A systematic procedure for economic plantwide control

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Outline

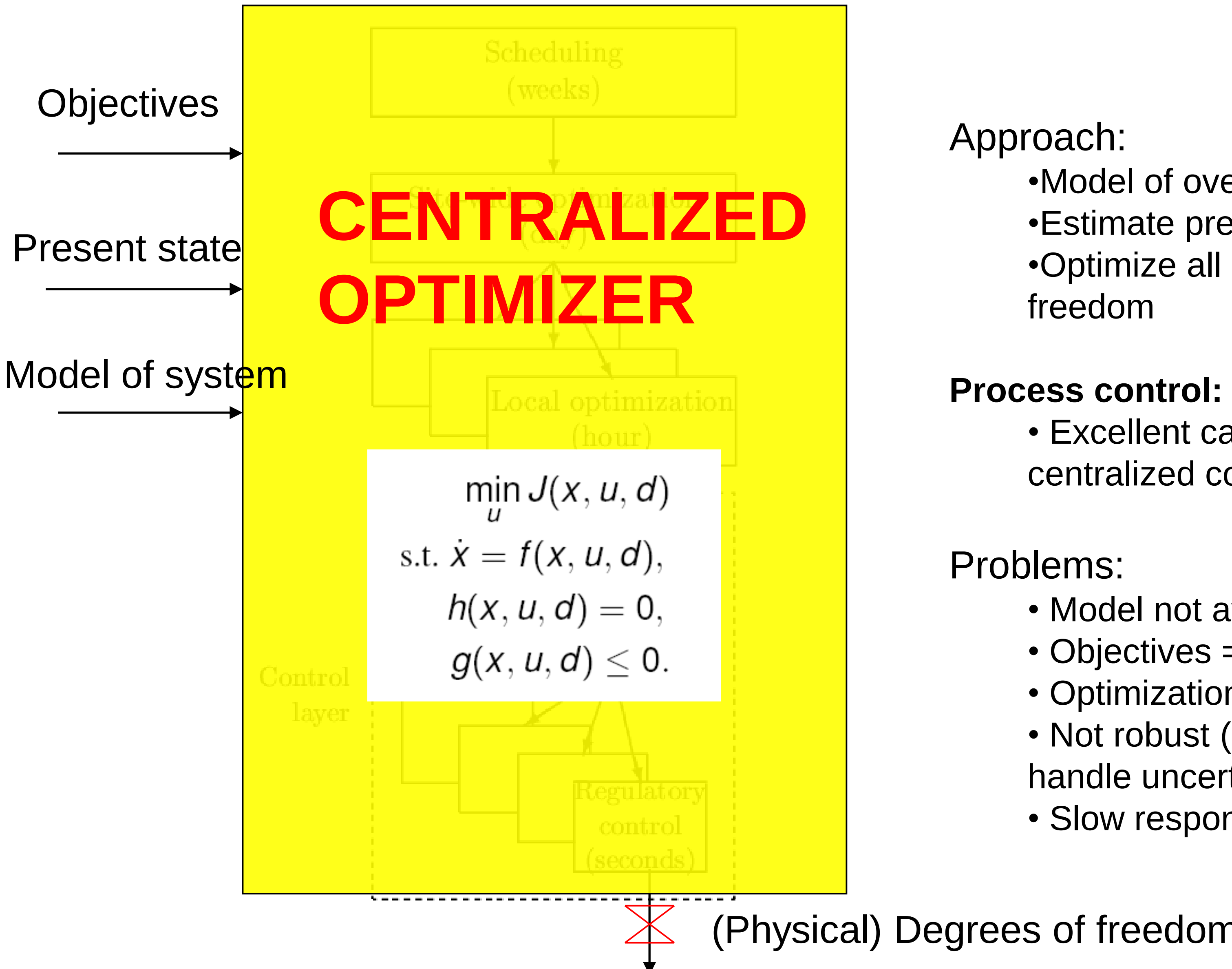
- Our paradigm basaed on time scale separation
- Plantwide control procedure based on economics
- Example: Runner
- Selection of primary controlled variables (CV_1=H y)
  - Optimal is gradient, $CV_1=J_u$ with setpoint=0
  - General CV_1=Hy. Nullspace and exact local method
- Throughput manipulator (TPM) location
- Examples
- Conclusion

This is
the truth
and
the only truth

How we design a control system for a complete chemical plant?

- Where do we start?
- What should we control? and why?
- etc.
- etc.

In theory: Optimal control and operation



Approach:

- Model of overall system
- Estimate present state
- Optimize all degrees of freedom

Process control:

- Excellent candidate for centralized control

Problems:

- Model not available
- Objectives = ?
- Optimization complex
- Not robust (difficult to handle uncertainty)
- Slow response time

Practice: Engineering systems

- Most (all?) large-scale engineering systems are controlled using hierarchies of quite simple controllers
  - Large-scale chemical plant (refinery)
  - Commercial aircraft
- 100's of loops
- Simple components:

  PI-control + selectors + cascade + nonlinear fixes + some feedforward

Same in biological systems

But: Not well understood

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- Alan Foss ("Critique of chemical process control theory", AIChE Journal,1973):

The central issue to be resolved ... is the determination of control system structure. ***Which variables should be measured, which inputs should be manipulated and which links should be made between the two sets?*** *There is more than a suspicion that the work of a genius is needed here, for without it the control configuration problem will likely remain in a primitive, hazily stated and wholly unmanageable form. The gap is present indeed, but contrary to the views of many, it is the theoretician who must close it.*

Previous work on plantwide control:

- Page Buckley (1964) - *Chapter on "Overall process control"* (still industrial practice)
- Greg Shinskey (1967) – *process control systems*
- Alan Foss (1973) - *control system structure*
- Bill Luyben et al. (1975-) – *case studies ; "snowball effect"*
- George Stephanopoulos and Manfred Morari (1980) – *synthesis of control structures for chemical processes*
- Ruel Shinnar (1981-) - *"dominant variables"*
- Jim Downs (1991) - *Tennessee Eastman challenge problem*
- Larsson and Skogestad (2000): *Review of plantwide control*

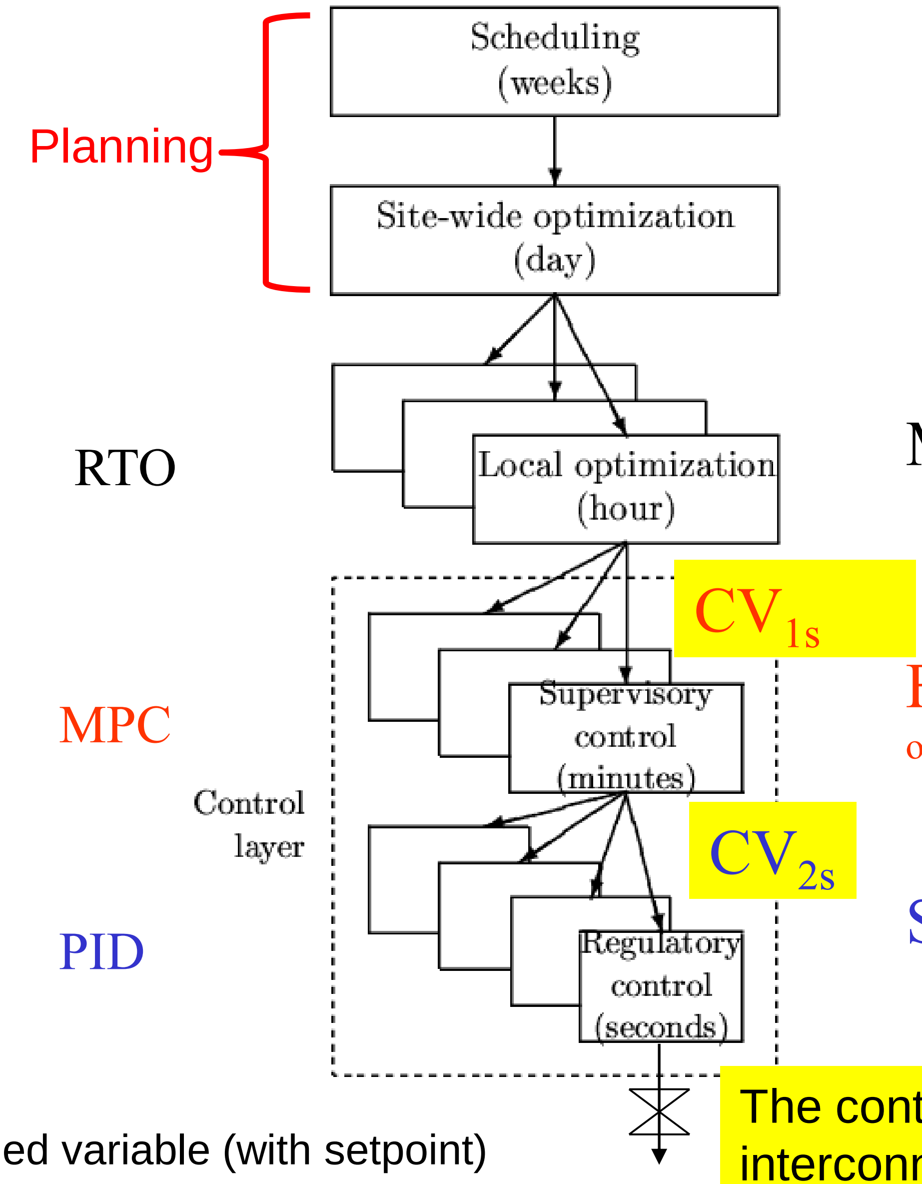
Main objectives control system

1. **Economics**: Implementation of acceptable (near-optimal) operation
2. **Regulation:** Stable operation

ARE THESE OBJECTIVES CONFLICTING?

- Usually NOT
  - Different time scales
    - Stabilization fast time scale
  - Stabilization doesn't "use up" any degrees of freedom
    - Reference value (setpoint) available for layer above
    - But it "uses up" part of the time window (frequency range)

Practical operation: Hierarchical structure



OBJECTIVE

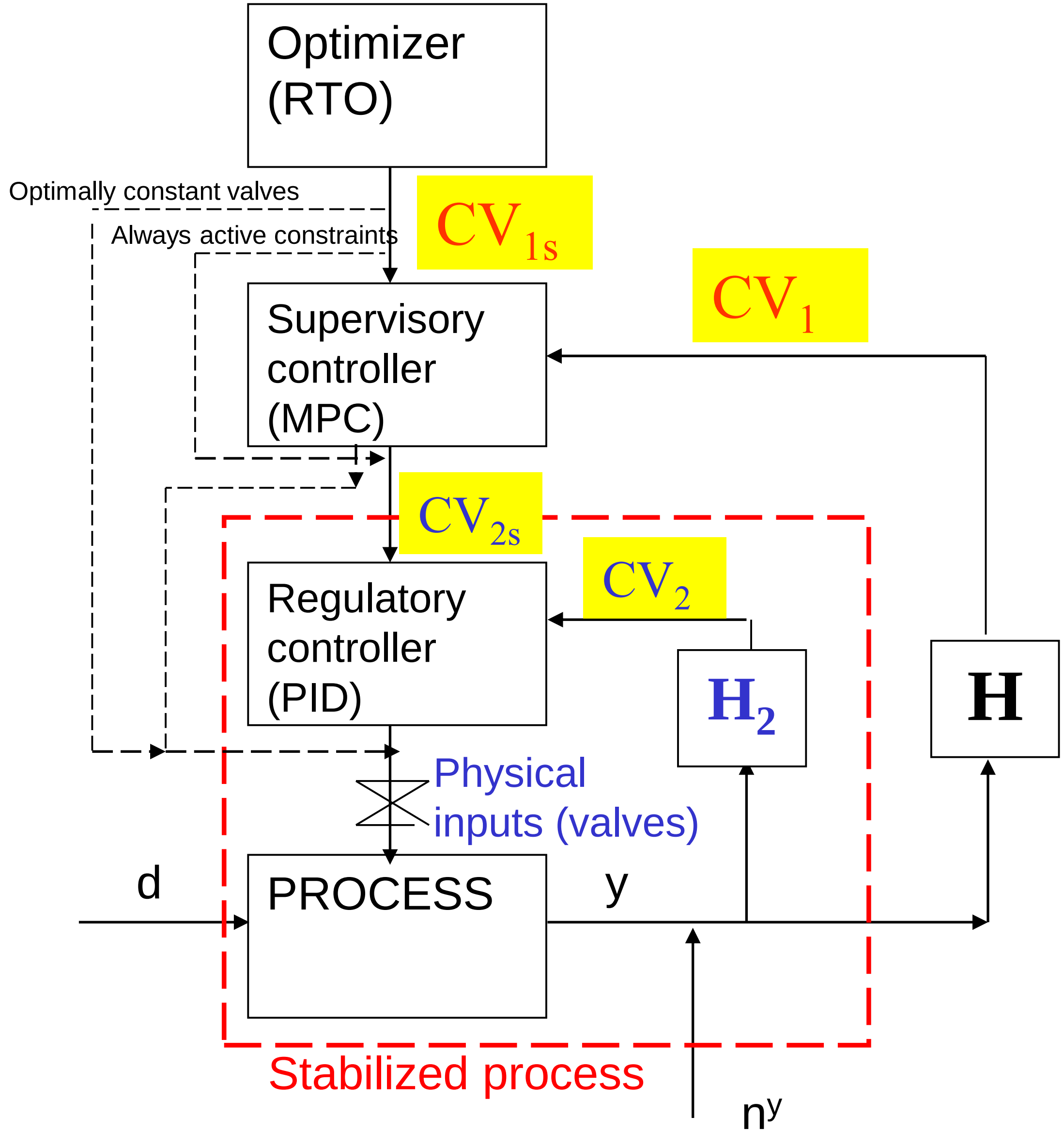
Min J (economics)

Follow path (+ look after other variables)

Stabilize + avoid drift

The controlled variables (CVs) interconnect the layers

CV = controlled variable (with setpoint)

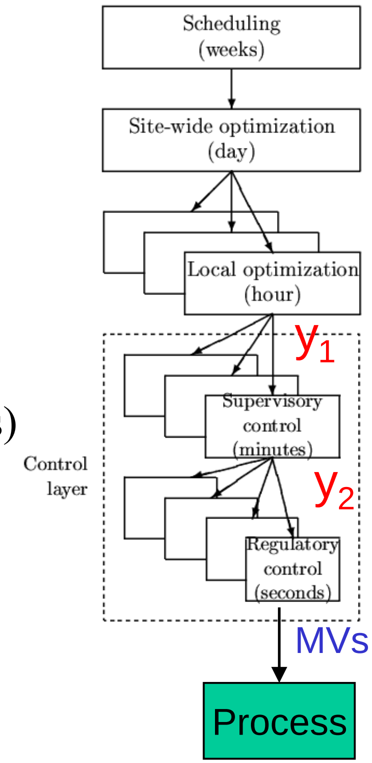


Degrees of freedom for optimization (usually steady-state DOFs), MVopt = CV1s
Degrees of freedom for supervisory control, MV1=CV2s + unused valves
Physical degrees of freedom for stabilizing control, MV2 = valves (dynamic process inputs)

Control structure design procedure

I Top Down (mainly steady-state economics, y_1)

- **Step 1:** Define operational objectives (optimal operation)
  - Cost function J (to be minimized)
  - Operational constraints
- **Step 2:** Identify degrees of freedom (MVs) and optimize for expected disturbances
  - Identify **Active constraints**
- **Step 3**: Select primary "economic" controlled variables $c=y_1$ (CV1s)
  - **Self-optimizing variables (find H)**
- **Step 4:** Where locate the **throughput manipulator (TPM)?**



II Bottom Up (dynamics, y_2)

- **Step 5**: Regulatory / stabilizing control (PID layer)
  - What more to control (y_2; local CV2s)? **Find H_2**
  - Pairing of inputs and outputs
- **Step 6:** Supervisory control (MPC layer)
- **Step 7:** Real-time optimization (Do we need it?)

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

Step 1. Define optimal operation (economics)

- What are we going to use our degrees of freedom u (MVs) for?
- Define scalar cost function J(u,x,d)
  - u: degrees of freedom (usually steady-state)
  - d: disturbances
  - x: states (internal variables)

  Typical cost function:

  J = cost feed + cost energy – value products

- Optimize operation with respect to u for given d (usually steady-state):

$$\min_u \; J(u,x,d)$$

subject to:

Model equations: $f(u,x,d) = 0$

Operational constraints: $g(u,x,d) < 0$

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Step S2. Optimize

(a) Identify degrees of freedom
(b) Optimize for expected disturbances

- Need good model, usually steady-state
- Optimization is time consuming! But it is offline
- Main goal: Identify ACTIVE CONSTRAINTS
- A good engineer can often guess the active constraints

Step S3: Implementation of optimal operation

- Have found the optimal way of operation. How should it be implemented?
- **What to control ?** (CV_1).
  1. Active constraints
  2. Self-optimizing variables (for unconstrained degrees of freedom)

Optimal operation of runner

– Cost to be minimized, J=T
– One degree of freedom (u=power)
– What should we control?

1. Optimal operation of Sprinter

- 100m. J=T
- Active constraint control:
  - Maximum speed (”no thinking required”)
  - CV = power (at max)

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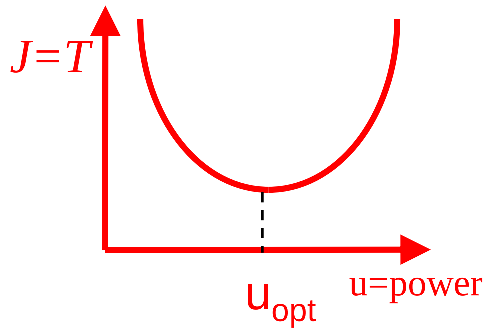
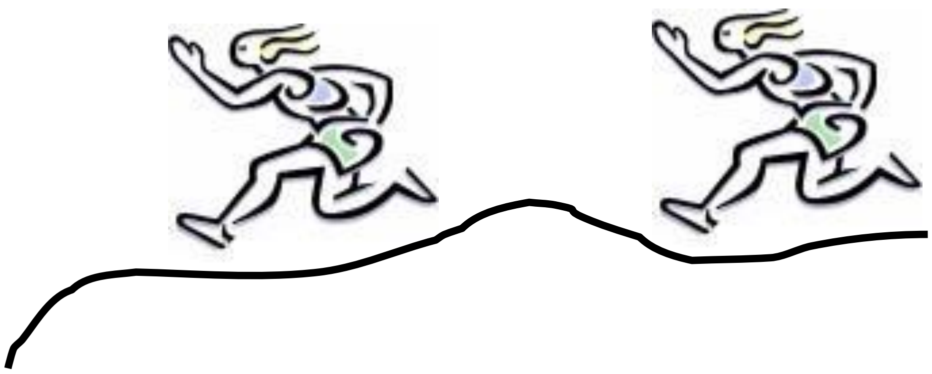
2. Optimal operation of Marathon runner

- 40 km. J=T
- What should we control? CV=?
- Unconstrained optimum





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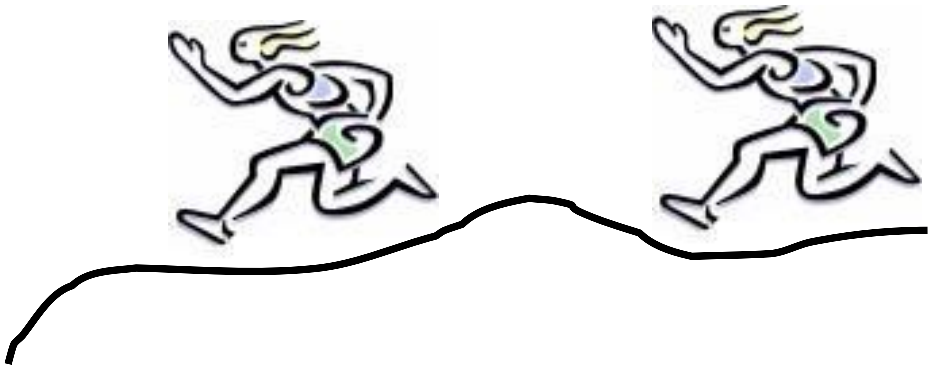
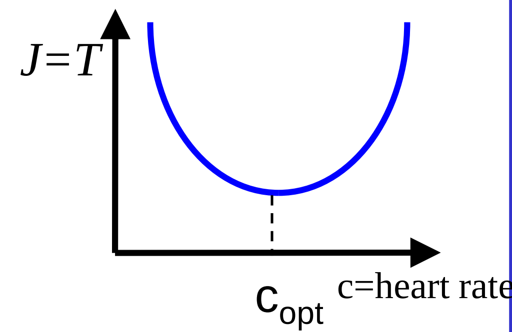
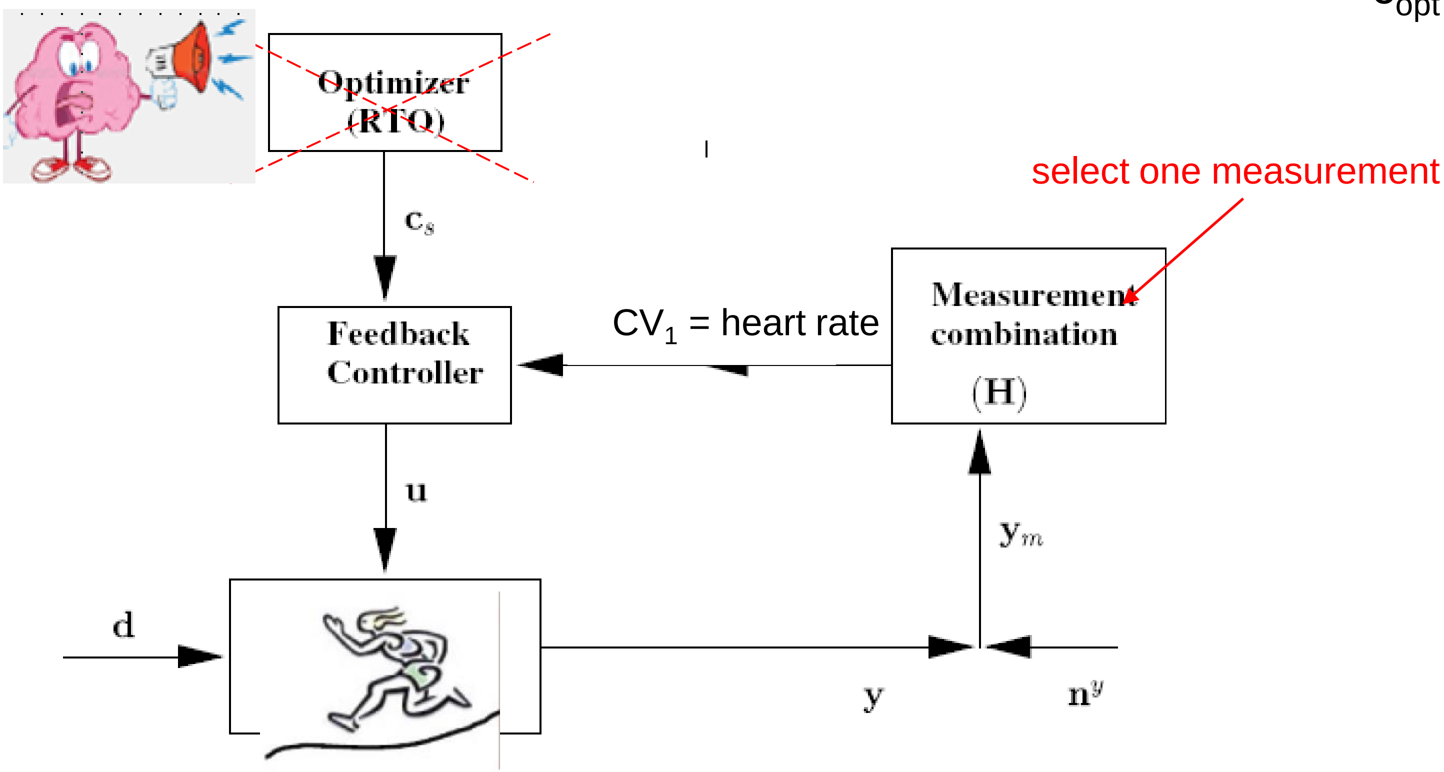
Self-optimizing control: Marathon (40 km)

- Any self-optimizing variable (to control at constant setpoint)?
  - c_1 = distance to leader of race
  - c_2 = speed
  - c_3 = heart rate
  - c_4 = level of lactate in muscles



Conclusion Marathon runner





- CV = heart rate is good “self-optimizing” variable
- Simple and robust implementation
- Disturbances are indirectly handled by keeping a constant heart rate
- <u>May</u> have infrequent adjustment of setpoint (c_s)

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Summary Step 3.
What should we control (CV_1)?

Selection of primary controlled variables $c = CV_1$

1. **Control active constraints!**
2. **Unconstrained variables: Control self-optimizing variables!**

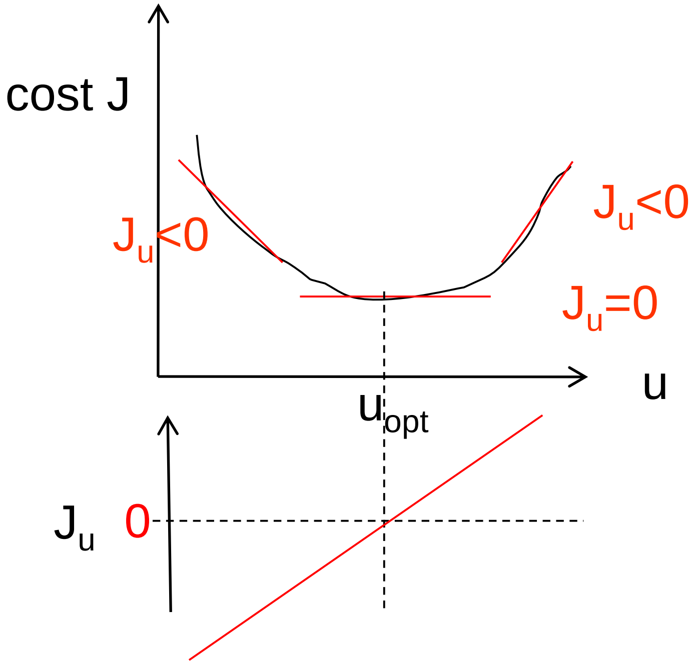
- Old idea (Morari *et al.*, 1980):

"We want to find a function c of the process variables which when held constant, leads automatically to the optimal adjustments of the manipulated variables, and with it, the optimal operating conditions."

The ideal "self-optimizing" variable is the gradient, J_u

$$c = \partial J/\partial u = J_u$$

- Keep gradient at zero for all disturbances ($c = J_u = 0$)
- Problem: Usually no measurement of gradient



$CV_1 = Hy$
Nullspace method for H (Alstad): HF=0 where $F = dy_{opt}/dd$

$$J_u(u,d) = \underbrace{J_u(u_{opt}(d), d)}_{=0} + J_{uu} \cdot (u - u_{opt})$$

$u - u_{opt} = (HG^y)^{-1}(c - c_{opt})$

Here: $c - c_{opt} = \Delta c - \Delta c_{opt}$

where we have introduced deviation variables around a nominal optimal point (c^*, d^*) (where $c^* = c_{opt}(d^*)$)

Assume perfect control of c (no noise): $\Delta c = 0$

Optimal change: $\Delta c_{opt} = H \Delta y_{opt} = HF \Delta d$

Gives: $J_u = -J_{uu}(HG^y)^{-1} HF \Delta d$

$\Rightarrow HF = 0$ gives $J_u = 0$ for any disturbance Δd

- Proof. Appendix B in: Jäschke and Skogestad, "NCO tracking and self-optimizing control in the context of real-time optimization", *Journal of Process Control*, 1407-1416 (2011)

With measurement noise

"Exact local method"

"=0" in nullspace method (no noise)

$$\min_H \|J_{uu}^{1/2}(HG^y)^{-1}H[FW_d \quad W_{n^y}]\|_2$$

"Minimize" in Maximum gain rule
(maximize S_1 G $J_{uu}^{-1/2}$, G=HG^y)

"Scaling" S_1

Analytical solution:

$H = G^{yT}(YY^T)^{-1}$ where $Y = [FW_d \quad W_{n^y}]$

- No measurement error: HF=0 (nullspace method)
- With measuremeng error: Minimize GF^c
- Maximum gain rule

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Example. Nullspace Method for Marathon runner

u = power, d = slope [degrees]

y_1 = hr [beat/min], y_2 = v [m/s]

$F = dy_{opt}/dd = [0.25 \;\; -0.2]'$

$H = [h_1 \;\; h_2]]$

HF = 0 **->** $h_1 f_1 + h_2 f_2 = 0.25\, h_1 - 0.2\, h_2 = 0$

Choose $h_1 = 1$ -> $h_2 = 0.25/0.2 = 1.25$

Conclusion: **c = hr + 1.25 v**

Control **c = constant** -> hr increases when v decreases (OK uphill!)

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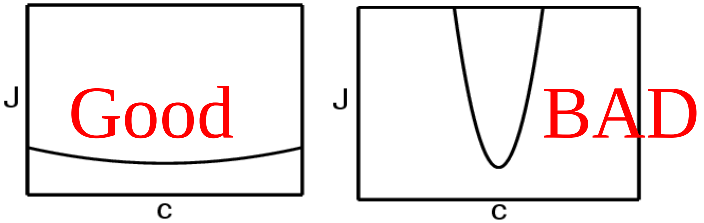
In practice: What variable c=Hy should we control? (for self-optimizing control)

1. **The *optimal value* of c should be *insensitive* to disturbances**
   - Small HF = dc_{opt}/dd
2. **c should be easy to measure and control**
3. **The *value* of c should be *sensitive* to the inputs** (“**maximum gain rule**”)
   - Large G = HG^y = dc/du
   - Equivalent: Want flat optimum



(b) Flat optimum: Implementation easy

(c) Sharp optimum: Sensitive to implementation erros

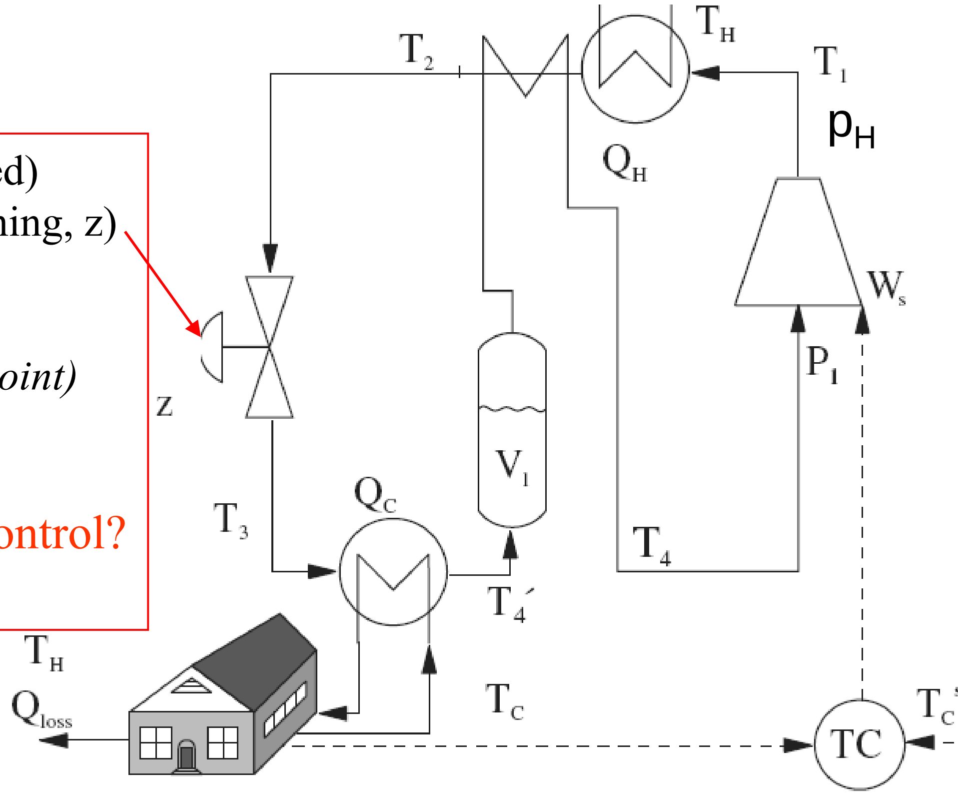
Note: Must also find optimal setpoint for $c=CV_1$

Example: CO2 refrigeration cycle

$J = W_s$ (work supplied)
DOF = u (valve opening, z)
Main disturbances:

$d_1 = T_H$
$d_2 = T_{Cs}$ *(setpoint)*
$d_3 = UA_{loss}$

What should we control?



CO_2 refrigeration cycle

Step 1. One (remaining) degree of freedom (u=z)

Step 2. Objective function. $J = W_s$ (compressor work)

Step 3. Optimize operation for disturbances ($d_1=T_C$, $d_2=T_H$, $d_3=UA$)

- Optimum always unconstrained

Step 4. Implementation of optimal operation

- No good single measurements (all give large losses):
  - p_h, T_h, z, …
- Nullspace method: Need to combine $n_u+n_d=1+3=4$ measurements to have zero disturbance loss
- Simpler: Try combining two measurements. Exact local method:
  - $c = h_1 p_h + h_2 T_h = p_h + k T_h$; $k = -8.53$ bar/K
- Nonlinear evaluation of loss: OK!

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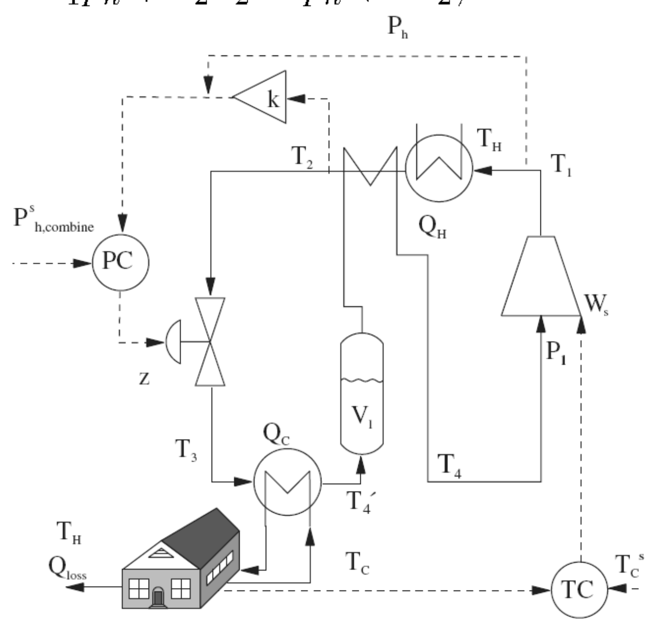
CO2 cycle: Maximum gain rule

Linear "maximum gain" analysis of controlled variables for CO_2 case

Variable (y)	Nom.	$G = \frac{\Delta y}{\Delta u}$	$\|\Delta y_{opt}(d_i)\|$ d_1 (T_H)	d_2 (T_C)	d_3 (UA_{loss})	$\|\Delta y_{opt}\|$	n	Span y $\|\Delta y_{opt}\| + n$	$\|G'\| = \frac{\|G\|}{\text{span} y}$
P_h/T_2' (bar °C^{-1})	0.32	−0.291	0.140	−0.047	0.093	0.174	0.0033	0.177	0.25
P_h (bar)	97.61	−78.85	48.3	−15.5	31.0	59.4	1.0	60.4	1.31
T_2' (°C)	35.5	36.7	16.27	−2.93	7.64	18.21	1	19.2	1.91
$T_2' - T_H$ (°C)	3.62	24	4.10	−1.92	5.00	6.75	1.5	8.25	2.91
z	0.34	1	0.15	−0.04	0.18	0.24	0.05	0.29	3.45
V_1 (m^3)	0.07	0.03	−0.02	0.005	−0.03	0.006	0.001	0.007	4.77
T_2 (°C)	25.5	60.14	8.37	0.90	3.18	9.00	1	10.0	6.02
$P_{h,combine}$ (bar)	97.61	−592.0	−23.1	−23.1	3.91	33.0	9.53	42.5	13.9
m_{gco} (kg)	4.83	−11.18	0.151	−0.136	0.119	0.235	0.44	0.675	16.55

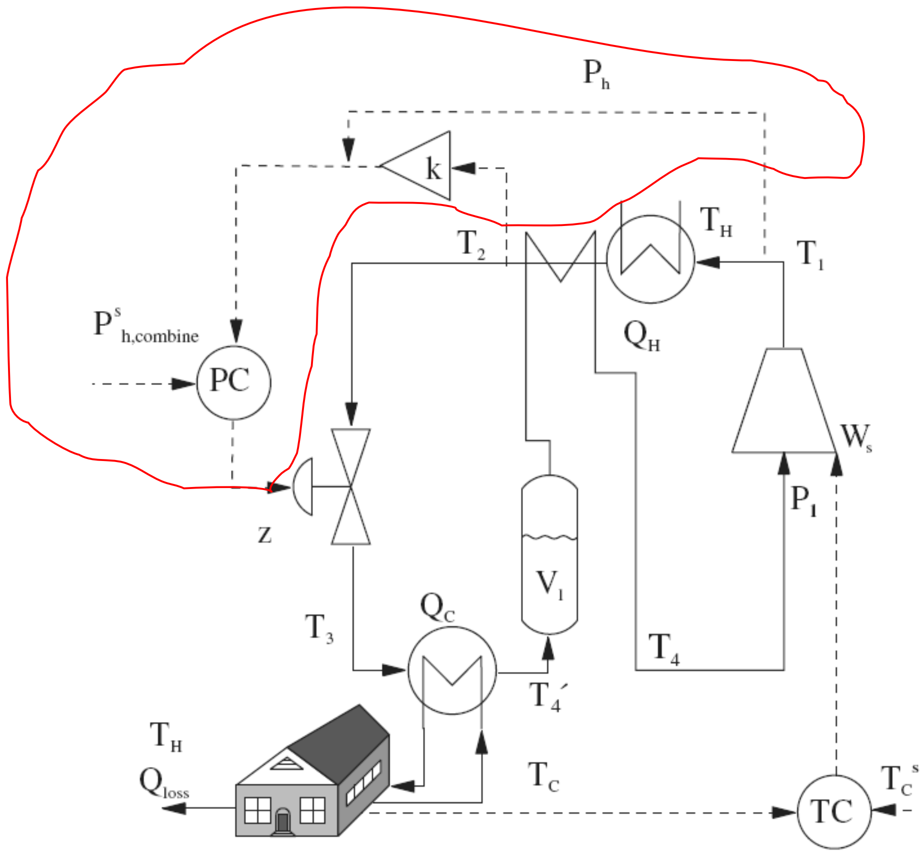
Nullspace method: $c = p_{h,\text{combine}} = h_1 p_h + h_2 T_2 = p_h + k T_2; k = -8.53$ bar/K



J.B. Jensen, S. Skogestad / Computers and Chemical Engineering 31 (2007) 1590–1601

CV=Measurement combination

Refrigeration cycle: Proposed control structure



CV1= Room temperature

CV2= “temperature-corrected high CO2 pressure”

Step 4. Where set production rate?

- Where locale the **TPM (throughput manipulator)?**
  - The ”gas pedal” of the process
- Very important!
- Determines structure of remaining inventory (level) control system
- Set production rate at (dynamic) bottleneck
- Link between **Top-down** and **Bottom-up** parts

- NOTE: TPM location is a dynamic issue.
  Link to economics is to improve control of active constraints (reduce backoff)

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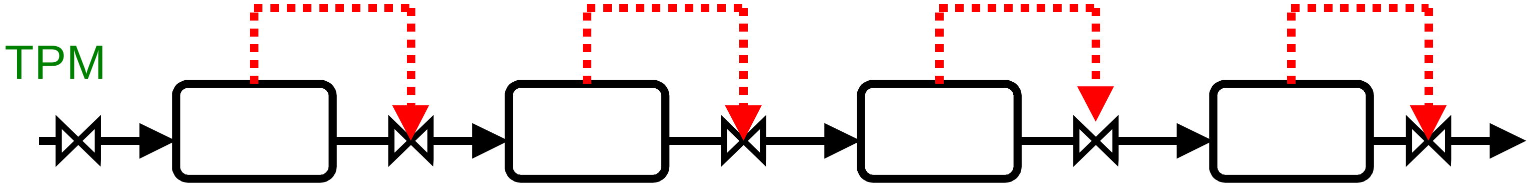
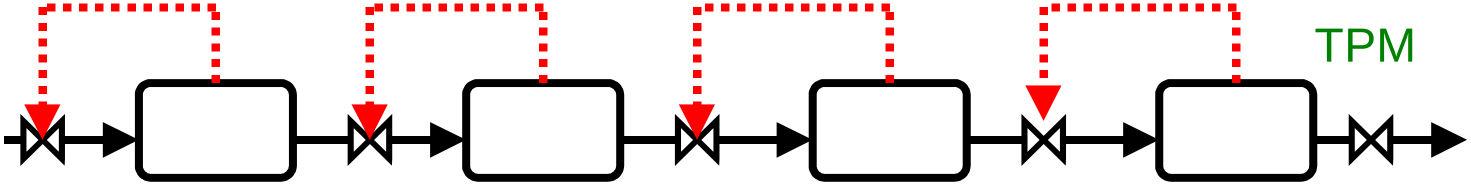
Production rate set at inlet : Inventory control in direction of flow*

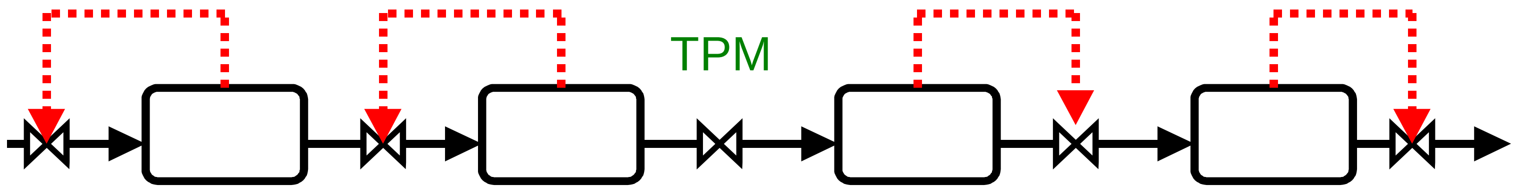


* Required to get “local-consistent” inventory control

Production rate set at outlet: Inventory control opposite flow



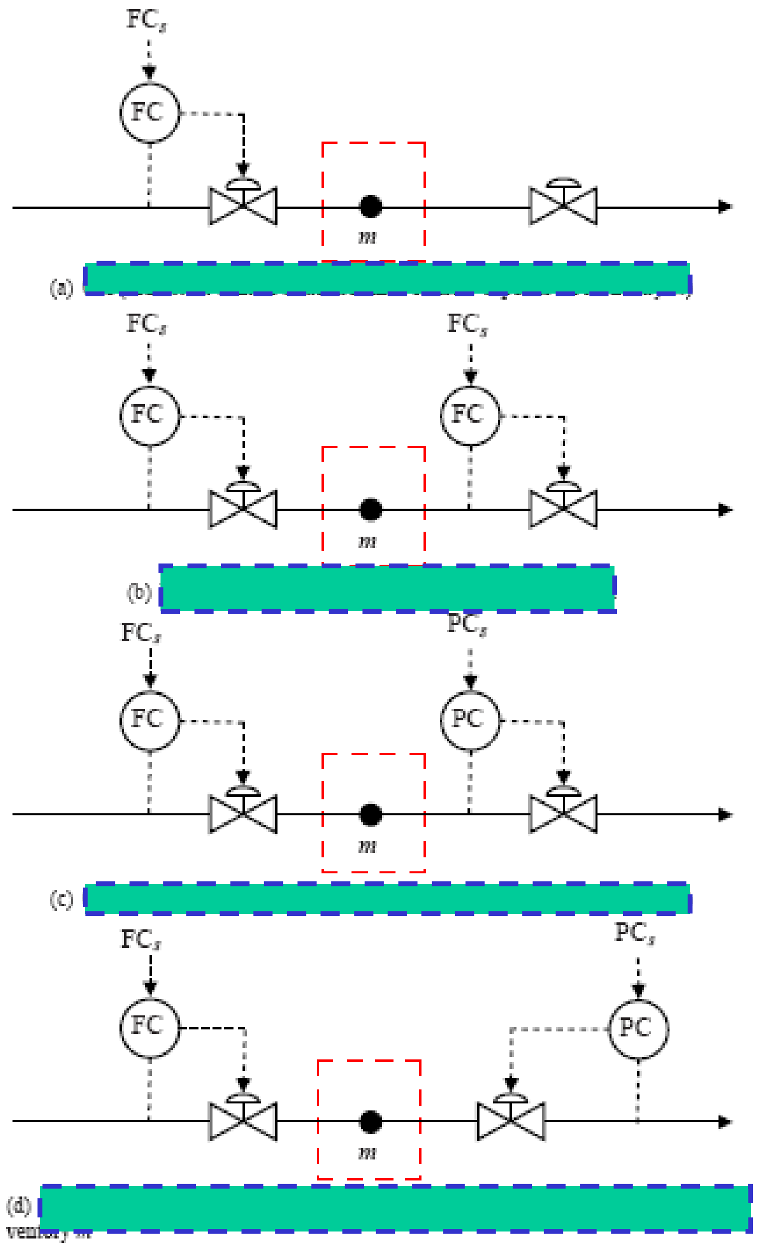
Production rate set inside process



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

QUIZ 1

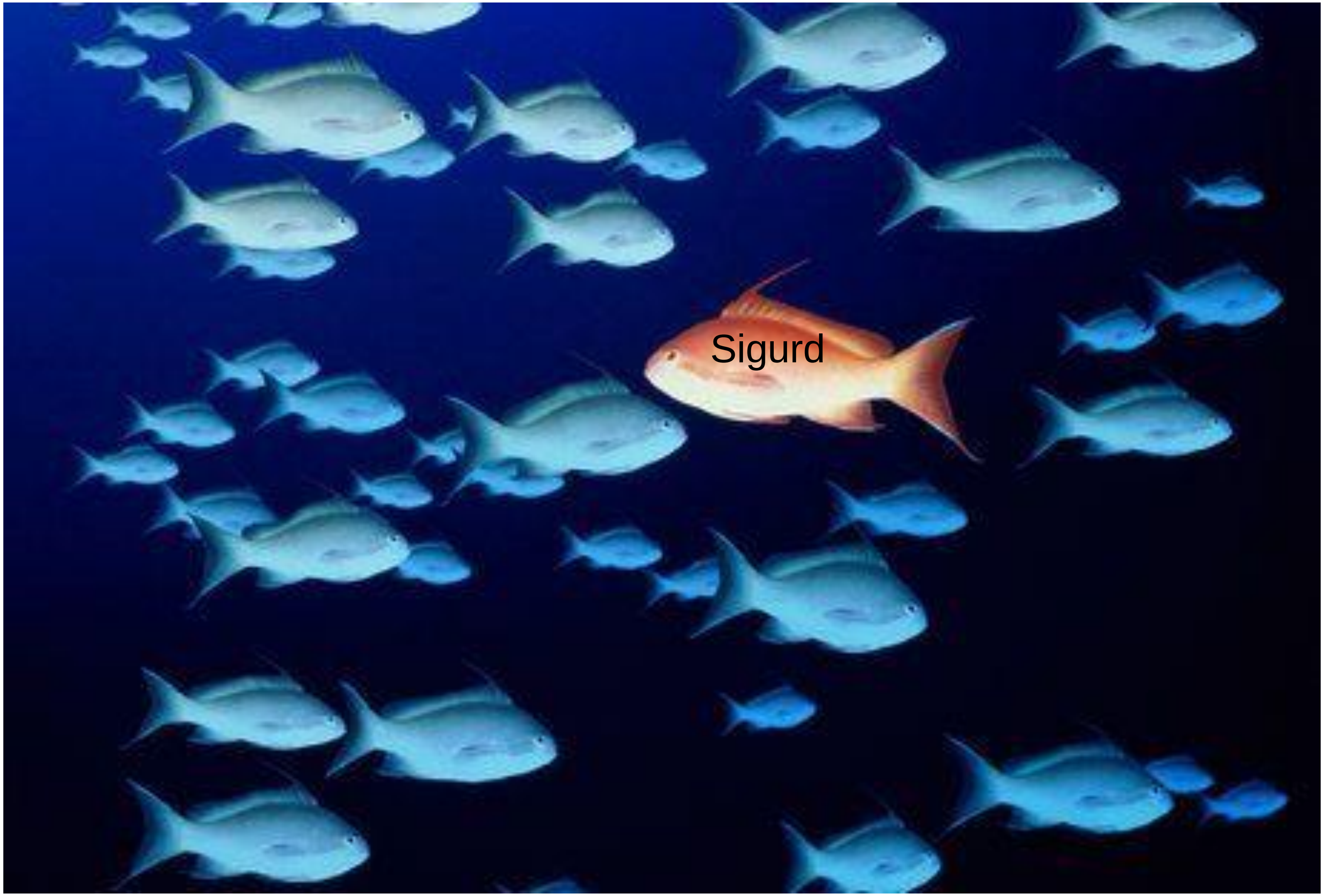
CONSISTENT?



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

Optimal centralized Solution (EMPC)

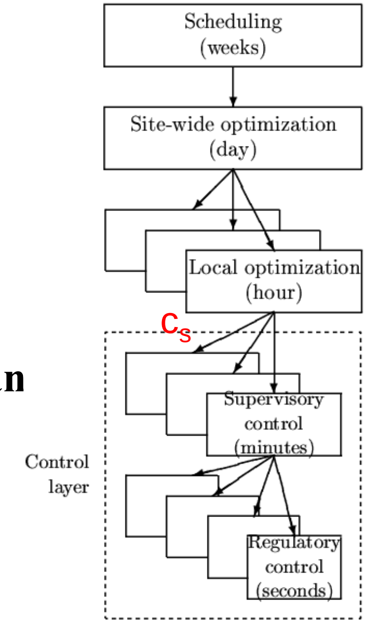
Academic process control community fish pond



Conclusion:
Systematic procedure for plantwide control

- **Start "top-down" with economics:**
  - Step 1: Define operational objectives and identify degrees of freeedom
  - Step 2: Optimize steady-state operation.
  - Step 3A: Identify active constraints = primary CVs c.
  - Step 3B: Remaining unconstrained DOFs: Self-optimizing CVs c.
  - Step 4: Where to set the throughput (usually: feed)

- **Regulatory control I: Decide on how to move mass through the plan**
  - Step 5A: Propose "local-consistent" inventory (level) control structure.
- **Regulatory control II: "Bottom-up" stabilization of the plant**
  - Step 5B: Control variables to stop "drift" (sensitive temperatures, pressures, ...)
    - Pair variables to avoid interaction and saturation
- **Finally: make link between "top-down" and "bottom up".**
  - Step 6: "Advanced/supervisory control" system (MPC):
    - CVs: Active constraints and self-optimizing economic variables +
    - look after variables in layer below (e.g., avoid saturation)
    - MVs: Setpoints to regulatory control layer.
    - Coordinates within units and possibly between units



http://www.nt.ntnu.no/users/skoge/plantwide

Summary and references

- The following paper summarizes the procedure:
  - S. Skogestad, ``Control structure design for complete chemical plants'', *Computers and Chemical Engineering*, **28** (1-2), 219-234 (2004).
- There are many approaches to plantwide control as discussed in the following review paper:
  - T. Larsson and S. Skogestad, ``Plantwide control: A review and a new design procedure'' *Modeling, Identification and Control*, **21**, 209-240 (2000).
- The following paper updates the procedure:
  - S. Skogestad, ``Economic plantwide control'', Book chapter in V. Kariwala and V.P. Rangaiah (Eds), *Plant-Wide Control: Recent Developments and Applications",* Wiley (2012).
- Another paper:
  - S. Skogestad "Plantwide control: the search for the self-optimizing control structure'", *J. Proc. Control*, 10, 487-507 (2000).
- More information:

http://www.nt.ntnu.no/users/skoge/plantwide