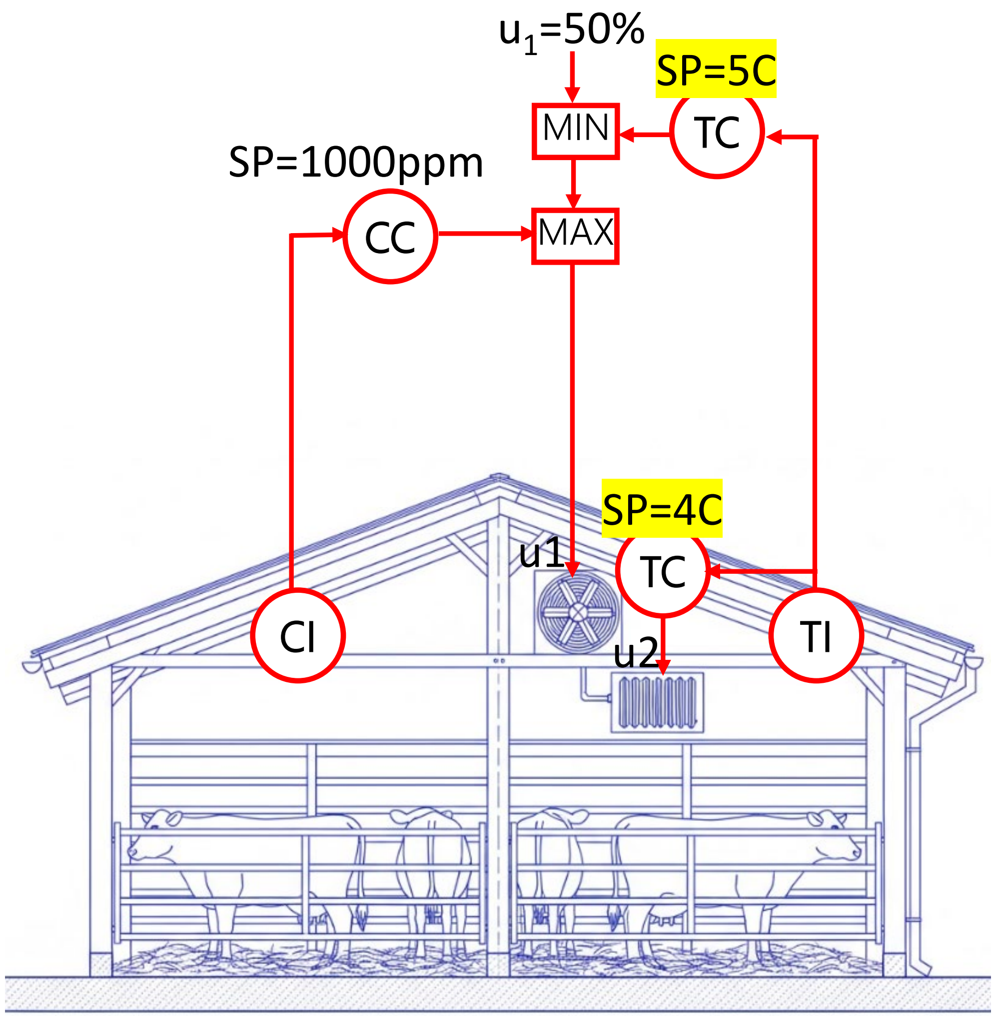

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Winter (even colder outide): Heater at max and T drops to 0C.
To avoid freezing unhappy cows: reduce fan speed and accept CO2 > 1000 ppm
Recall: Higher T (above 0C) is satisfied by small fan speed ⇒ MIN-selector

Happy cows
- y1=C (CO2) less than 1000 ppm
- y2=T between 5C and 20C
- Not too much draft or noise from fan
    - 50% fan speed is good

Unhappy cows
- y2=T less than 0C

Even more unhappy
- y1=C above 3000 ppm (poor air quality)

MVs
- u1=fan (cheap)
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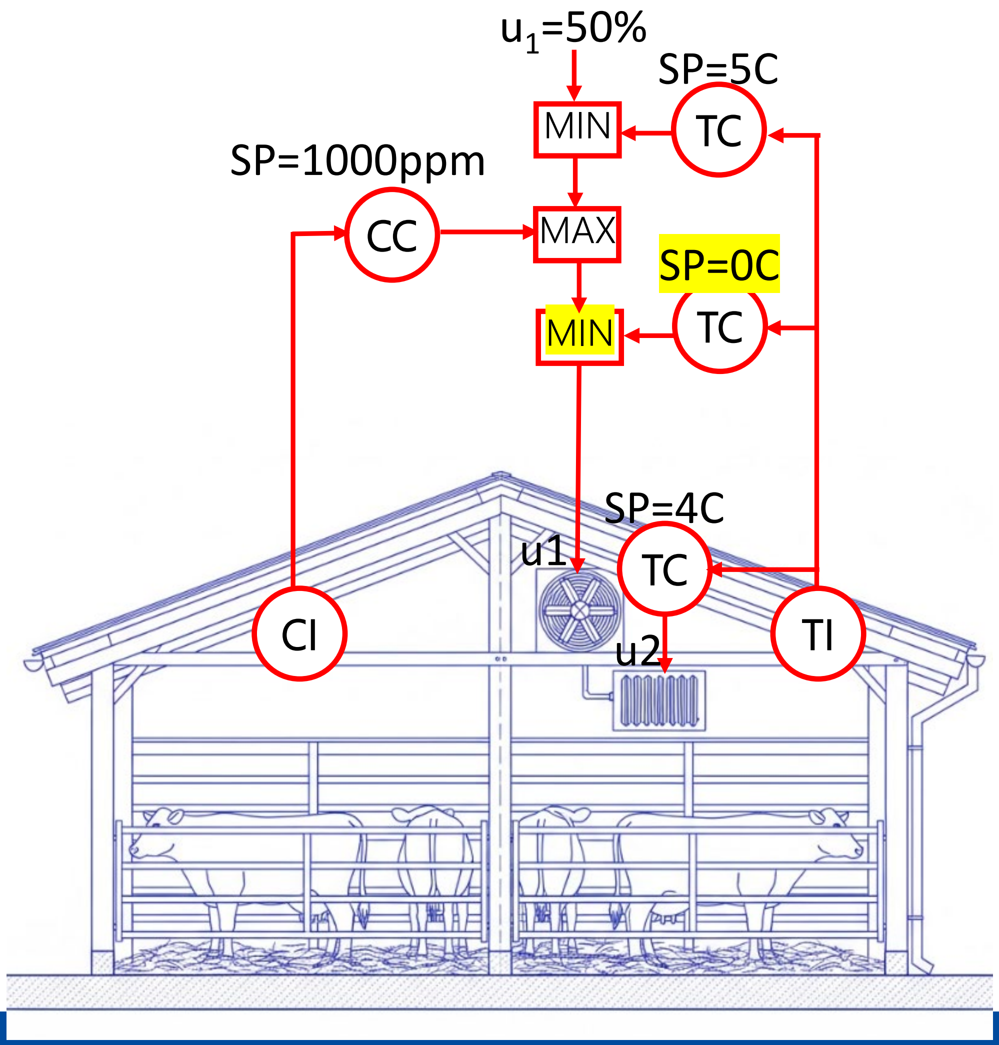

Winter (even colder outside): CO_2 reaches unacepptable level (3000ppm)
Recall: Lower CO_2 is satisfied by large fan speed ⇒ MAX-selector

Happy cows

- y1=C (CO_2) less than 1000 ppm
- y2=T between 5C and 20C
- Not too much draft or noise from fan
  - 50% fan speed is good

Unhappy cows

- y2=T less than 0C

Even more unhappy

- y1=C above 3000 ppm (poor air quality)

MVs

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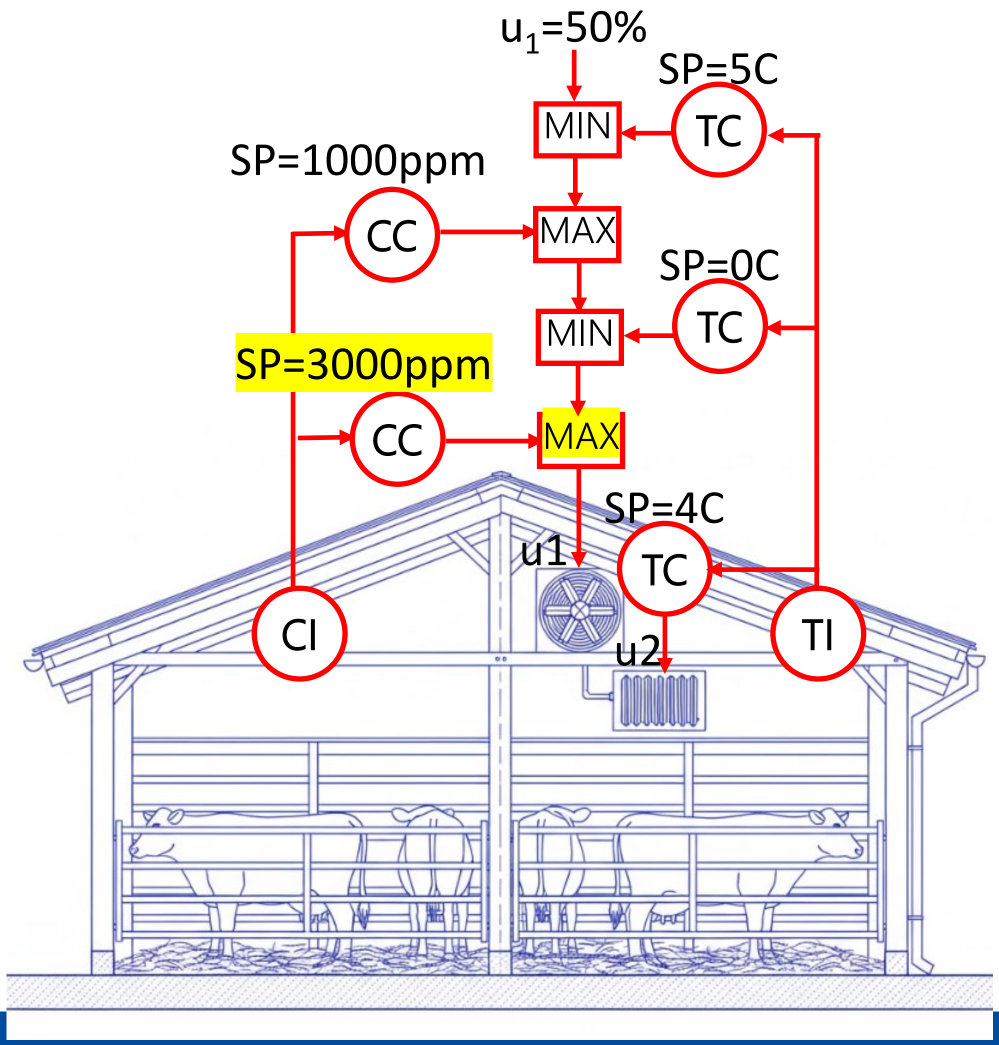

Lower T (below 20C) is satisfied by large fan speed ⇒ MAX-selector
(Consistent with large fan speed (MAX-selector) to keep CO2 < 3000ppm!)

Happy cows

- y1=C (CO2) less than 1000 ppm
- y2=T between 5C and 20C
- Not too much draft or noise from fan
  - 50% fan speed is good

Unhappy cows

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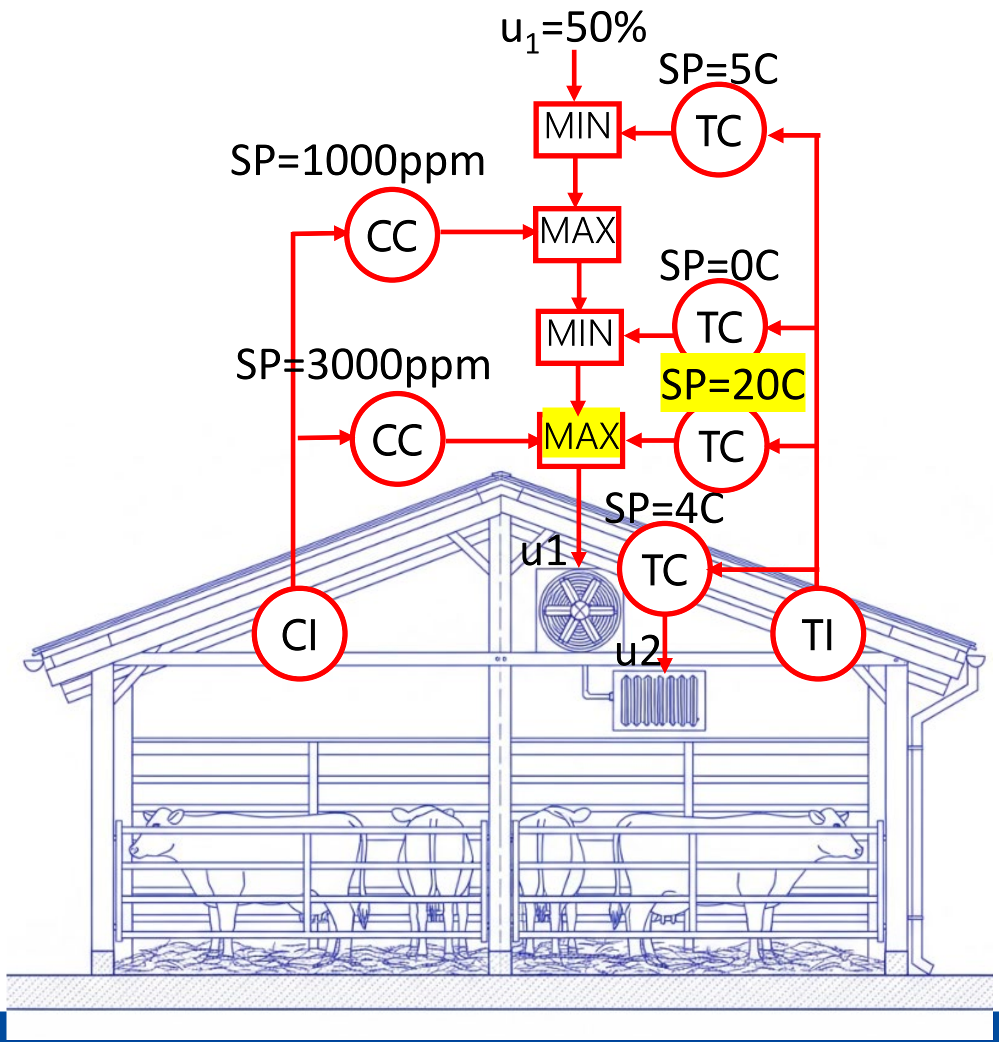

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FINAL OPTIMAL CONTROL STRUCTURE:
4 TCs, 2 CCs, 4 selectors

If extreme cold: Use blankets for cows
If very hot: Spray water on cows

Happy cows
- y1=C (CO_2) less than 1000 ppm
- y2=T between 5C and 20C
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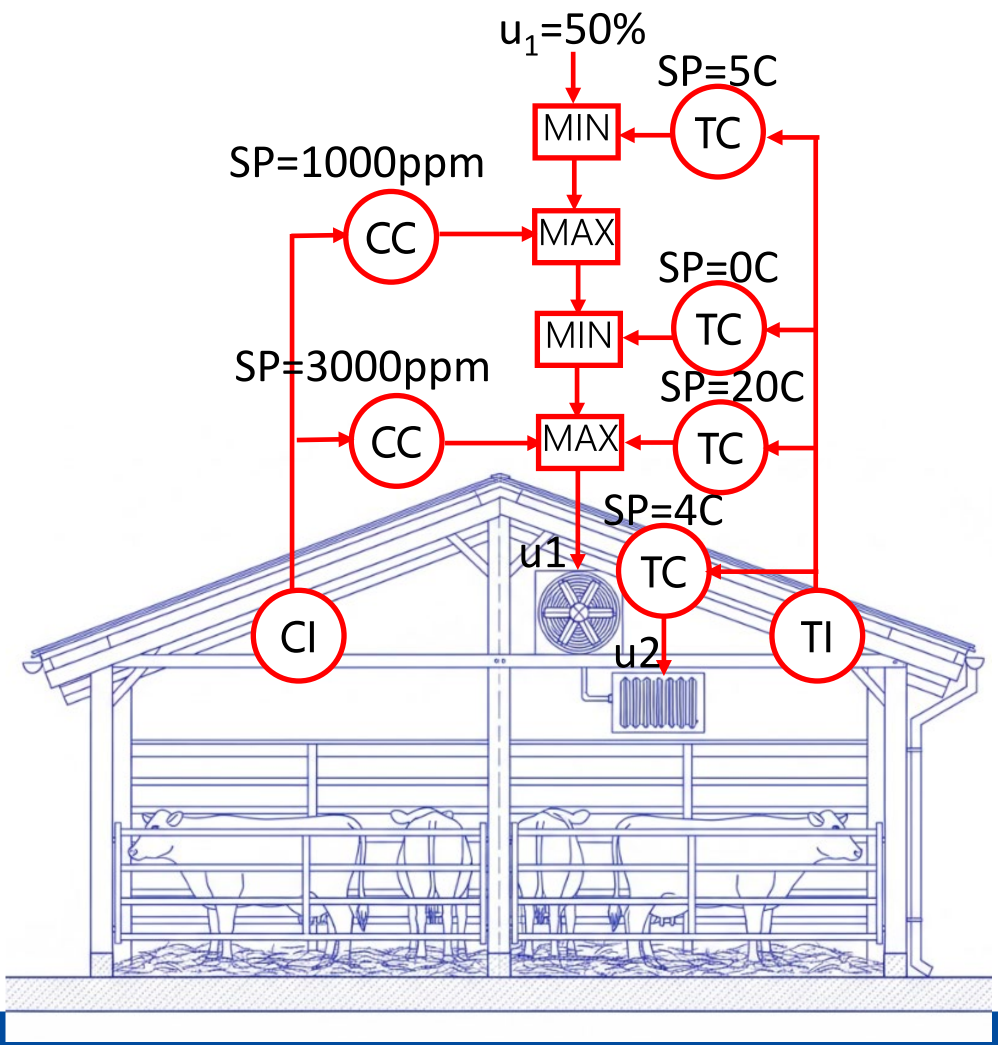
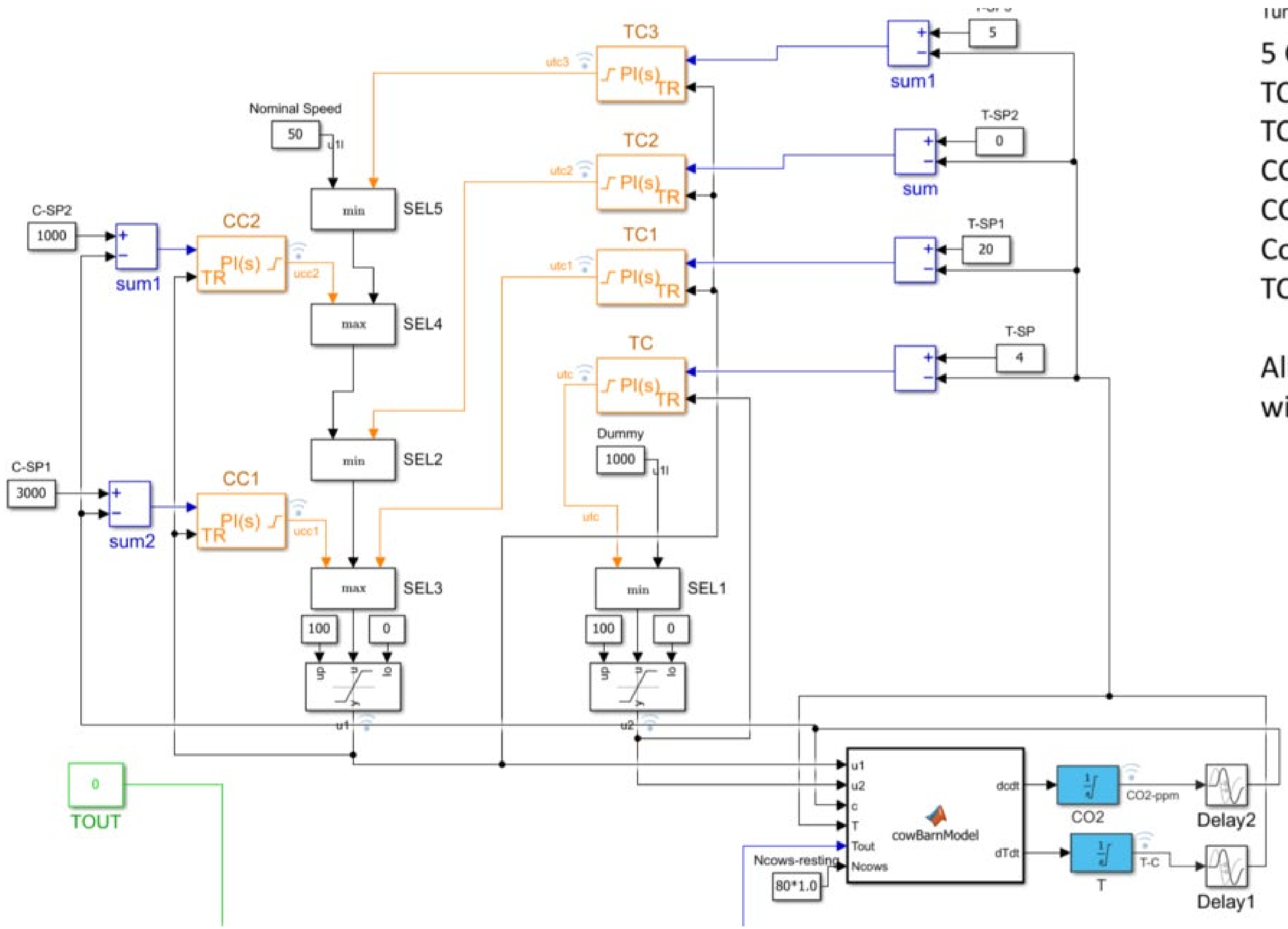


SIMULINK Simulation



Tunings

5 Controllers using u1=fan

TC3, TC1. Kc=-10, taui=350

TC2. Kc=-10/3, taui=350*3

CC2. Kc=-0.1, taui=350

CC1. Kc=-0.1/5, taui=350*5

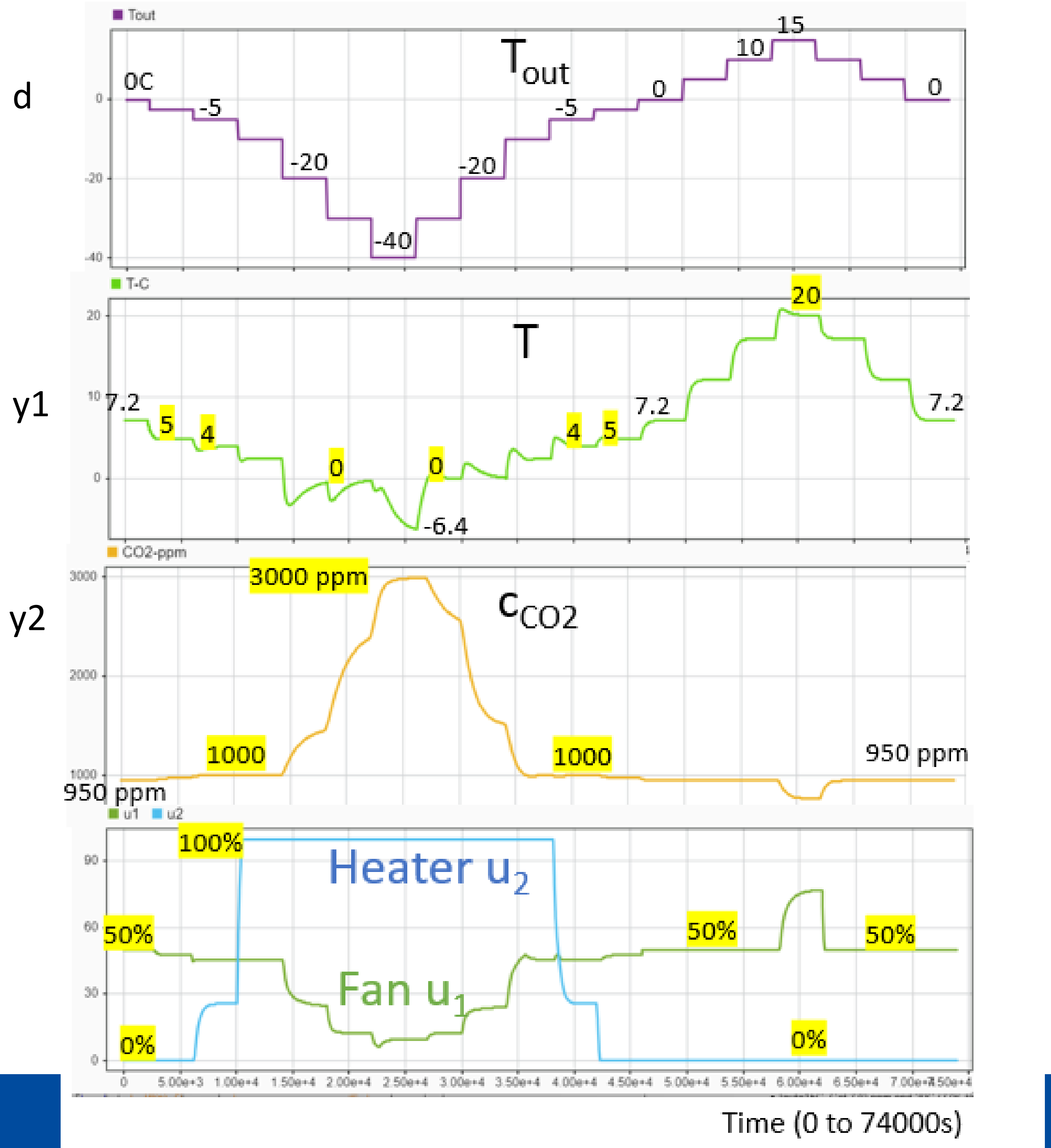
Controller using u2=heat

TC. Kc=22, taui=350

All controllers use anti-windup with tracking: tauT=taiu

Table 2. Parameters for cow case study II.

Symbol	Value	Description
V	$3\,000\,\mathrm{m}^3$	Air volume of the barn
N_{cows} (nominal)	80	Cow occupancy
$G_{\mathrm{CO_2}}$	$5 \times 10^{-5}\ \frac{m^3/s}{cow}$	Per-cow CO_2 generation
Q_{cow}	$1\,000\ \mathrm{W/cow}$	Per-cow metabolic heat
$q_{\max}, q_{\min}$	$15,\ 0.1\,\mathrm{m}^3/\mathrm{s}$	Fan airflow at 100 % and 0 %
$Q_{\mathrm{h,max}}$	$50\ 000\ \ \mathrm{W}$	Heater rating at 100 %
UA	$2\ 000\ \mathrm{W/K}$	Barn heat-loss coefficient
c_{out}	420 ppm	Outdoor CO_2 concentration



In yellow:
Active constraint/setpoint
(always 2 active)

y1(T): 20C, 5C, 4C, 0C
y2(CO2): 1000 ppm, 3000 ppm
u1(Fan): 50%
u2(Heater): 0%, 100%

Conclusion Advanced process control (APC)

- Classical APC, aka «Advanced regulatory control» (ARC) or «Advanced PID»:
  - Works very well in many cases
  - Optimization by feedback (active constraint switching)
  - Need to pair input and output.
    - Advantage: The engineer can specify directly the solution
    - Problem: Unique pairing may not be possible for complex cases
  - Need model only for parts of the process (for tuning)
  - Challenge: Need better teaching and design methods

- MPC may be better (and simpler) for more complex multivariable cases
  - Main challenge: Need dynamic model for whole process
  - Other challenge: Tuning may be difficult

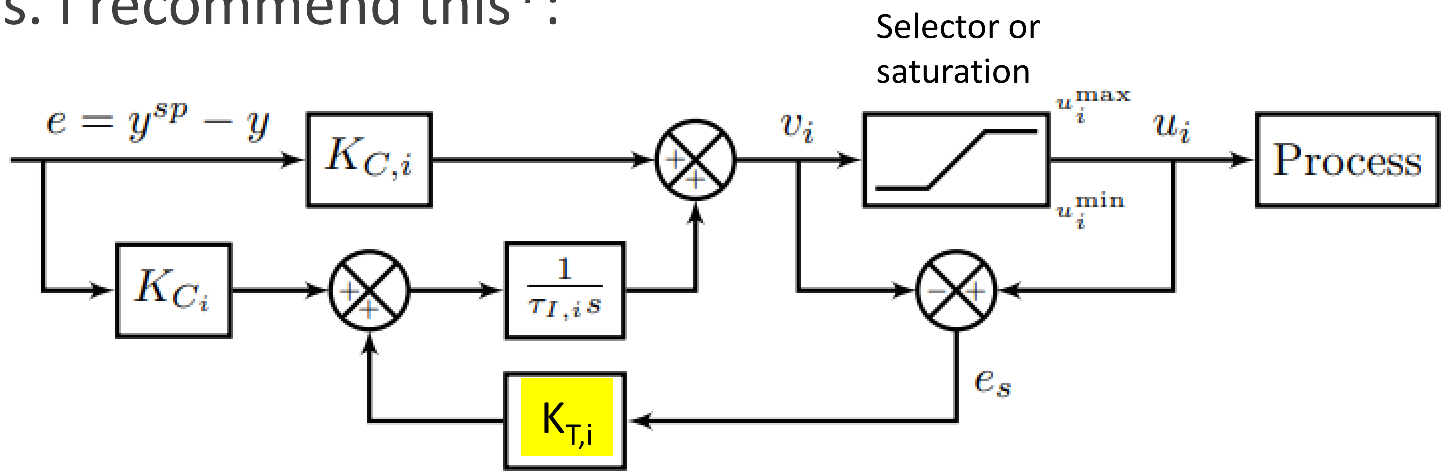
Academic process control community fish pond

Optimal centralized Solution (**EMPC**)

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

Anti-windup

- All controllers with I-action need anti-windup to «stop integration» during periods when the controller output (v_i) is not affecting the process:
  - Controller is disconnected (e.g., because of selector)
  - Physical MV u_i is saturated
- Many approaches. I recommend this*:



Anti-windup using tracking/back-calculation*. Typical choice for tracking constant, K_T=1

*Åström, K. J., & Hägglund, T. (1988). *Automatic tuning of PID controllers*. ISA.

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Important insight

- Many problems: Optimal steady-state solution always at constraints
- In this case optimization layer may not be needed
  - if we can identify the active constraints and control them using selectors

8.1. A list of specific research tasks

Here is a list of some research topics, which are important but have received limited (or no) academic attention:

1. Vertical decomposition including time scale separation in hierarchically decomposed systems (considering performance and robustness)
2. Horizontal decomposition including decentralized control and input/output pairing
3. Selection of variables that link the different layers in the control hierarchy, for example, self-optimizing variables (CV1 in Fig. 4) and stabilizing variables (CV2).
4. Selection of intermediate controlled variables (w) in a cascade control system.[9]
5. Tuning of cascade control systems (Figs. 9 and 10)
6. Structure of selector logic
7. Tuning of anti-windup schemes (e.g., optimal choice of tracking time constant, τ_T) for input saturation, selectors, cascade control and decoupling.
8. How to make decomposed control systems based on simple elements easily understandable to operators and engineers
9. Default tuning of PID controllers (including scaling of variables) based on limited information
10. Comparison of selector on input or setpoint (cascade)
11. A concise list or library of special (smart) control structures (inventions) that solve specific control problems, for example, cross-limiting control

What about research on PID tuning? Except for the problem of "default tunings", PID tuning has probably received enough academic attention. One exception may be oscillating systems, but these are rare in process control provided robust tunings have been used in the lower-layer control loops. In addition, both for unstable and oscillating processes, a better approach may be to use cascade control on top of a fast inner P- or PD-controller which stabilizes or removes oscillations (see footnote 4). In summary, "PID control" researchers are recommended to switch their attention to "advanced PID control", that is, the interconnection of the PID controller with the other advanced control elements.

In summary, "PID control" researchers are recommended to switch their attention to "advanced PID control", that is, the interconnection of the PID controller with the other advanced control elements.

Sigurd Skogestad, "Advanced control using decomposition and simple elements". Annual Reviews in Control, vol. 56 (2023), Article 100903