
AS-74.4192 Elementary Cybernetics

Lecture 9: About “Artificial Evolution”



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- Neocybernetic visions have been tested also in practice – there are various doctoral theses being completed in 2009:
 - *Kalle Halmevaara*
 - *Optimization of large-scale plant/model parameters*
 - *Jani Kaartinen*
 - *Camera analysis in mineral processing*
 - *Olli Haavisto*
 - *Enhancing measurements using visual spectra*
 - **Neocybernetics is not explicitly mentioned in these theses!**



Views into future

- In process automation, we are still at the level of constructing simple controls (or *constraints*) one by one
- In the long run, however, “nothing in complex systems (now *industrial automation*) makes sense without ... evolution”
- One should understand the general process of enhancing of processes – perhaps neocybernetic intuitions can help here?
- In what follows, **examples of “artificial evolution” are studied**
- Remember the inverse view: The systems are seen from above, assuming they are internally consistent and controlled – they yield when they are pushed, and this happens in the directions of the linear *degrees of freedom*



“Artificial cells” with “synthetic metabolism”

- Production plants are changing into “bio-logical cells”:
 - There is intake of raw materials, production of “metabolites” (products) being as efficient as possible
 - There is a balance among economical constraints and technical possibilities, new innovations changing this balance
 - After adaptation there is better balance also in terms of tolerance against disturbances and changes in the environment
 - Evolution in the system is manifested in terms of new local controls that make the system stiffer and more robust, the system becoming “pancausal”
 - Systems are “allo cybernetic”, evolution being implemented by humans (or, engineers): whenever there is new information, there are new feedbacks
 - Local adaptations are typically implemented in terms of SISO (PID!) controls, such “atoms of enhancement” decreasing degrees of freedom by one
 - On the other hand, cybernetized systems become more and more unstable, oscillating on the edge of chaos!



Cybernetization – systems become “stiffer”

- Humans are the agents that implement the enhancements
- However, the dynamics are not dictated by the humans, systems having their own internal dynamics
 - The local goals are: The subsystem “tries” to become somehow *better* – faster, cheaper, more accurate, ...
 - Typically, the system goal is hypothetical, never reached – for example, zero cost, zero delay, etc.
 - The cybernetic balance is determined by technical / economical / social possibilities and constraints
 - Another factor in the dynamics is inertia among people, limiting the rate of change in the system
- This is very heuristic – is there any way of making the discussions more concrete?



Towards “smooth evolution”

- The evolutionary processes are often thought to be random walk processes with no continuity / differentiability properties

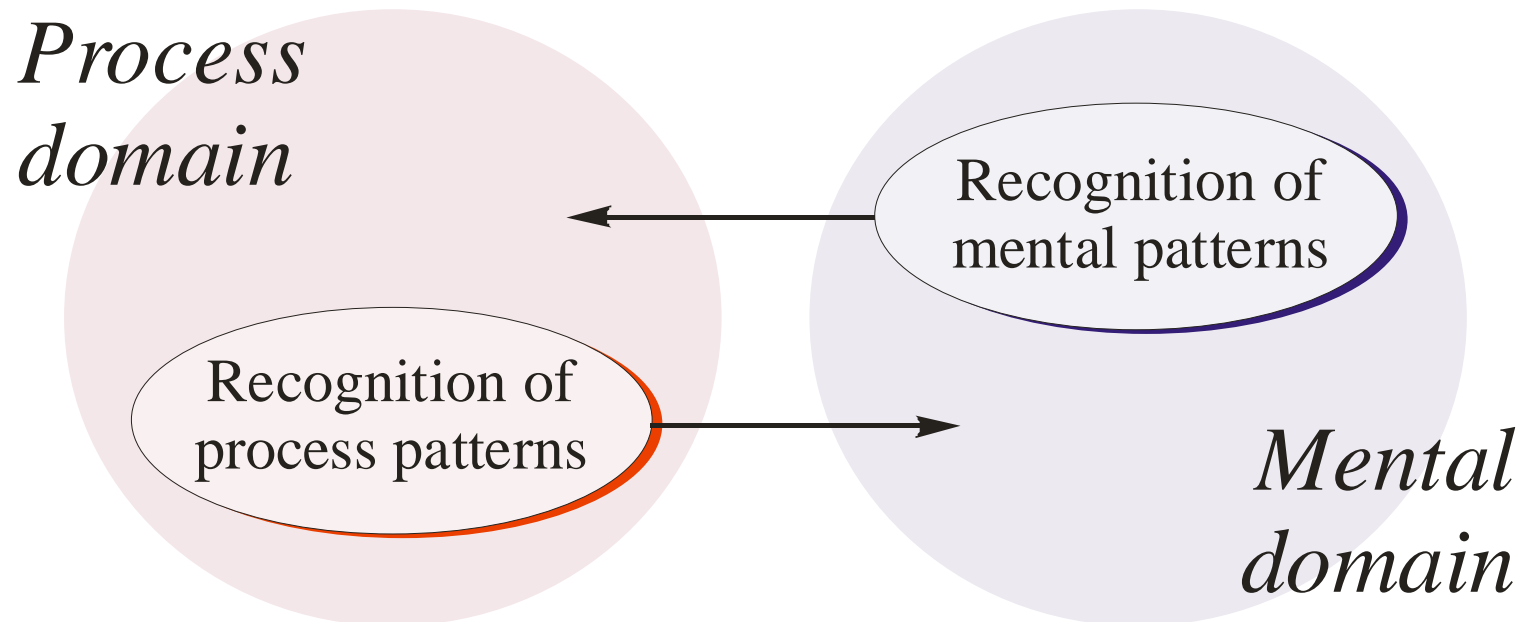
Is this assumption always necessary?

- No – the claim here is that (at least in some cases, when remaining *within one structural alternative*) the process of evolution can be continuous and differentiable
- On the higher level, system parameters are the variables of the emergent model
- There exist degrees of freedom in that parameter space with continuity of behaviors, regardless of underlying constraints
- **Smoothness is mechanism applied by natural evolution, too**



“Second-Order Neocybernetics” simplified

- Now it is assumed that both domains can be modeled in linear terms: just one operating regime – simple “patterns”



Conclusion from before

- Cybernetic models have the same structure, no matter if they are based on populations, networks, or constraints – **Linear reduced-dimension latent variable subspace, multivariate models representing dynamic equilibria**
- All systems can be studied in the same framework – applying PCA / factor analysis, etc., as seen from above
- High dimensionality, redundancies, noise, etc., are efficiently tackled with
- However, one is not interested in the “natural direction”, but one would like to affect this according to expert knowledge – do not trust input data alone (PCA style), but find a **compromise between variation in input and in output.**



Restructuring data

- To reach practically applicable models, the homogeneous data has to be divided in input and output parameters:

“Qualifiers” $\theta = \begin{pmatrix} \theta_1 \\ \vdots \\ \theta_n \end{pmatrix}$ and $\Theta = \begin{pmatrix} \theta^T(1) \\ \vdots \\ \theta^T(k) \end{pmatrix}$

“Process domain”
(inputs)

Not only parameters but
reference values, ...

“Qualities” $q = \begin{pmatrix} q_1 \\ \vdots \\ q_m \end{pmatrix}$ and $Q = \begin{pmatrix} q^T(1) \\ \vdots \\ q^T(k) \end{pmatrix}$

“Mental domain”
(outputs)

Quality characteristics of
practical interest

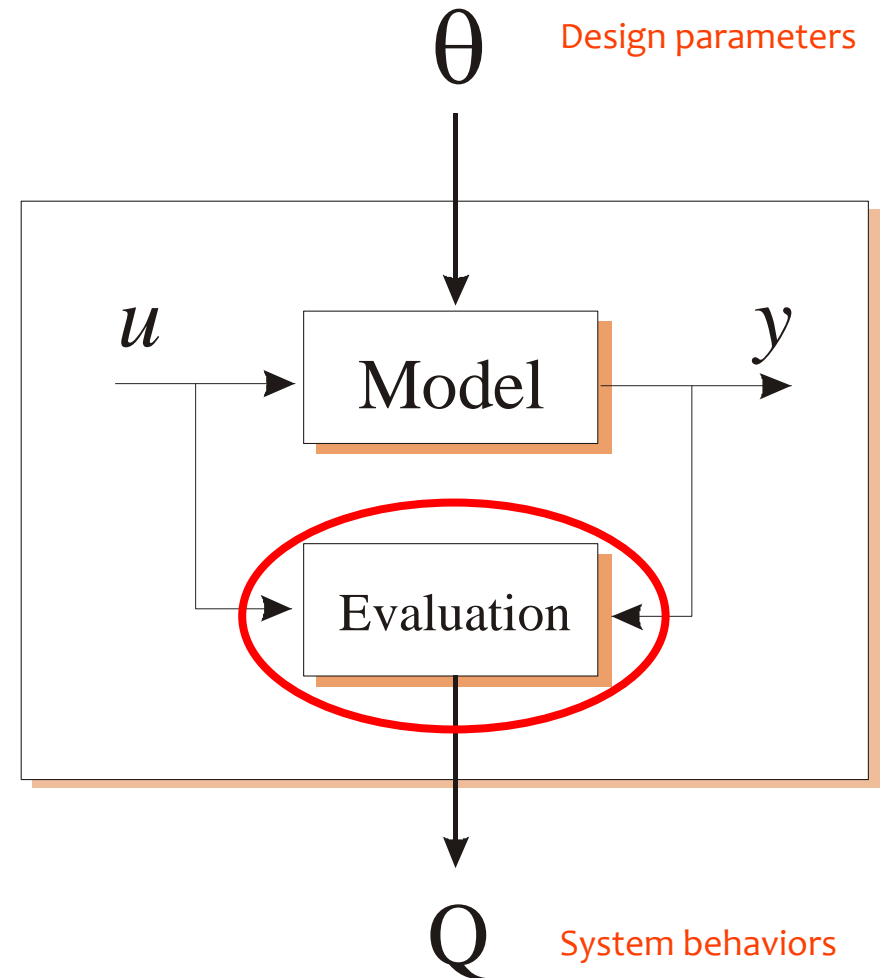
- Determination of the causal structure has to be carried out by a domain area expert

“Inputs” and “outputs” very
different from actual time
domain signal realizations



From signals to “emergent-level variables”

- Higher abstraction level for looking at processes on a slower time scale
- Model from *quantifiers* Θ to *qualities* Q rather than between signals u and y
- Evaluation = link between statistics and conceptually relevant structures
- Abstraction and data compression based on behavior-based relevance



Advantages of the approach

- **Simplicity**

- Dynamic structures can be studied *statically*, individual signal realizations can be forgotten

- **Homogeneity**

- Model outlook remains consistent, no matter how high in the hierarchy the submodel is

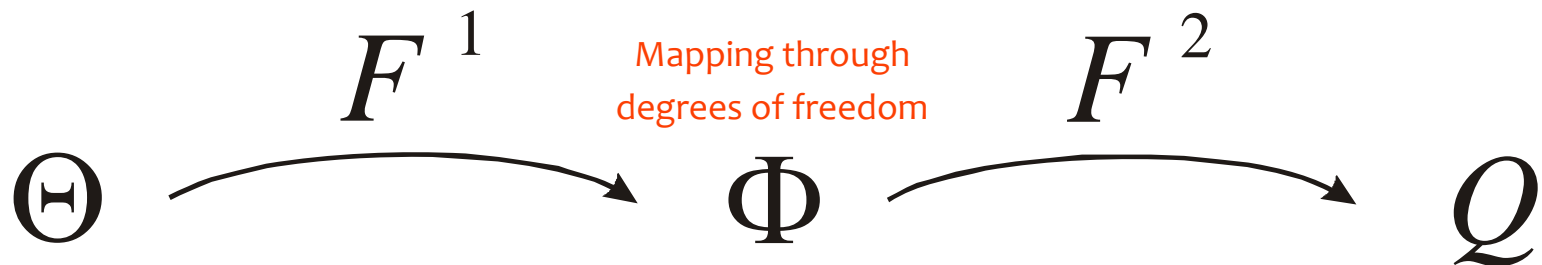
- **Generality**

- All systems can be studied in the *same* framework, no matter what the physical system structures or their models (NN, FS, standard mathematics) are like, or where the system is in the hierarchy
- The data can be delivered not only by a real system but also by a simulator = “hardware-in-a-loop”
= Integrated modeling and simulation environments possible...



- Signals u and y are more or less arbitrary, relationship between them being stochastic; still, some dependence between Θ and Q exists (assume they are mean-centered)
- Use statistical tools to model the dependence
 - MultiLinear Regression (MLR)?
 - Principal Component Regression (PCR)?
- **PLS regression** is defined through

$$\frac{1}{k^2} \cdot \Theta^T Q Q^T \Theta \cdot \phi_i = \lambda_i \phi_i$$



Regression

- Applying the latent variables the model becomes

$$F_{\text{PLS}} = \phi \left(\phi^T \Theta^T \Theta \phi \right)^{-1} \phi^T \Theta^T Q$$

and if the quality measure is scalar,

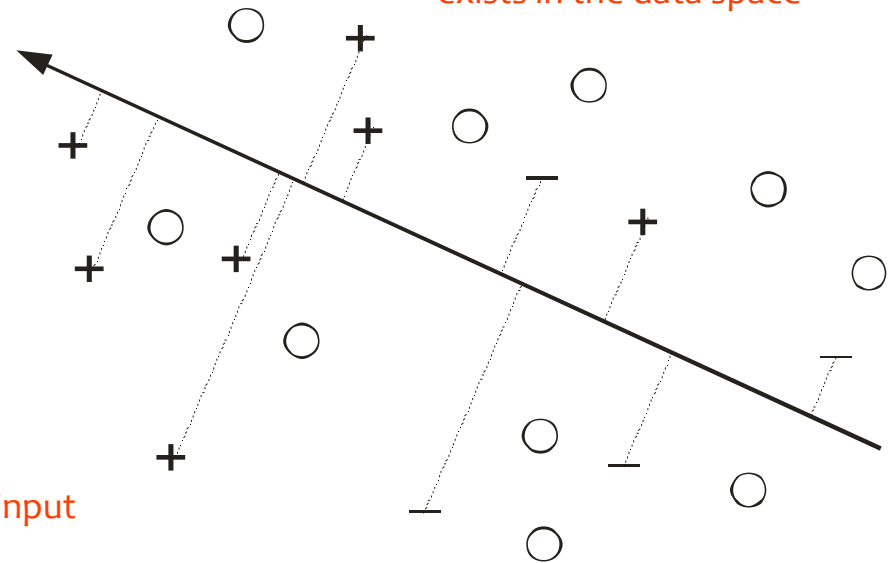
$$f = \frac{\phi \phi^T \Theta^T Q}{\phi^T \Theta^T \Theta \phi}$$

For the estimate one has

$$\hat{q} = f^T \cdot \theta$$

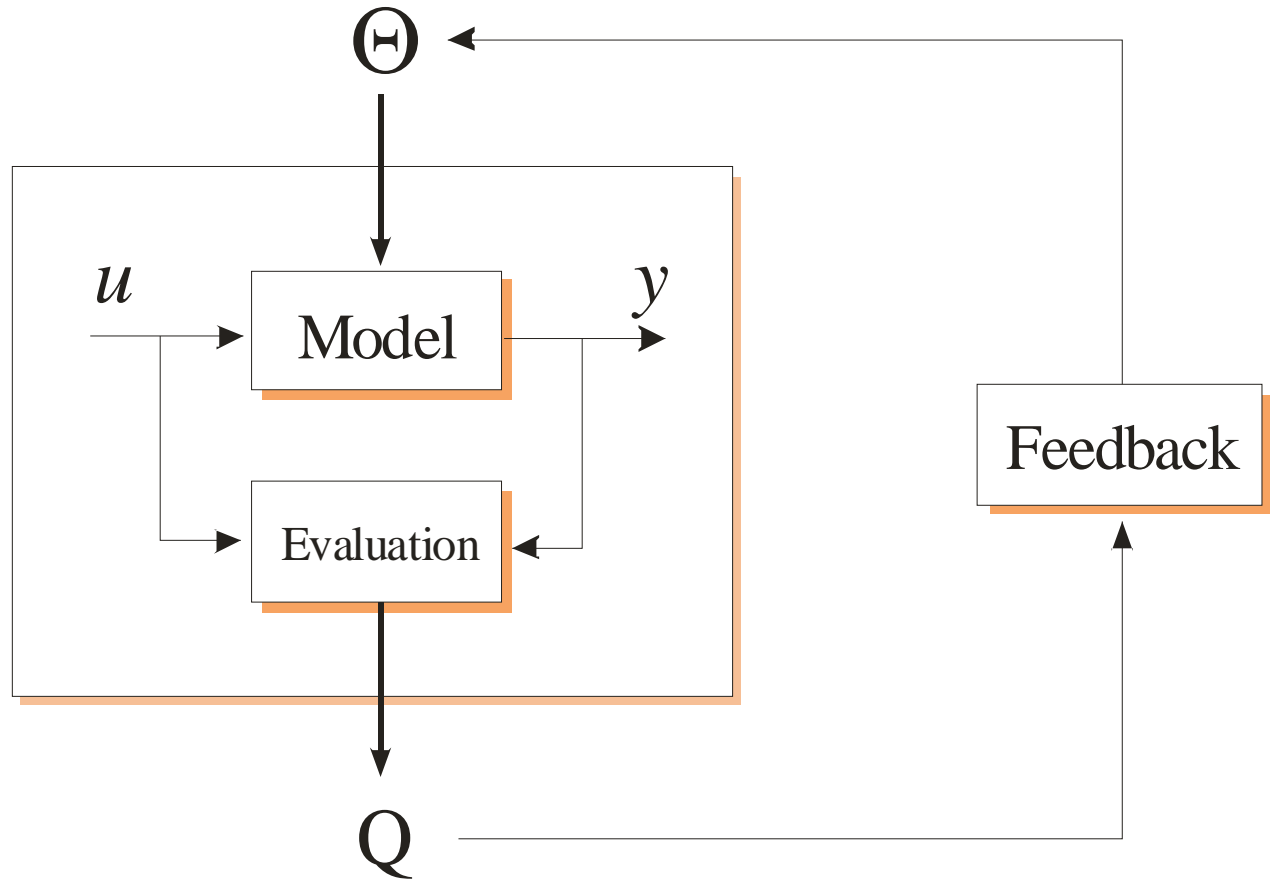
PLS is a linear latent variables based regression method weighting both input and output variables appropriately

If only one quality measure, only one non-trivial direction exists in the data space



Applications

- Higher-level adaptation scheme (applicable not only for adaptive control):



Iterative optimization

- Assume that the cost criterion is defined as

$$\hat{J} = \sum_i w_i \hat{q}_i = w^T \hat{q}$$

Noticing that

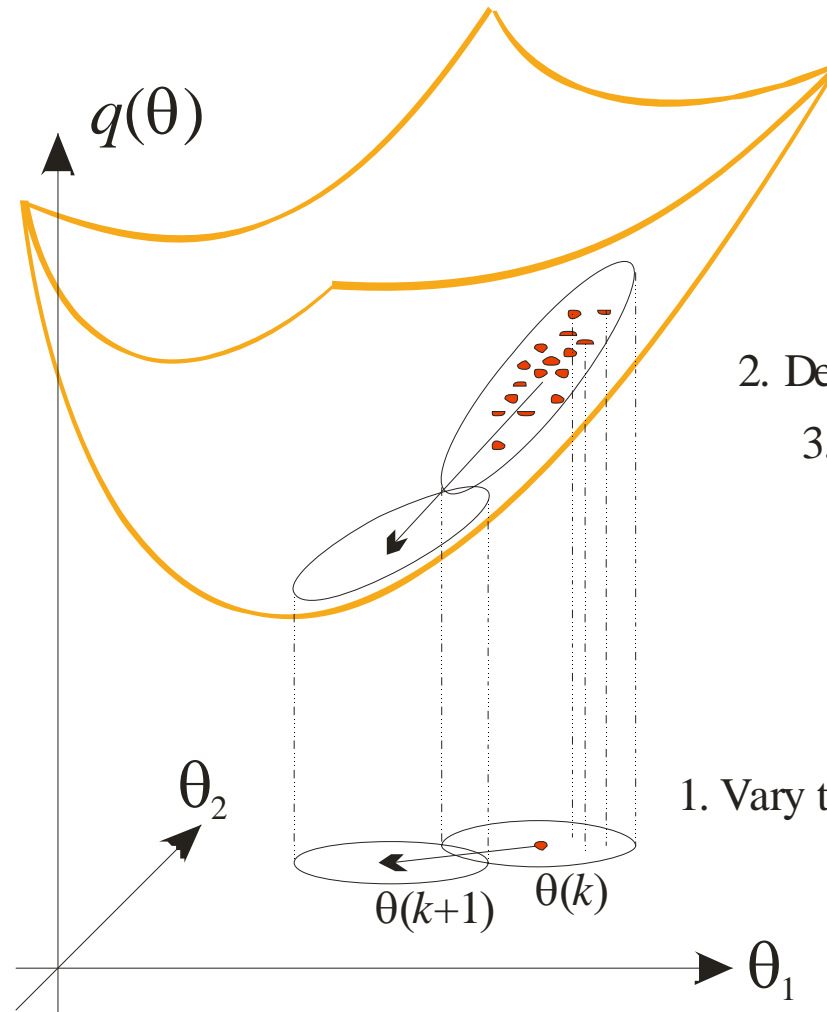
$$\frac{d\hat{J}}{d\theta} = \frac{d}{d\theta} (w^T \hat{q}) = \frac{d}{d\theta} (w^T f^T \theta) = fw$$

one can write the steepest descent algorithm as

$$\theta \leftarrow \theta - \mu \cdot \frac{d\hat{J}}{d\theta} = \theta - \mu \cdot fw.$$



- Visual version



2. Determine the $\theta - q$ dependency
3. Find the gradient direction

1. Vary the prevailing parameters θ
4. Update nominal values



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- Adaptive manipulation of models is a notorious problem – why closed-loop identification is no problem now?
 1. First, one is searching for static, not dynamic mapping between variables – there are less variables to search for
 2. It is not actually a closed loop that one is identifying when seen at the higher level – there do not (yet) exist feedbacks between the qualities and qualifiers
 3. After all, one has to think of the case in the perspective of emergent models: It is not individual parameters, etc., that are being detected, but the remaining degrees of freedom in data.



Theoretical benefits

- Typically, adaptive control structures are *bilinear*, resulting in theoretical problems:

$$y(k) = \theta^T(k) \cdot x(k)$$

- Now, however, there are two *separate* linear models on different levels:

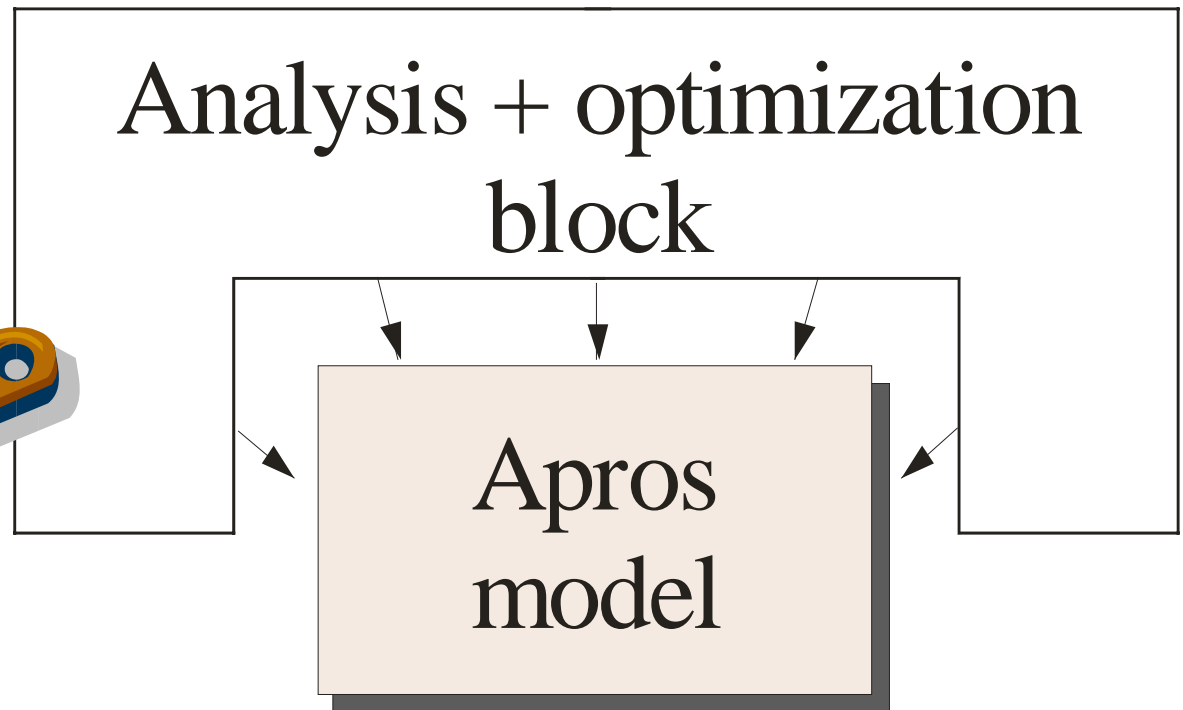
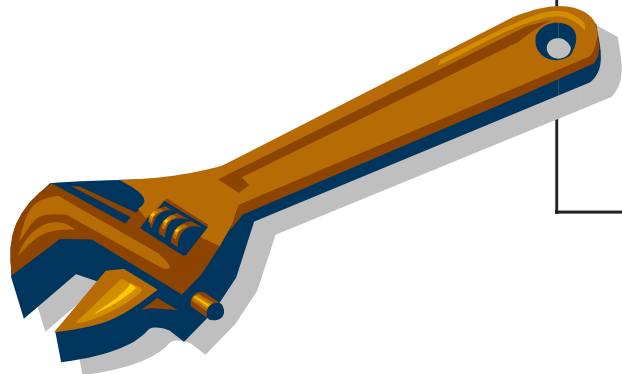
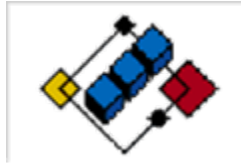
$$y(k) = \theta^T \cdot x(k)$$

$$q(t) = \phi^T \cdot \theta(t)$$

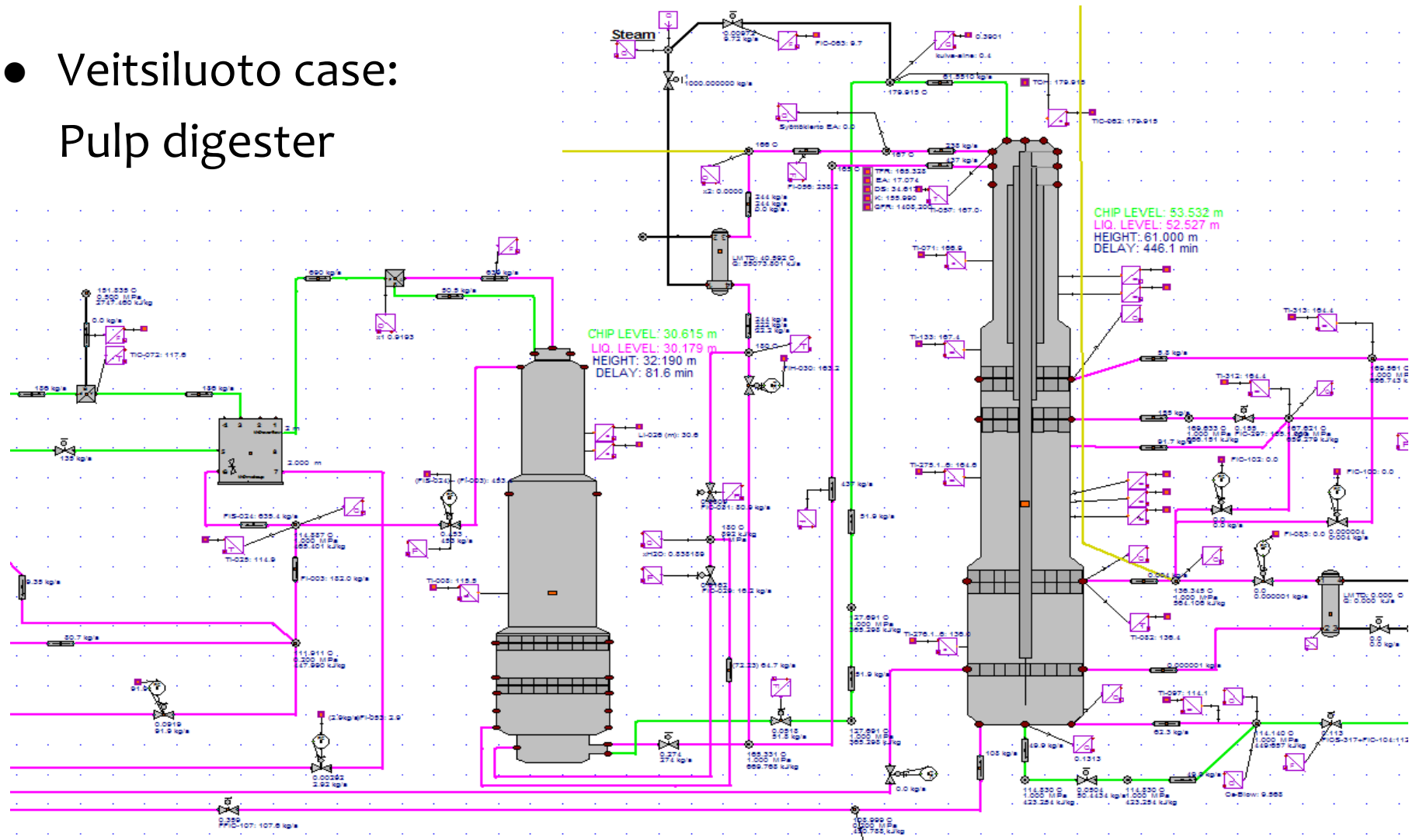
- Explicit distinction between levels makes it possible to reach theoretically simpler analyses.



- Project “Testing Manager”: Evaluate the controller optimization scheme in practice



- Veitsiluoto case:
Pulp digester



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- 20 parameters (7 PI controllers + 2 model based controllers)
 - 6 quality measures:

- q_1 : Kappa number in blow
- q_2 : Wash coefficient
- q_3 : Digester liquor level
- q_4 : Digester chip level
- q_5 : Impregnation vessel chip level
- q_6 : H factor

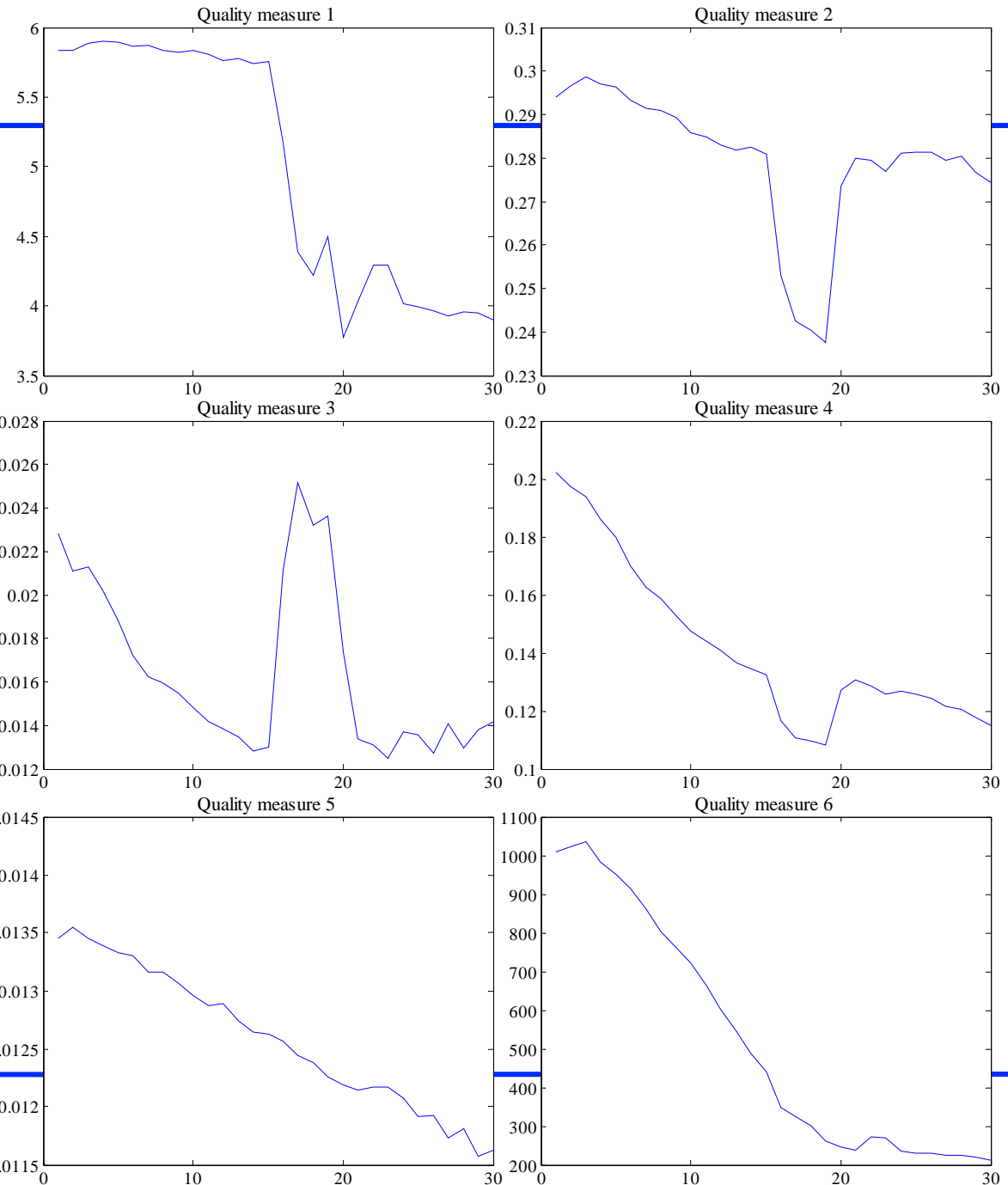
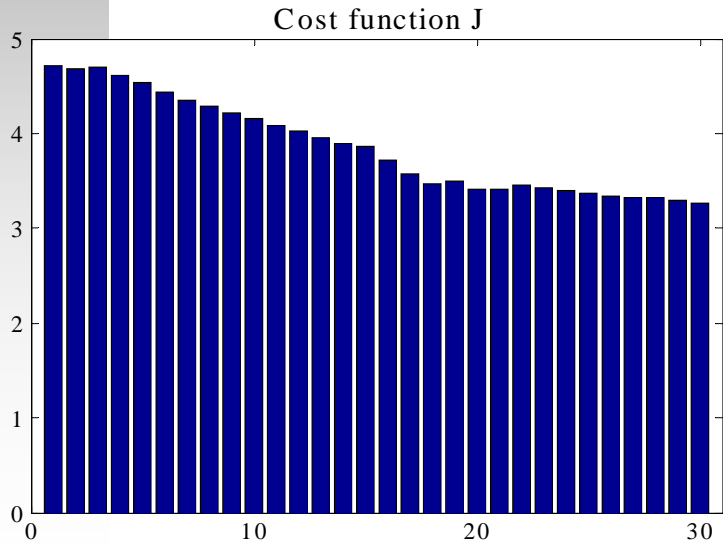
- Cost criteria

$$q_i = \frac{1}{T} \sum_{t=1}^T |x_{sp}(t) - x(t)|, \quad i = 1, \dots, 6$$

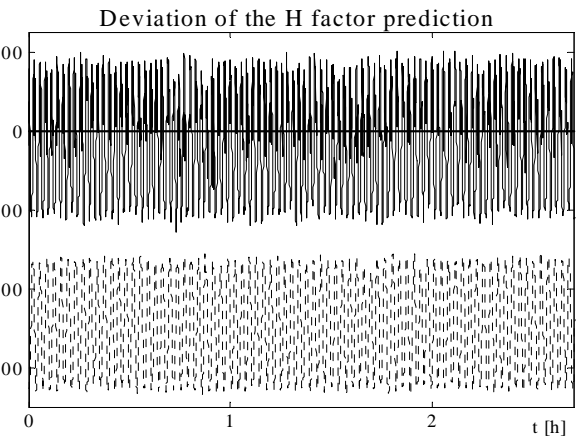
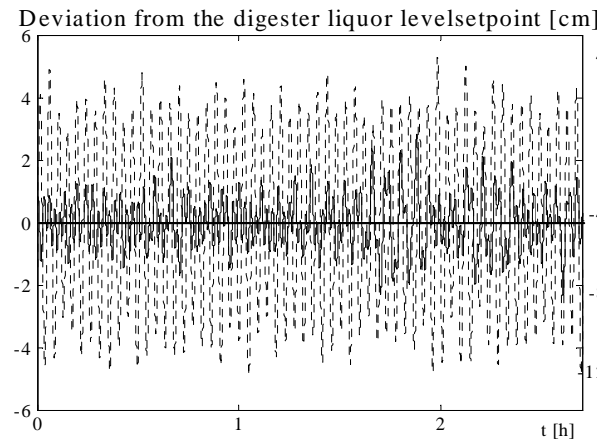
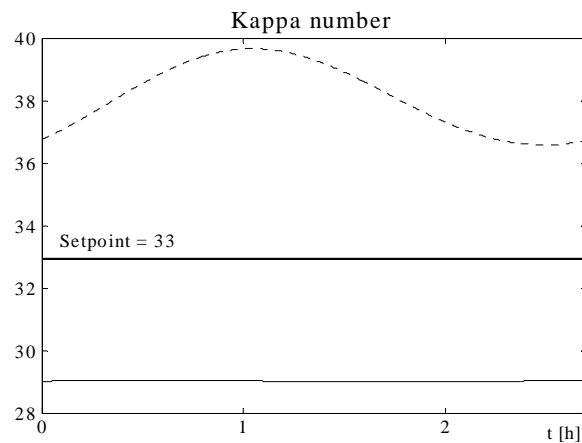
- Optimization based on the PLS model



- Optimization process



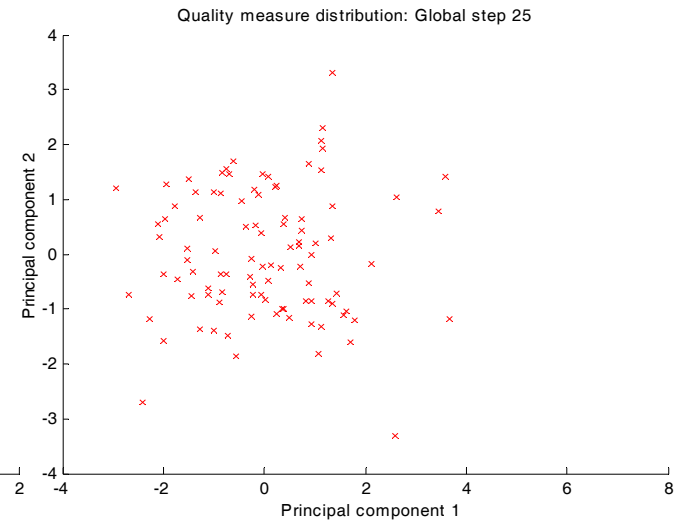
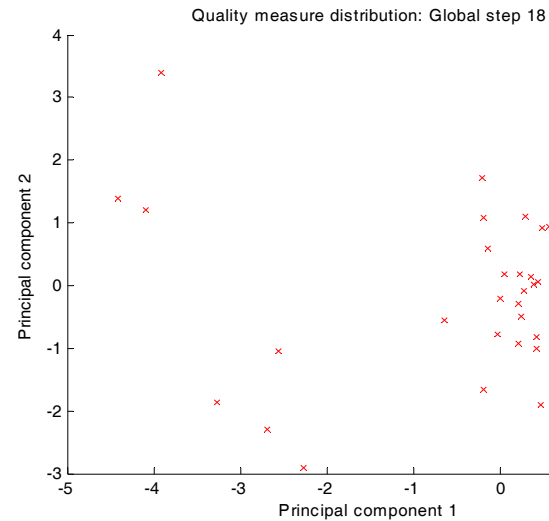
- Results promising – various issues where further analysis is needed ...



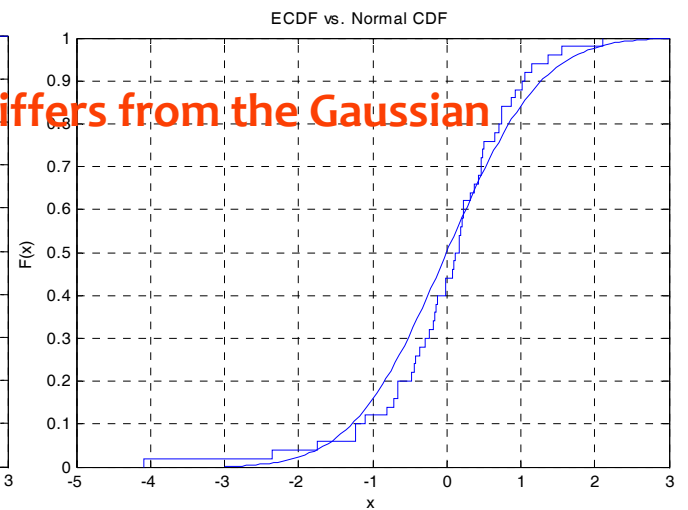
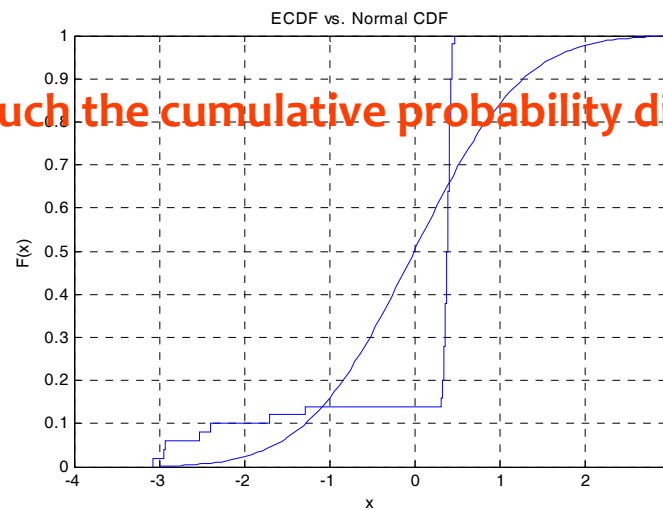
K	q_1	q_2	q_3	q_4	q_5	q_6
0	5.0	0.30	0.047	0.27	0.014	982
30	4.0	0.28	0.014	0.12	0.012	219



- Test for Gaussianity = check for validity of the linearity assumption

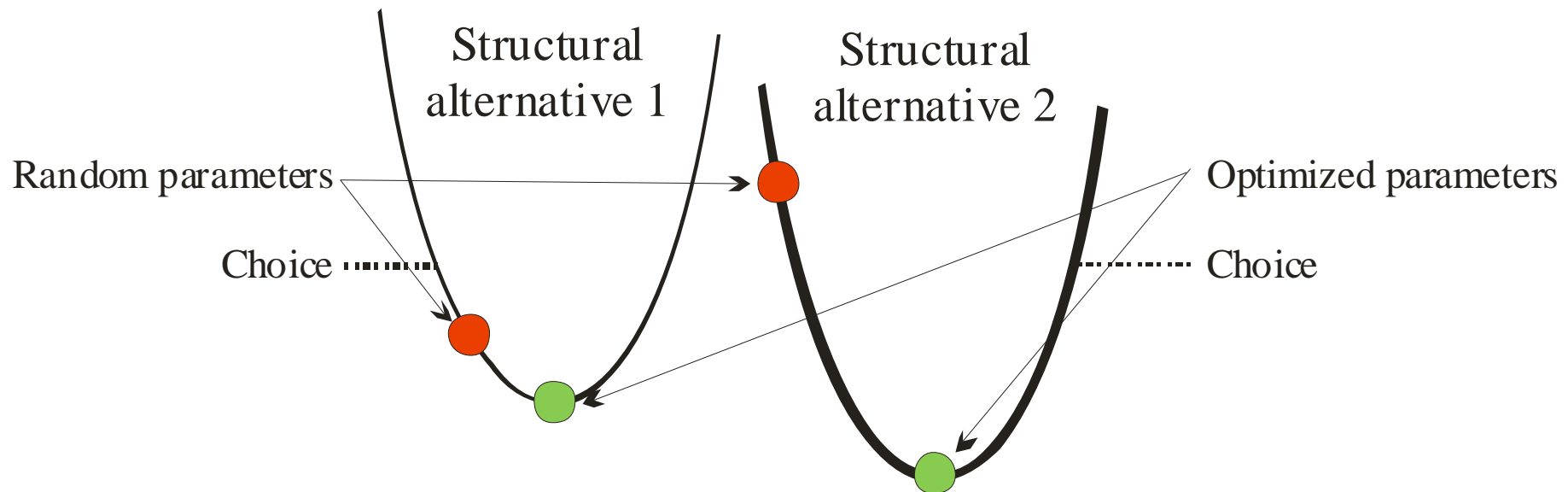


How much the cumulative probability differs from the Gaussian



Further views

- Gaining intuition on assumptions: What the assumed quality criteria truly *mean* in practice = level of iteration gets higher
- Concrete comparison of structural alternatives:

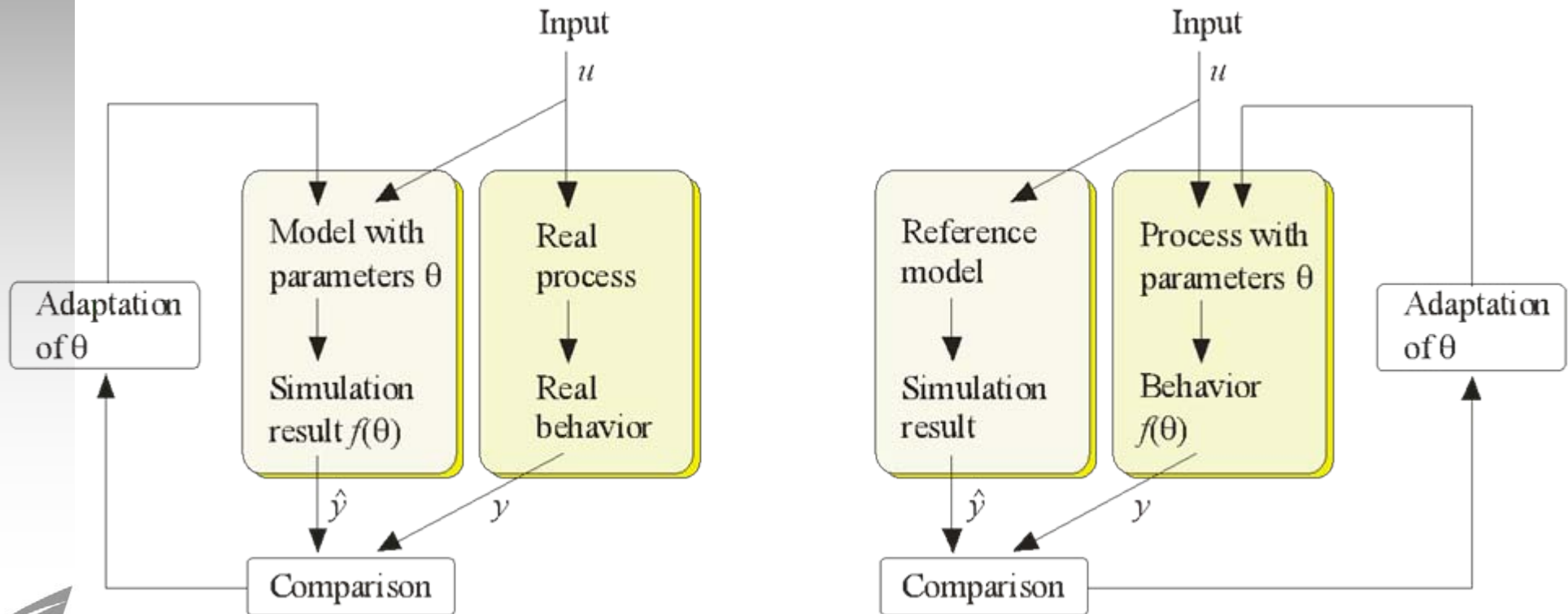


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- Typically, even the expert intuitions of the process performance are vague
 - The experts cannot express what is *good behavior* in the process
 - Selection of quality measures and weighting among them is today heuristic
 - When there is a tool to carry out any quality optimization, **iteration gets from the low level to the high level**
 - It is operators (or practicing process personnel) who now do the iteration, tuning the controllers at the factory floor level
 - Having the new optimization tools this iteration is carried out by the experts, who *tune their process intuitions*



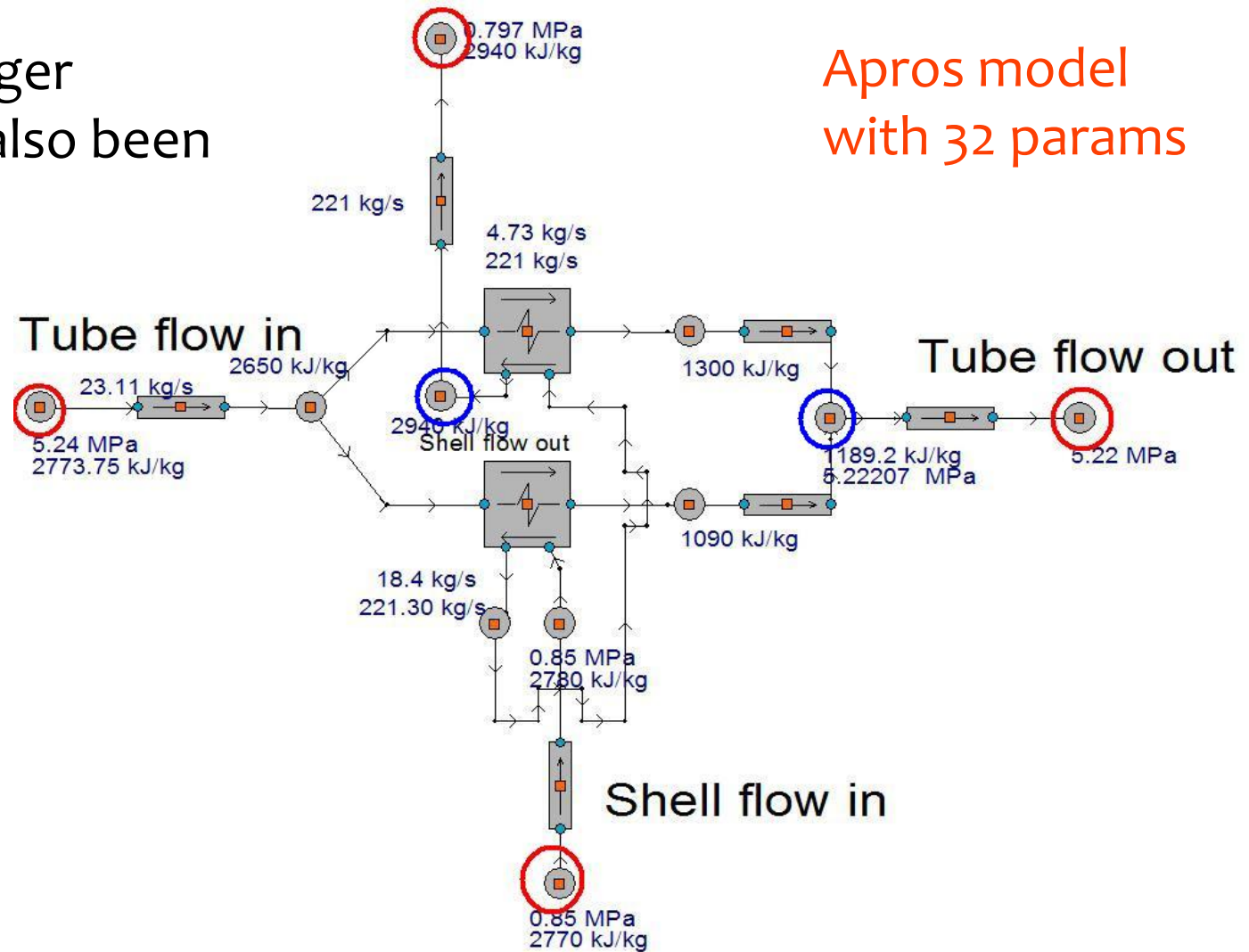
Opposite view

- The parameters to be optimized can also be in the model – applying the same procedure, model can be tuned



- Heat exchanger parameters also been optimized

Apros model with 32 params

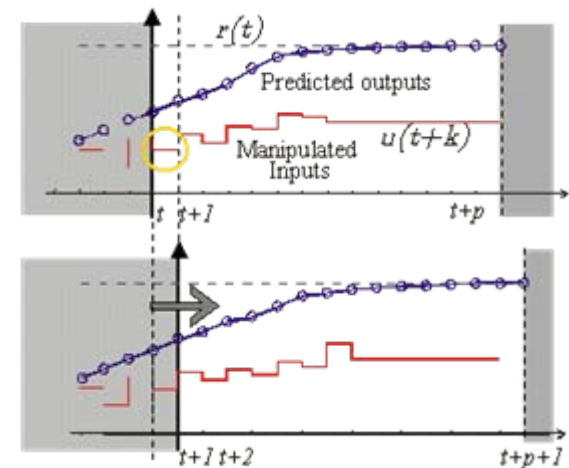
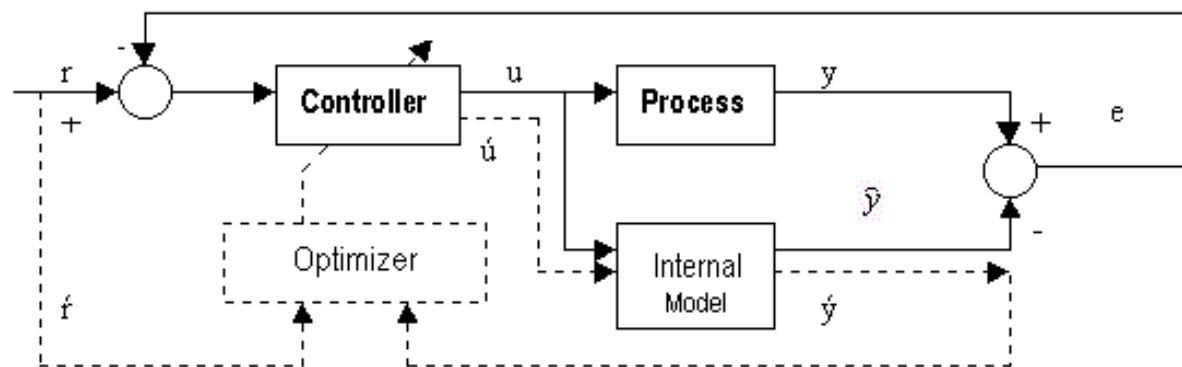


Simulation-based practices

- Simulation-assisted engineering practices would boost process design, testing, and training
- However, today's model structures and simulators are too inflexible: Level of abstraction cannot be changed
 - Too accurate models – slow simulations, but also numerical problems, stochastic peaks and transients in simulations
- Perhaps the new scalable model structures make it possible to reach “standardized” plant models
- Key point: The modeling load can be distributed to the device/model suppliers, maybe resulting in the explosion of off-the-shelf up-to-date model components as in Internet
- “Hardware-in-a-loop” can be implemented

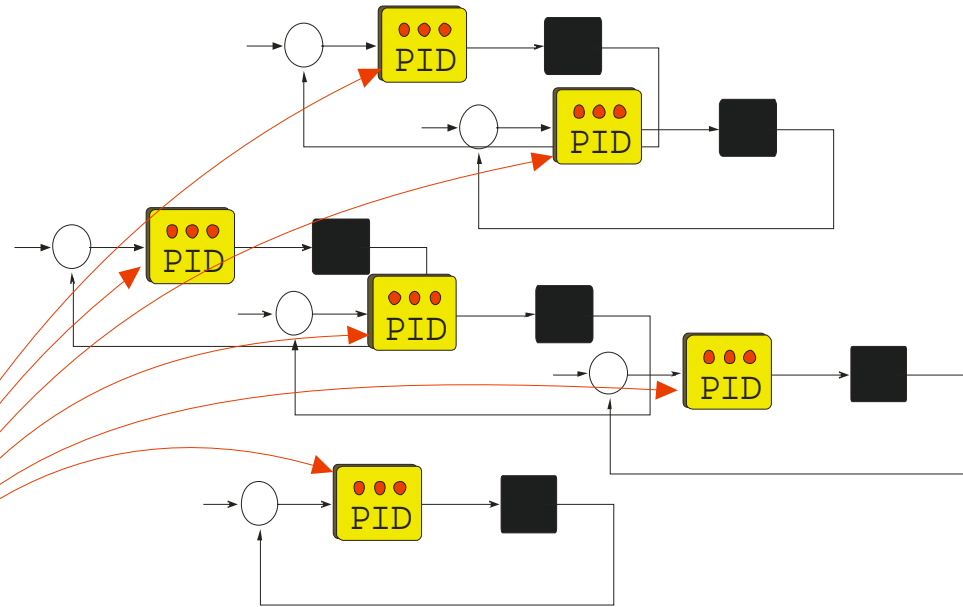


- Again, there is a close connection to traditional practices: Model Predictive Control (MPC) is among those modern methods that have become widely adopted in practice – model is needed to predict process behavior
- Good, efficient models are needed to implement these control schemes

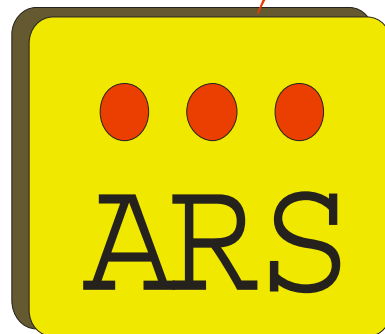


Extending the operator view

- Explicit optimization is often not possible
- The *slopes* of criteria can still be found
- The tuning knobs can be made to reflect *relevance*



Lower-level controllers tuned in a coordinated manner according to a model where control parameters affect qualities



“Higher-level PID’s”

- Power of PID: *Intuitiveness*

- Proportional action
- Integrative action
- Derivative action

- Correspondingly:

- “Accuracy action”
- “Robustness action”
- “Speed action”

To be accepted *not too much* can be changed

Now, good match with the operator’s mental view?



Evolution in technical systems – *in general*

- Basic observation: The more there is information and understanding, the more there is exploitation
- The observed correlations between signals are exploited by implementing interactions and feedback controls
- External disturbances and environmental changes are taken care of better and better, system becoming better in balance
- Finally, the system becomes more or less fully connected, “pancausal”

Evolutionary systems typically evolve towards being more and more cybernetic



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- The cases studied before still do not address the real complexity of systems with *structural adaptation*
 - One would like to understand the underlying structure and dynamics of *evolutionary cybernetic systems*
 - The same pressures govern behaviors in very different phenospheres:
 - Social, economical, and technical systems that are optimized by humans
 - Biological systems that are optimized by Darwinian evolution, etc.
 - It turns out that still higher levels of abstraction need to be employed: Earlier, the abstract flows of information rather than the physical flows in the cybernetic system were studied – now study the level of “knowhowflow” ... **What?!**

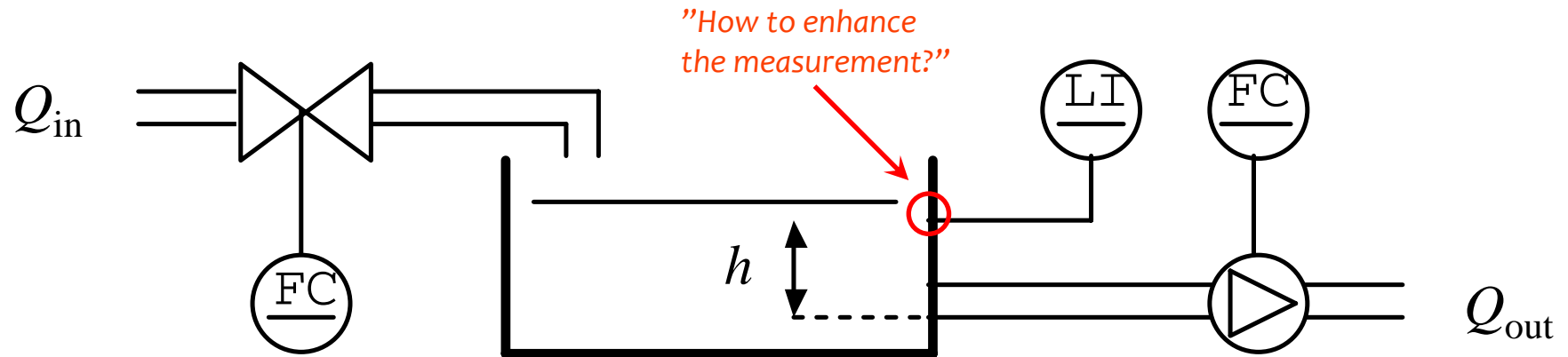


From quantitative to *qualitative* enhancements

- Assumption: Automation systems become more and more cybernetic, even though continuity cannot be assumed
- Very little can be said about evolutionary processes, or “cybernetization”, in general terms – it is about *innovations*
- Innovations are unique and cannot be captured in the statistical neocybernetic framework
- Some visions are presented below, and a case study from a real plant, visualizing the *fractality of developments*
- Basic rules – where to head towards: **Increase stiffness** – where there is variation, more resources should be invested; **relieve tensions**, if desires and reality are in imbalance



Example: Process levels



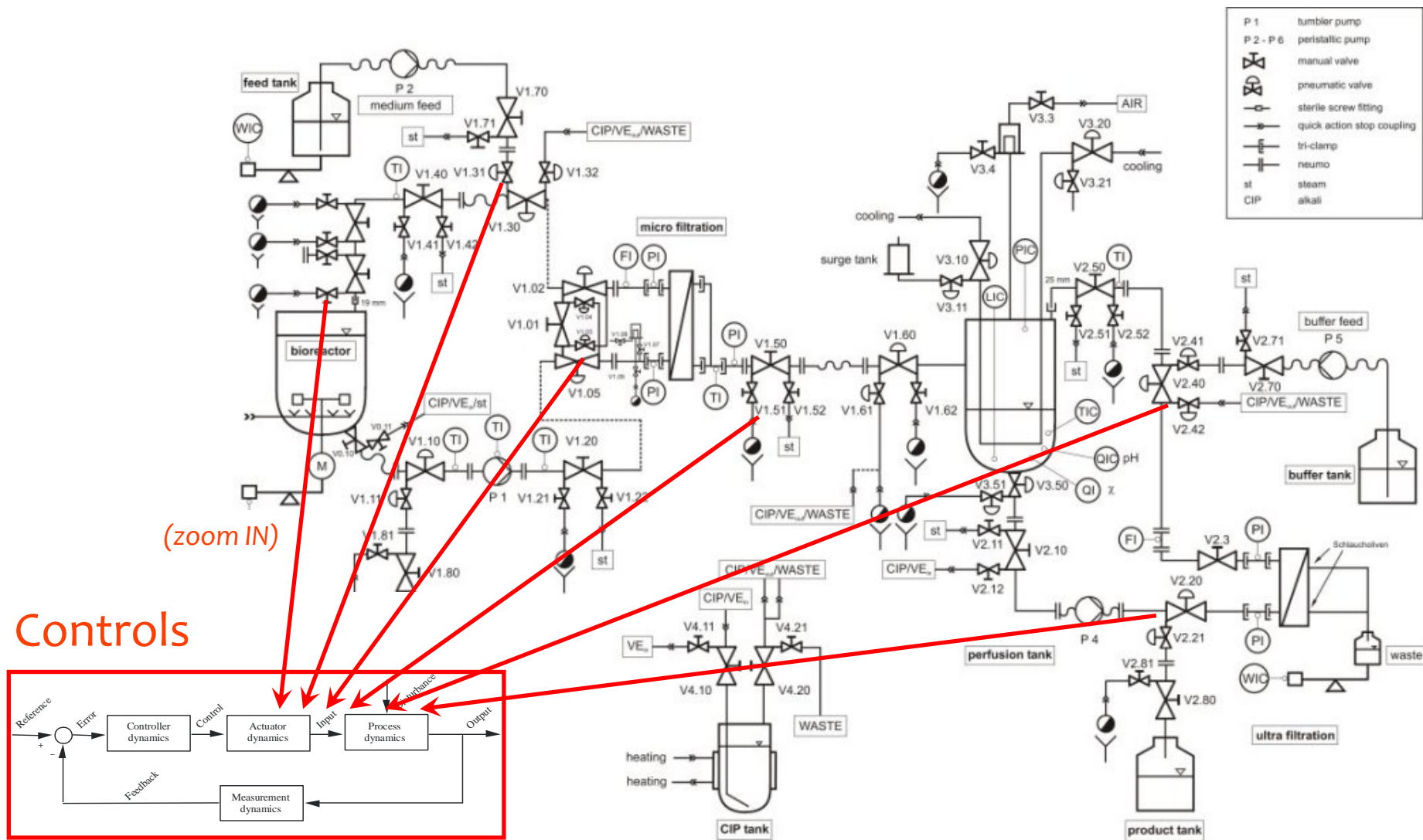
- *Physical level* (formation): Input Q_{in} , output Q_{out} ; based on the actual process structure and its energy/matter flows
- *Information level* (metaformation): Inputs Q_{in} and Q_{out} , output h ; based on what can be measured and what can be affected
- *Knowledge level* (metainformation): Inputs are now the *tensions* of the system, outputs are its resulting *properties*



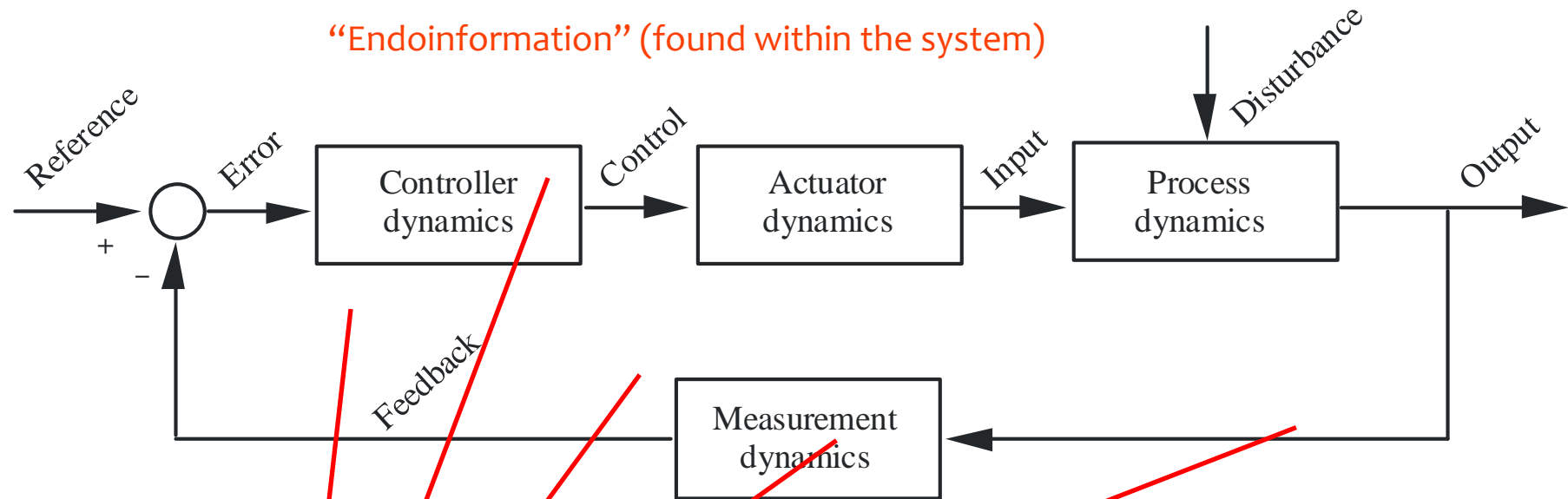
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- There are some structural similarities typically found in different levels of system flows
 - On the *information processing level*, it is the **feedback control loop** that is typically found (in some form or another)
 - On the *knowledge processing level*, the behaviors can be captured in the **cybernetic model**
 - Any part of the system can be in “informational imbalance”, constituting a tension for further “dynamics” in the system
 - The knowledge level cannot be mechanized: Exogenous information is needed that is not available in the process
 - Expertise and “common sense” is needed to select the information and to exploit it appropriately



From process flows to information flows ...

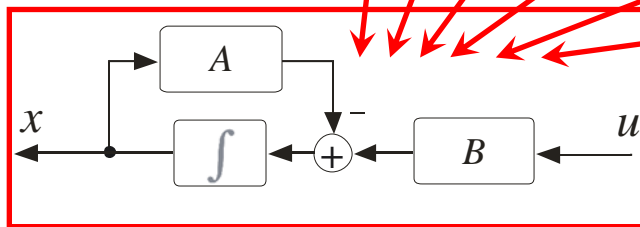


... From information flows to “knowhowflows”



(zoom OUT)

“Controls”

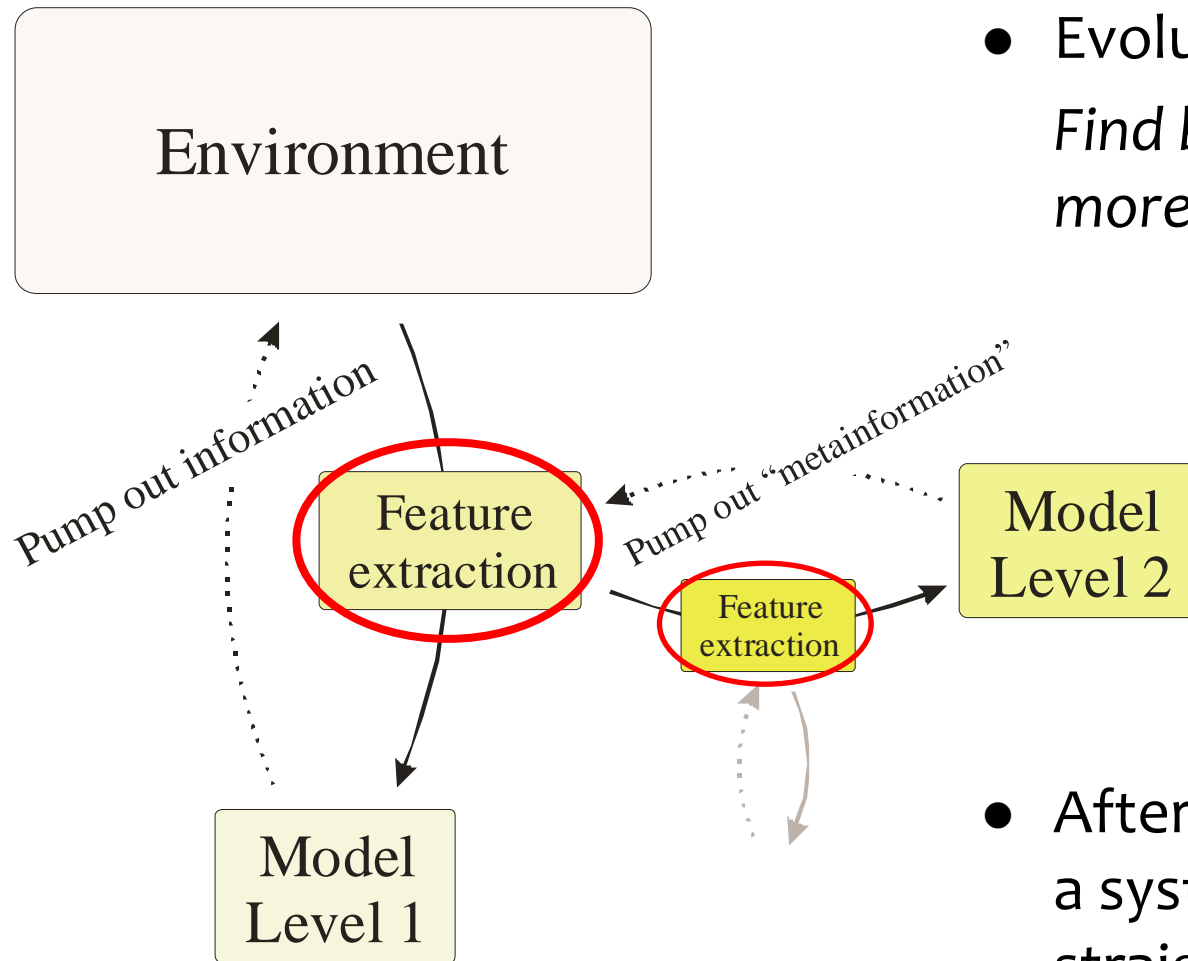


“Eksoinformation”

Large amounts of appropriately chosen external information and understanding



Yet another view: Role of semiosis



- Evolution goal focused:
Find better – streamlined – more effective features

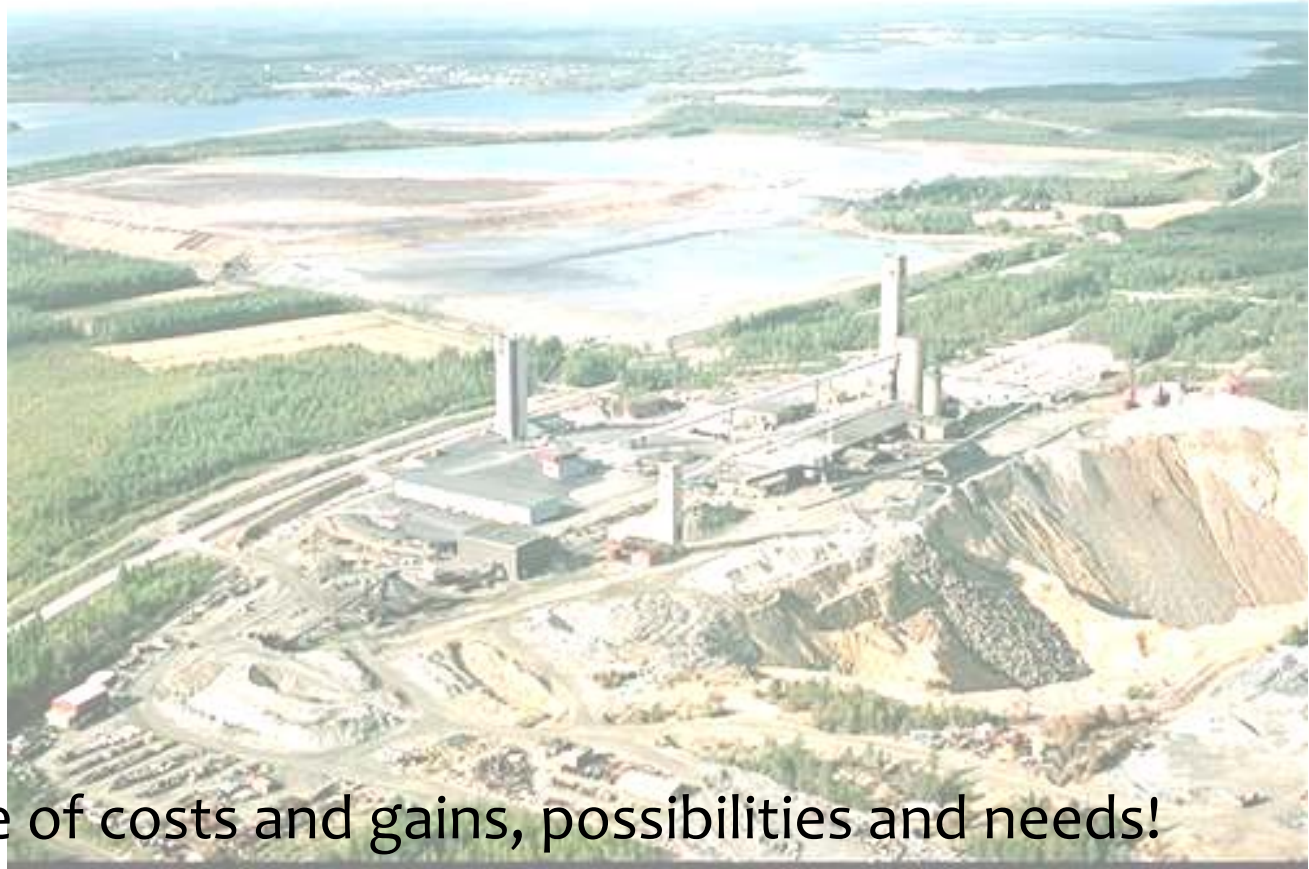
- After that, adaptation in a system is more or less straightforward



Case study: “Cybernetization” of a plant

- Pyhäsalmi Mine in central part of Finland
- Copper, zinc and sulphur concentrated by *flotation*

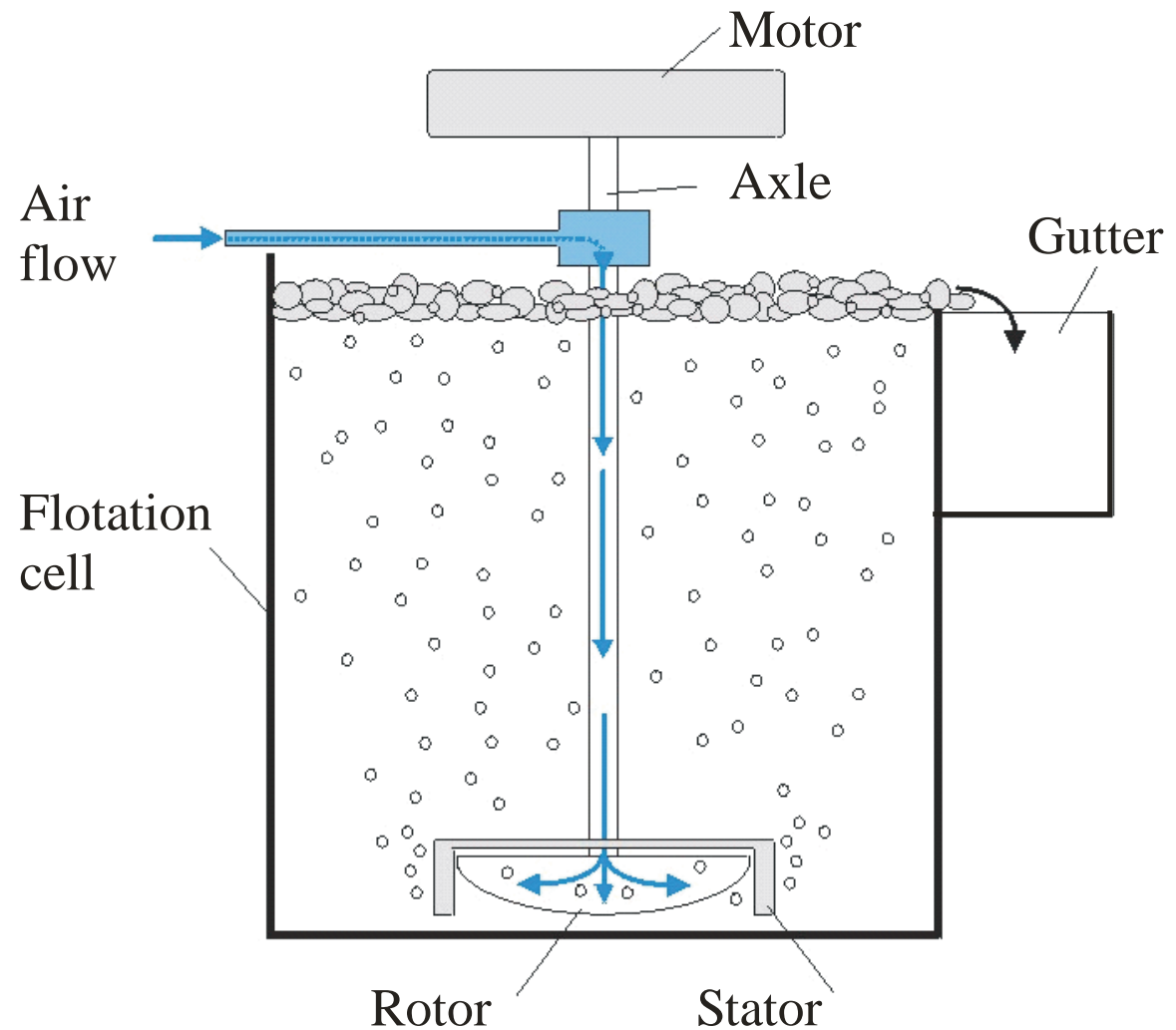
Simple?



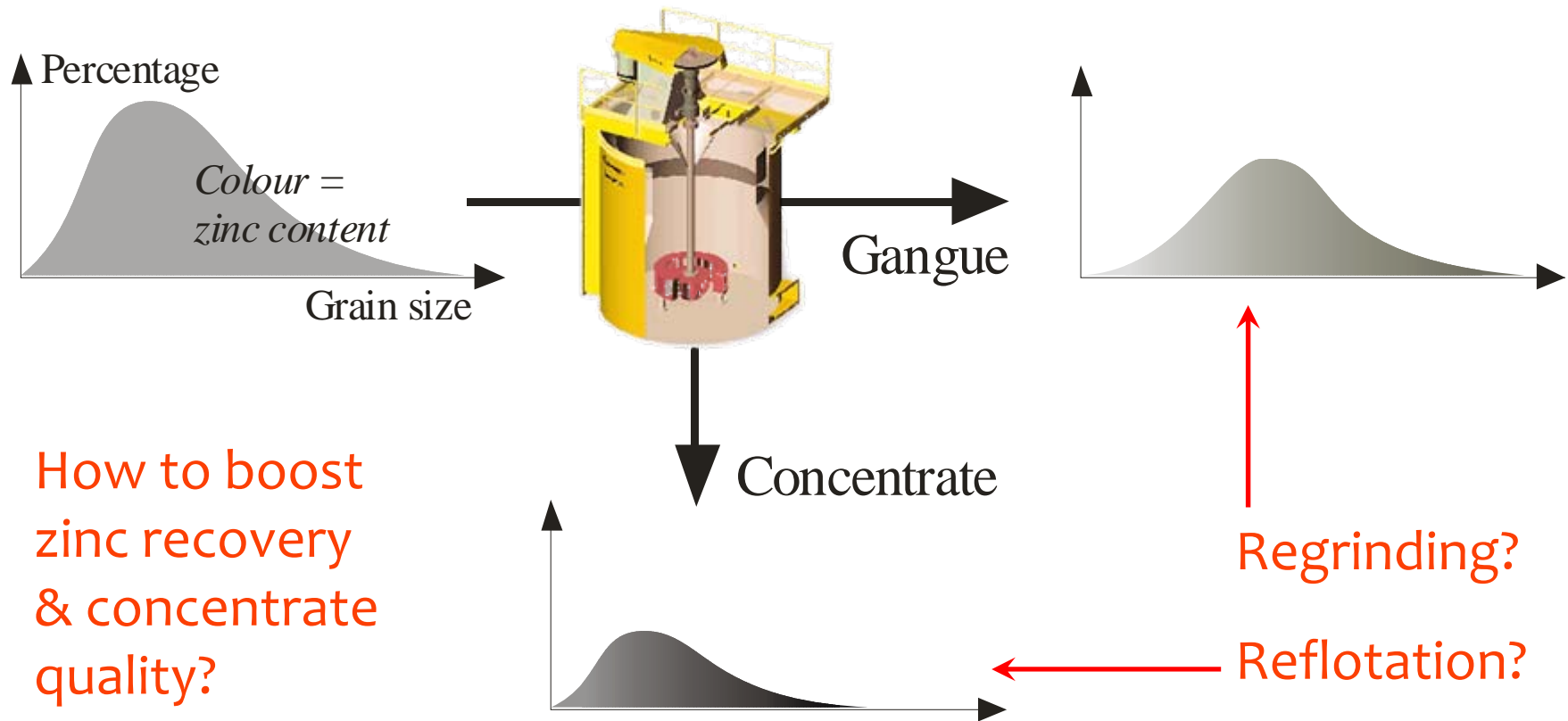
Find the balance of costs and gains, possibilities and needs!



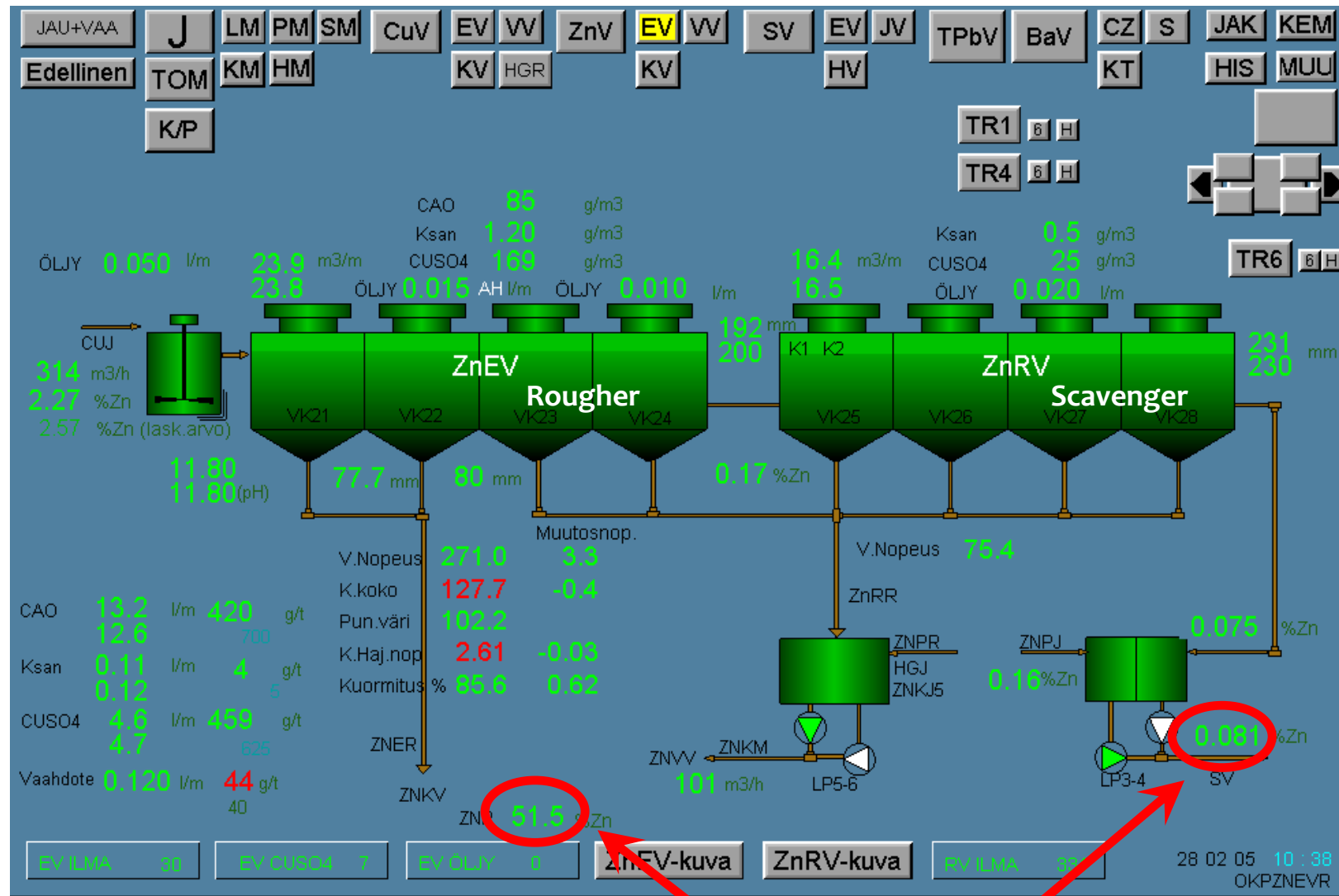
- Flotation cell:
Air bubbles bring the hydrophobic mineral grains onto the froth surface
- Simple?
- Increasing understanding makes things more and more complicated...



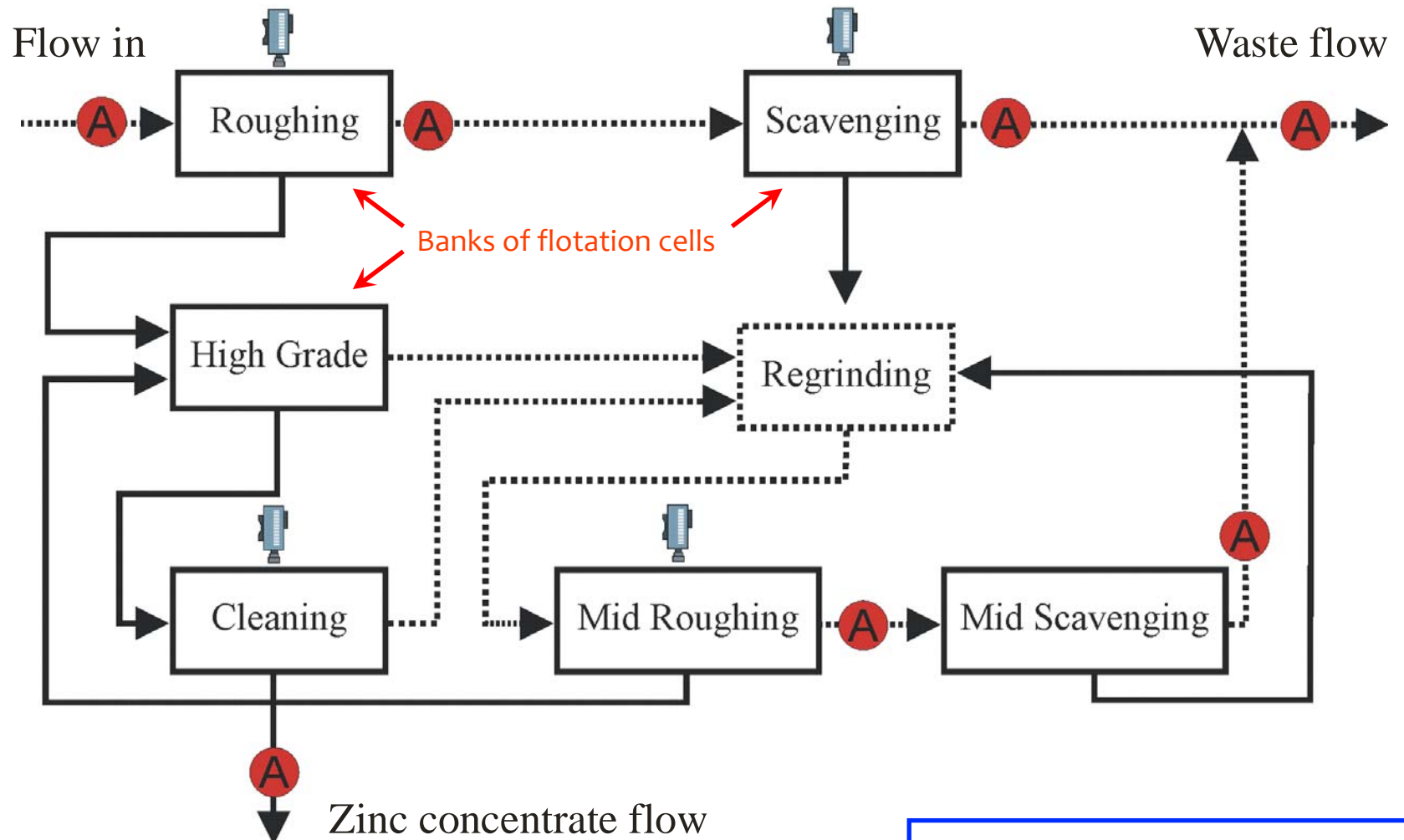
- Closer analysis: How the need for more sophistication in the flotation process emerges



Optimization between grade and recovery



Zinc circuit



Final structure is
“self-organized”!



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- Flotation circuit designs vary in structure depending on the type of mineral, degree of liberation of valuable minerals, intended grade (purity) of the product, and its value
 - The first rougher stages produce a good grade concentrate, but recovery is only medium, the second rougher stage is designed to maximize recovery
 - The scavenger cells increase the recovery when particularly valuable minerals are being treated, reprocessing the rougher waste
 - Cleaner cells maximize the grade of the final concentrate, reprocessing the concentrate; the volumes are lower than in rougher stage
 - Regrinding is needed to liberate zinc from larger grains where there is waste minerals mixed with valuable minerals
 - The designs are plant-specific, and typically evolve during the life-span of the plant



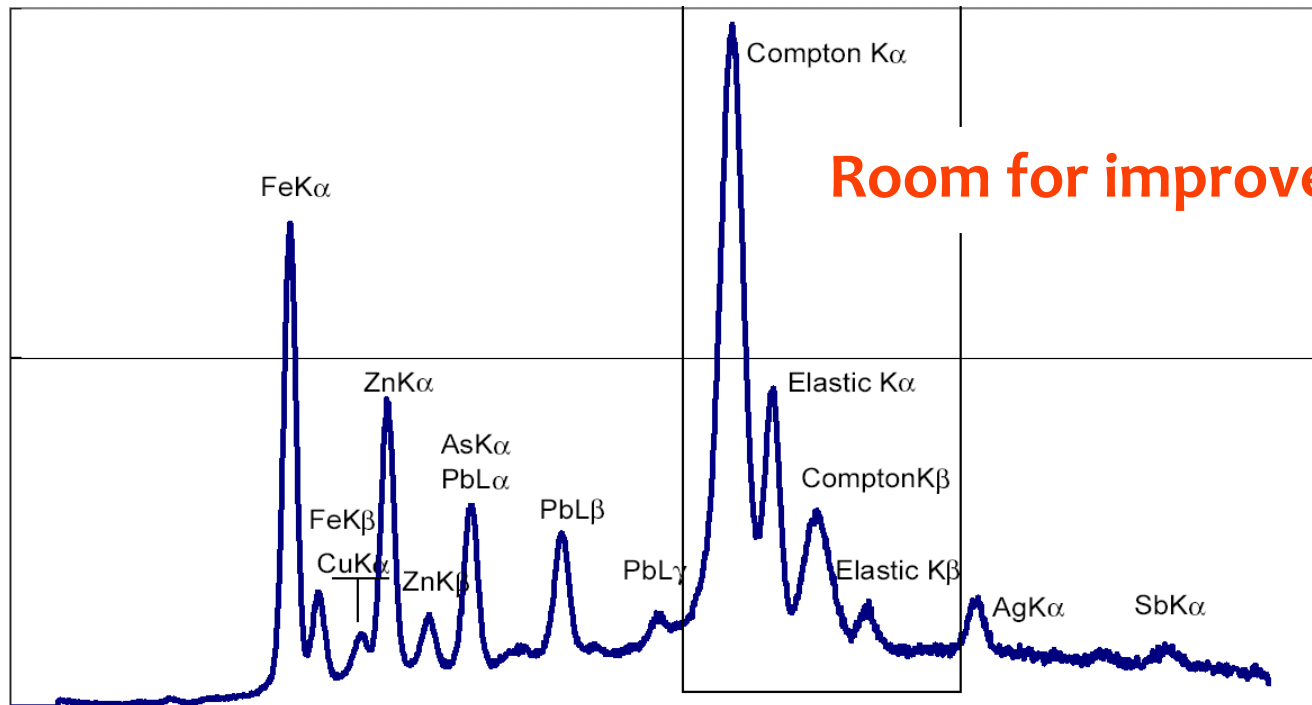
Information processing level

- Understanding the functional structure of the process also makes the physical structure become more sophisticated
- Above the physical level, information processing structures determine another level of complex networks
- It is not only understanding the structure in general – one also needs to know the volatile current state
- Goals: Understanding the signals and measuring them; later finding their relationships + utilizing these in controls
- First step: Efficient, accurate data capture, transfer, and storage – then exploitation of the information, or control
- For example, concentration measurements are carried out using an *X-ray analyzer*



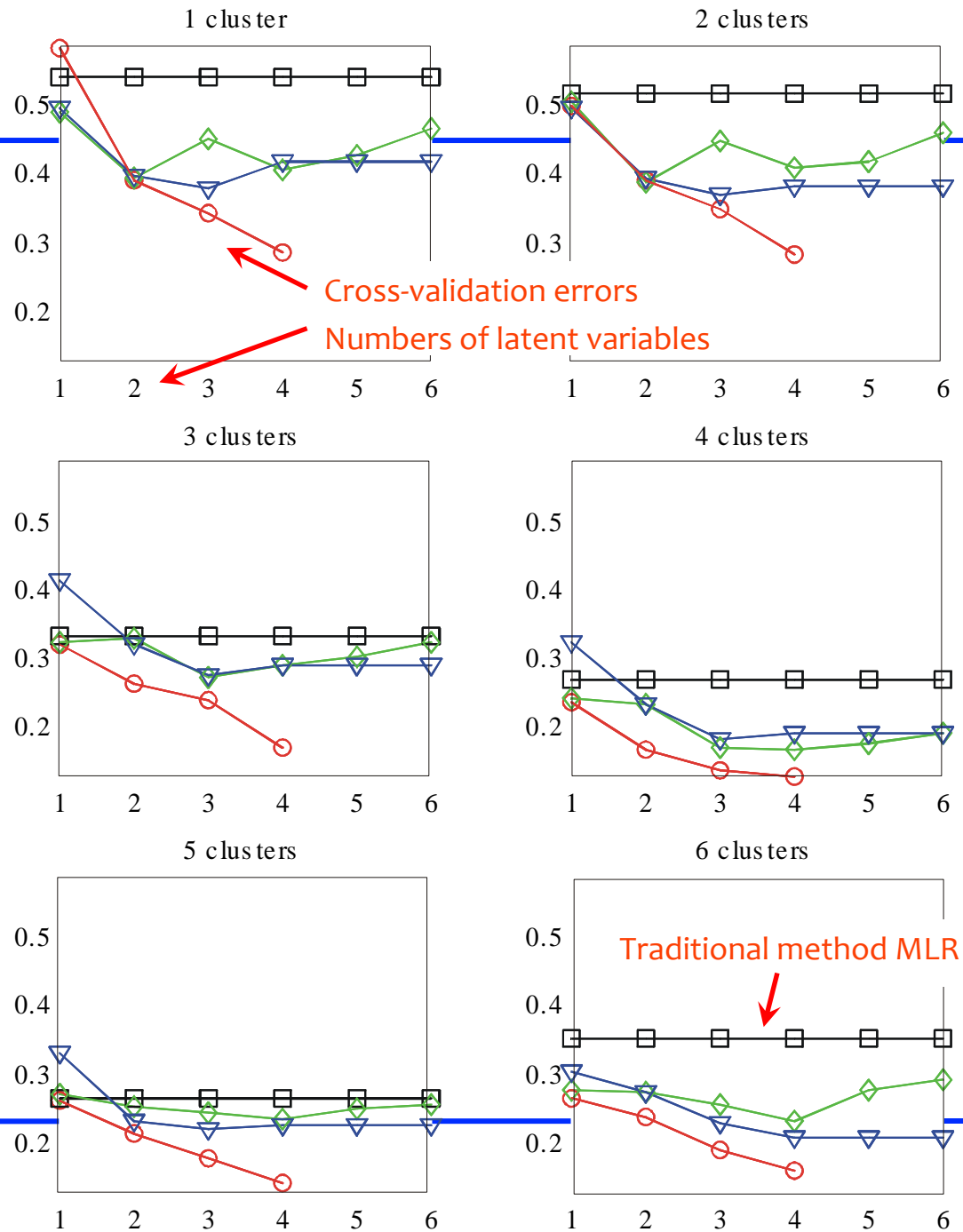
X-ray fluorescence analysis of slurry

- In principle, spectra are uniquely determined by atoms
- In practice, problems because of uneven slurry densities, imperfect sensing technology, external noise, ...



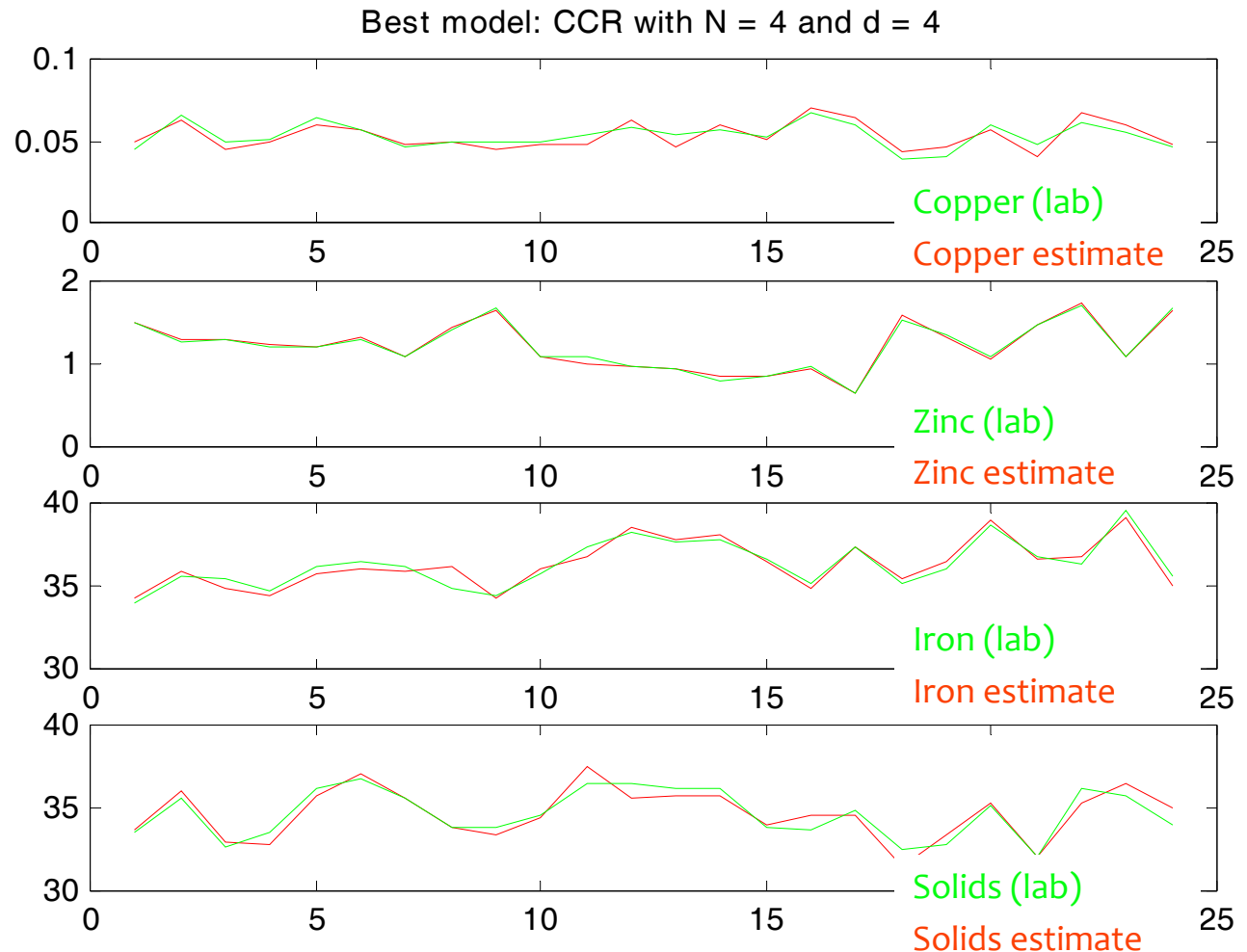
- Calibration model needed from measurements to atom concentrations
- New approaches being developed...
- Statistical multivariate models:

- MLR
- PCR
- PLS
- CCR



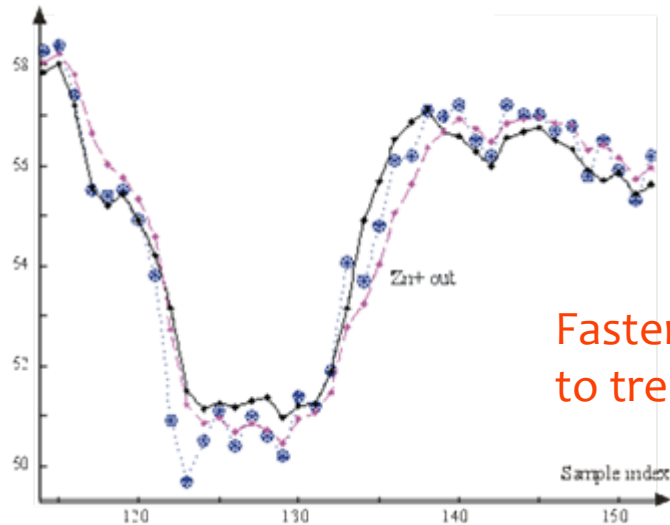
More accurate measurements reached

- Estimates OK, but...
- Measuring using X-ray analysis is slow – there is a 20 min interval
- Additionally, the data has to be filtered

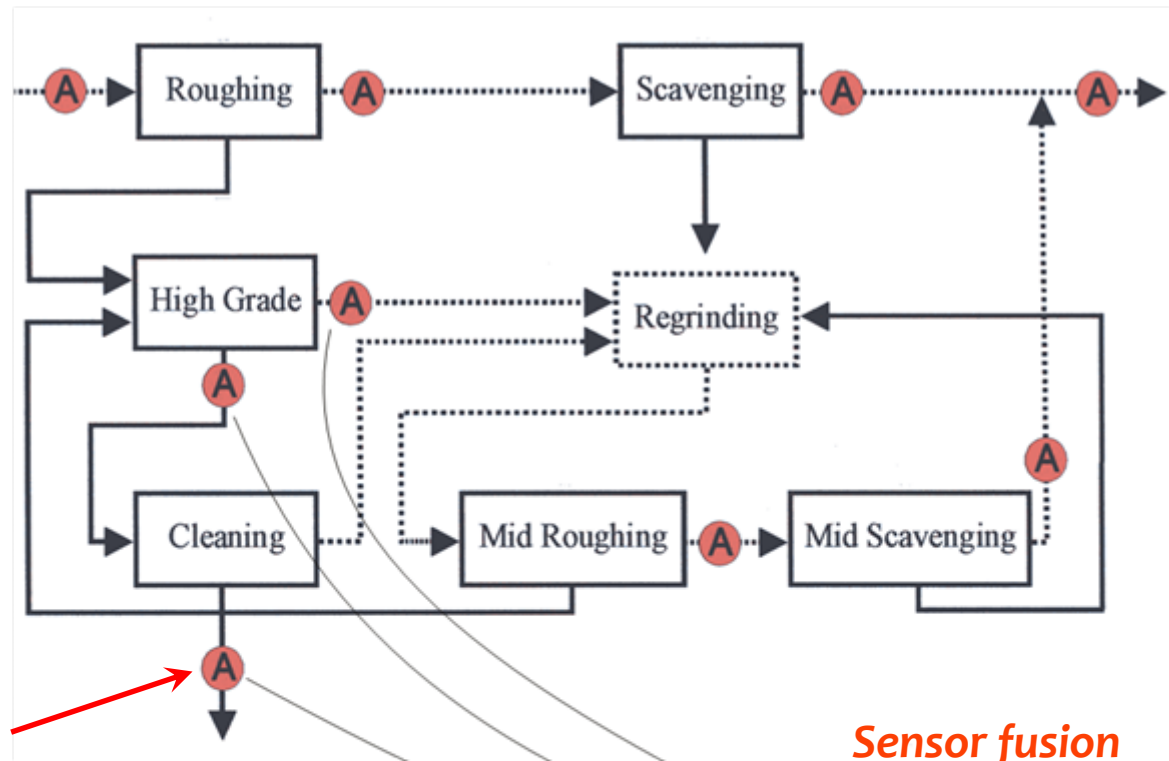


Towards “smart devices”

- Correlations between signals can be exploited to reach better estimates



Faster reactions
to trends



Sensor fusion



“Data mining” for mining data

- New understanding: Correlation between incoming (scaled) zinc concentration and froth “redness” in the rougher

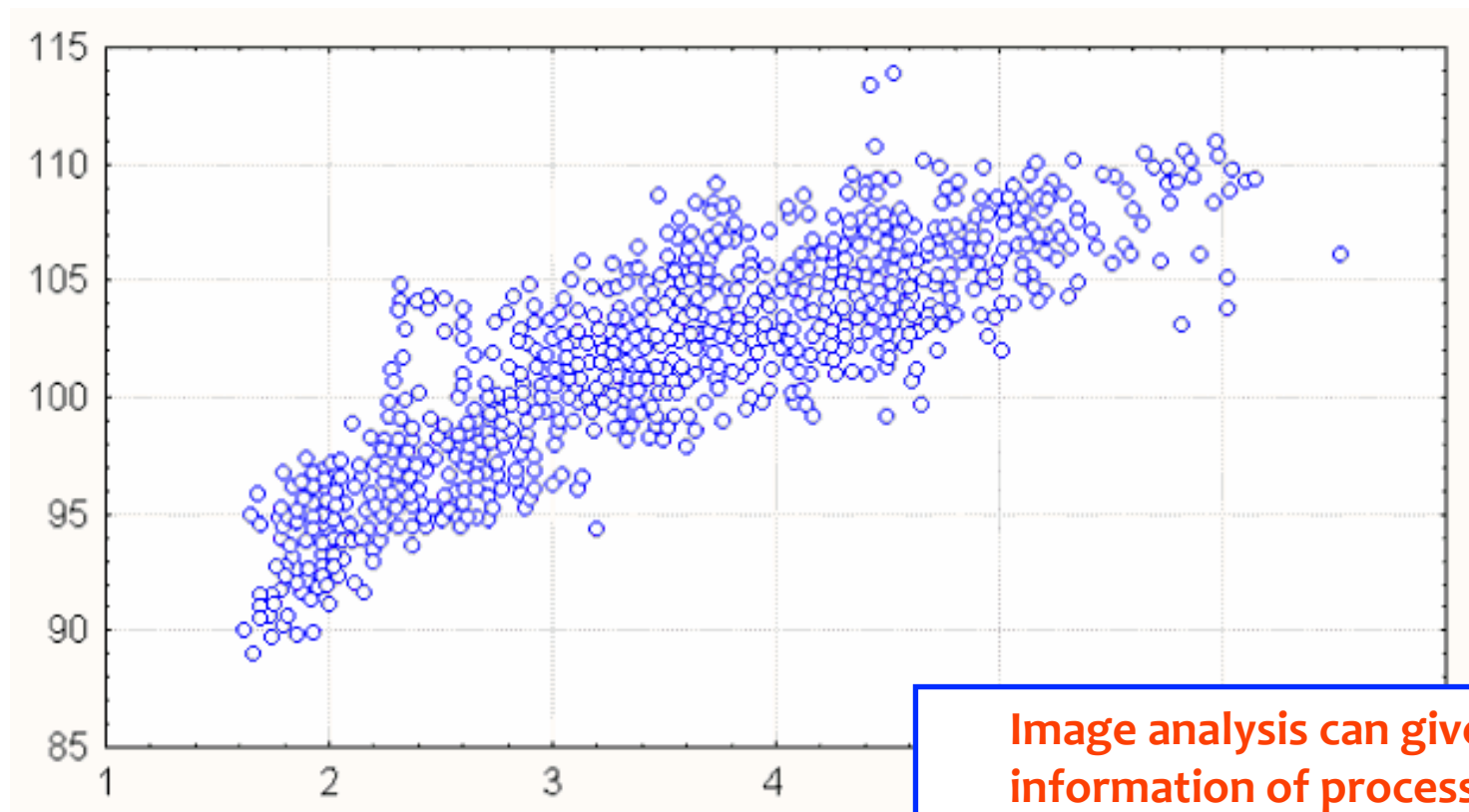
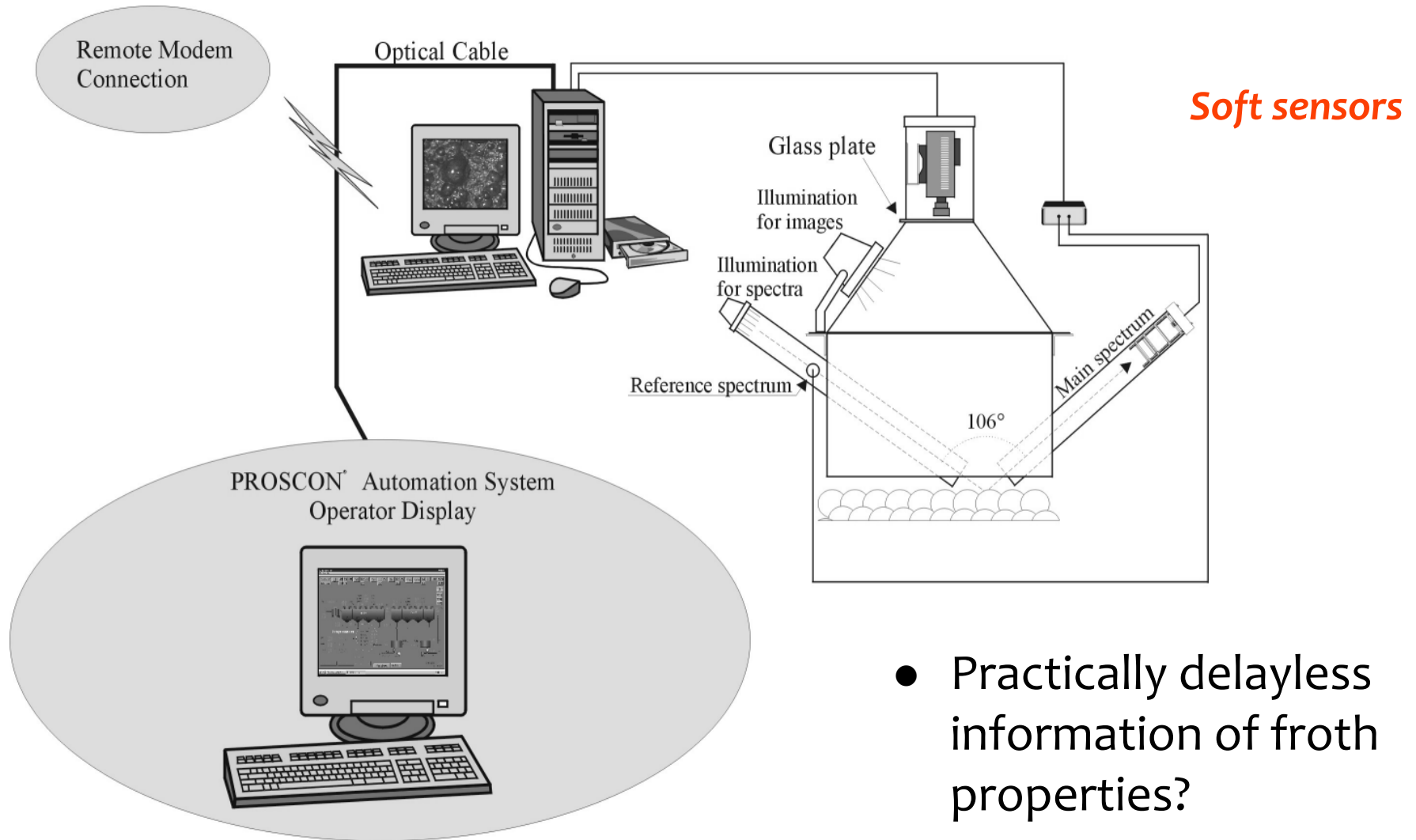


Image analysis can give information of process state also between X-ray analyses – utilize this!?



Projects “ChaCo”, “Väsy”, “Äksy”, “Rike” ...



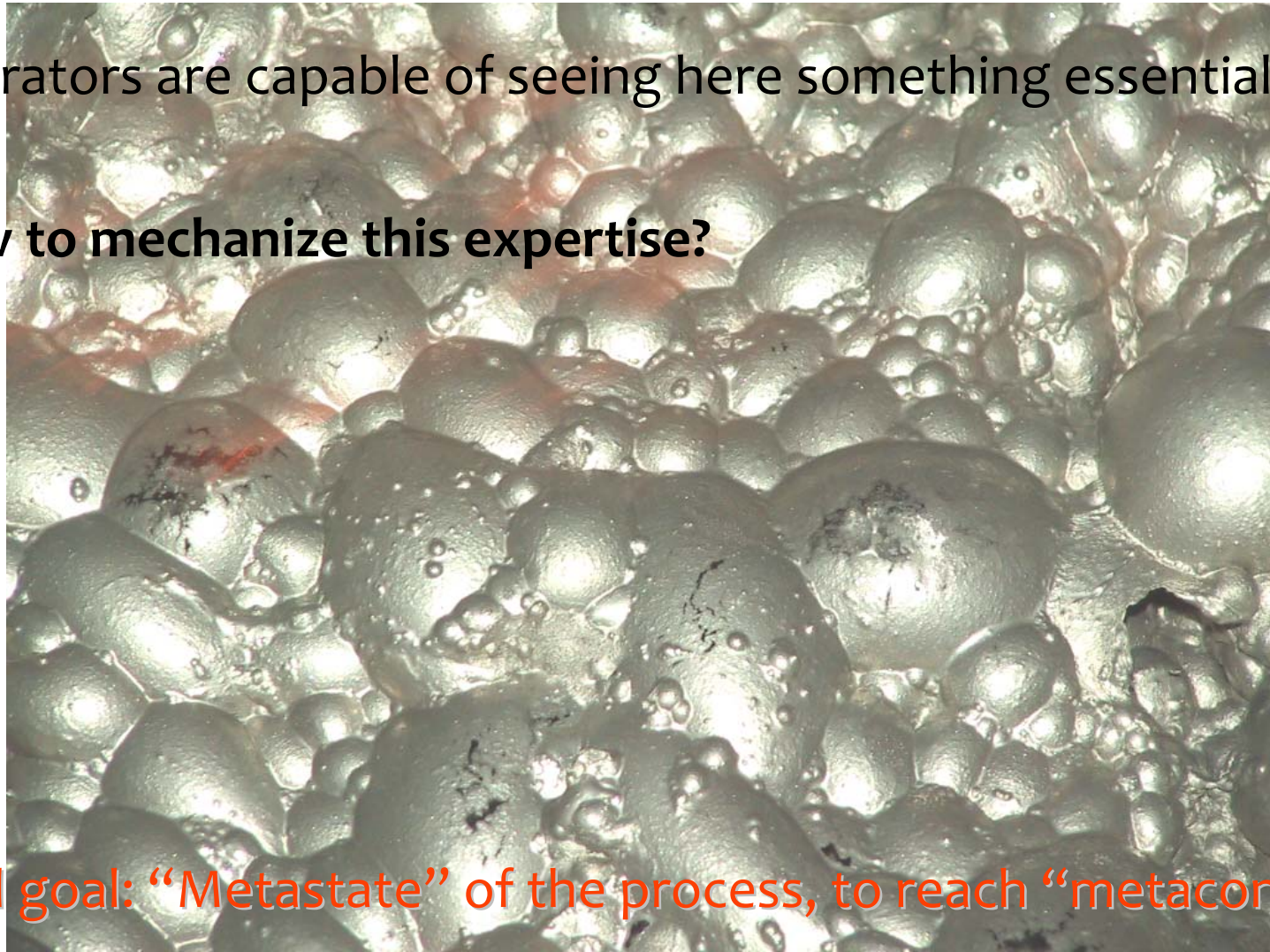
- Practically delayless information of froth properties?



Need of pattern recognition

- Operators are capable of seeing here something essential...

How to mechanize this expertise?



Overall goal: “Metastate” of the process, to reach “metacontrols”



Implementing controls

- First only necessary controls, simple SISO style – the acute goal is to keep the process up and running
- Later optimizations to enhance, stability, product quality, etc. = to maximize profit
- Very much is dependent of the technical and economical constraints: Lesser optimizations are too expensive
...until technology perhaps offers new possibilities, changing the balances among what is realistic and what is not
- Specially, *information technology* has boosted **availability**
 - Field buses are used for information transfer *from* and *to* the process
 - Computers make it easier to implement new control schemes
 - Automation systems are used for mastering the overall complexity



Towards stability or instability?

- Automation system becomes less and less stable!
- Reasons for this:
 - Explicit optimization, making the system faster or more “sensitive”
 - Control strategies oscillate, trying to keep track of time-varying processes
- For example, the CuSO_4 dosage at the Pyhäsalmi plant actively maps the dynamic range, ending in a limit cycle:

Ranking	Condition	Action
1.	IF <i>froth thickness</i> < <i>lower limit</i>	Froth collapse situation —
2.	IF <i>BCR</i> < <i>lower limit</i> OR <i>bubble transparency</i> < <i>lower limit</i>	Too “stiff” froth —
3.	IF <i>zinc content in rougher tailing</i> > <i>upper limit</i>	Try to optimize +
4.	IF <i>zinc content in scavenger tailing</i> > <i>upper limit</i>	... +
5.	IF <i>froth thickness</i> > <i>upper limit</i>	Try to condense froth +
6.	IF <i>BCR</i> OR <i>bubble transparency</i> OR <i>bubble size</i> > <i>upper limit</i>	Too “wet” froth +
7.	ELSE	Finally, try to save reagents —



-
- Marginally stable cyclic behavior effectively maps the dynamic range of the process
 - This gives the possibility of gaining information of the process –
“Apply small fluctuations – avoid big catastrophes”!
 - Different parts of a process have characteristic “frequencies” that are determined by the underlying dynamics
 - Complex processes at “evolutionary balance” are characterized by *spectra* of frequencies
 - CLAIM: *Complex systems being coupled need to have compatible spectra (see Lec. 11)!*



Operators still needed in the loop

The screenshot displays a complex industrial control interface with multiple data panels and control buttons. At the top, there are numerous buttons for different units or processes, such as JAU+VAA, J, LM, PM, SM, CuV, EV, WV, ZnV, EV, WV, SV, EV, JV, TPbV, BaV, CZ, S, JAK, KEM, Edellinen, TOM, KM, HM, KV, HGR, KV, HV, TPbV, BaV, CZ, S, HIS, and MUU. Below these are buttons for K/P and various TR (TR1-TR6) units. A speaker icon is visible on the right side.

The main data area is divided into several sections:

- Process Parameters:**

Lämpötila	-14.2	CuR	5.3	LM2	433	42.8	Syöttö yht	173	%
Kalkkim.%	13.9	ZnR	7.1	PM1	336		Murske	133	76
Tuorevesi	100	SRI	39	PM2	342		Palat	27	15
Pal.vesi	132	SRII	50	PM3	351		Lohk.	15	9
Boksivesi	190	H2S	0	KM2	404				
- Raekokojak. (HKU2):**

Murske -30 mm	6	AC1
Palat 30-100 mm	H	AC2
Lohk. +100 mm		AC3
- VRK:n alusta:**

	CuV	Cu%	Zn%	S%	Pb%	ZnV	Zn%	Fe%	Cu%	SV	S%	Zn%	Cu%
Syöttö t	892	M	1.03	2.54	39.6	0.03	ZnEJ	0.26		SJ	7.3	0.06	
" t/h	155	CuPJ	0.70	6.11			ZnRJ	0.075					
Cu/M %	1.02	CuRJ	0.044	2.12			ZnVJ	0.71					
Zn/M %	2.57	CuJ	0.056	2.36	39.0		ZnPJ	0.20					
S/M %	39.5	CuKJ	9.2	6.57			ZnR	50.6	11.5				
Cu/CuR %	29.0	CuR2	31.0	1.67	0.51		ZnJ	0.757					
Zn/ZnR %	54.6	CuR	29.3	1.80	0.53		Tavoite	0.108					
S/SKR %	52.6						RZnV	96.0	%				
Cu-saanti	94.9	RCu	94.8	%	94.5		RZn	93.8	%	91.3			
Zn-saanti	93.4	Zn-saanti/CuR	2.35	%	2.78		ZnInd	0.9					
S-saanti	76.1	Culnd	0.3										
- Tal.tunnusluvut vrk:n alusta t€/d:**

CuRt€	84	ZnRt€	57	SRt€	33	Yht.t€	173
Culnd	0.3	ZnInd	1.3	RikInd	1.6	K.kate	88

A video window titled "Historiakuva 11 (Ero: 9min 11s)" is overlaid on the bottom right, showing a close-up of a metallic surface with a circular callout containing the text "Do something!".



Some controls in the zinc circuit

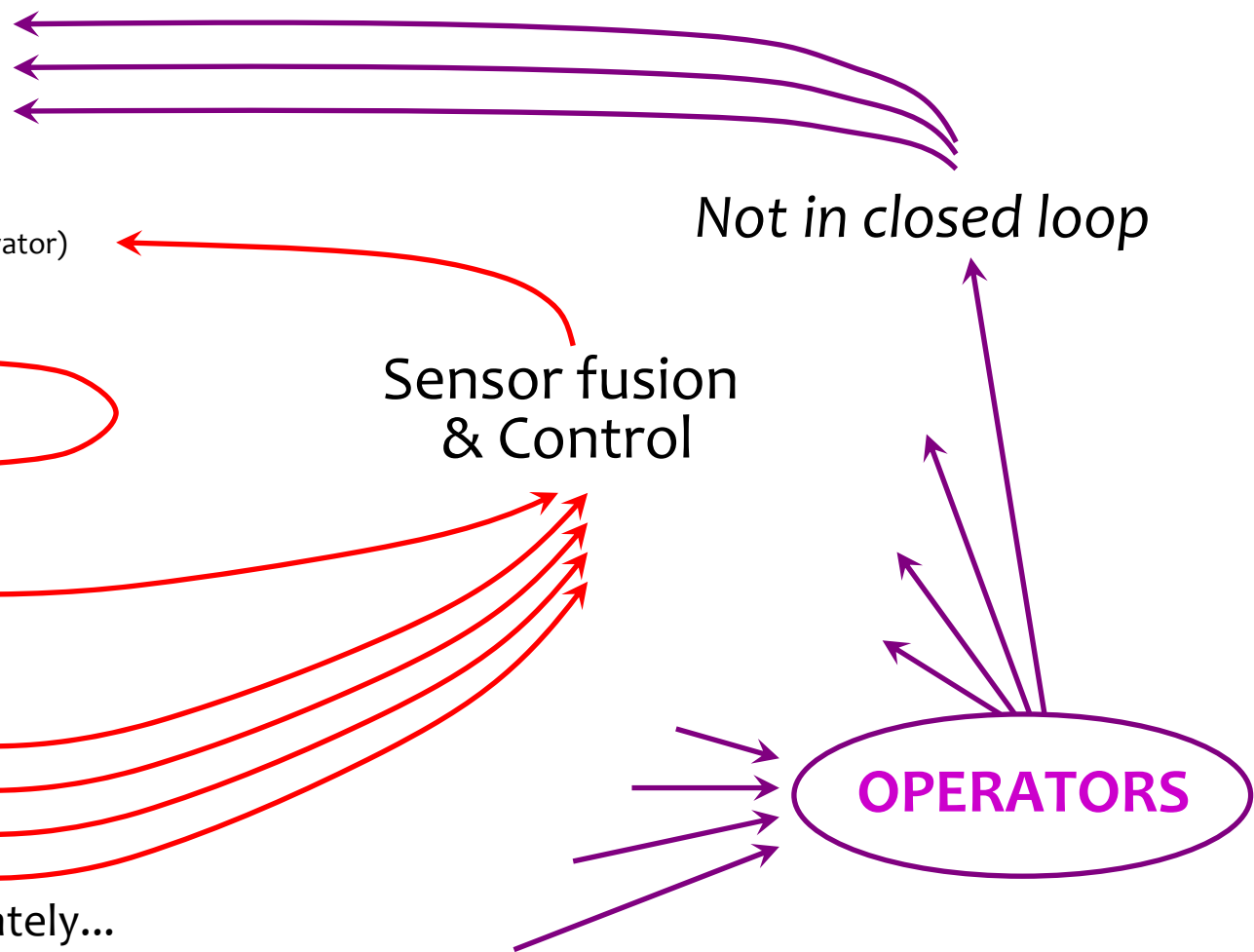
- Some inputs

- Ore deposit selection
- Grain sizes
- Air flows
- Acidity (pH)
- Chemicals
 - Copper sulphate (activator)
 - Xanthate (collector)
 - Oil (frother)
- Slurry flow

- Some outputs

- Cell slurry level
- Froth thickness
- X-ray analyses (slow)
 - Zinc contents
 - etc.
- Camera analysis
 - froth speed
 - bubble size
 - bubble load
 - "redness"
 - transparency

- Alarms analyzed separately...



-
- Goal 1: Maximize zinc content in the concentrate, minimize it in the waste
 - Goal 2: Robust, reliable production – with no breaks
 - Goal n : Relieve humans (operators) from the system
 - Cybernetic balance among the needs and possibilities / savings and costs has not yet been reached at the plant
 - There exist too many unknown variables and unknown dependencies among them
 - And even if there existed knowledge, understanding is not deployed: There is no time/instrumentation to implement; finally, it would be **too expensive** – there are balances.

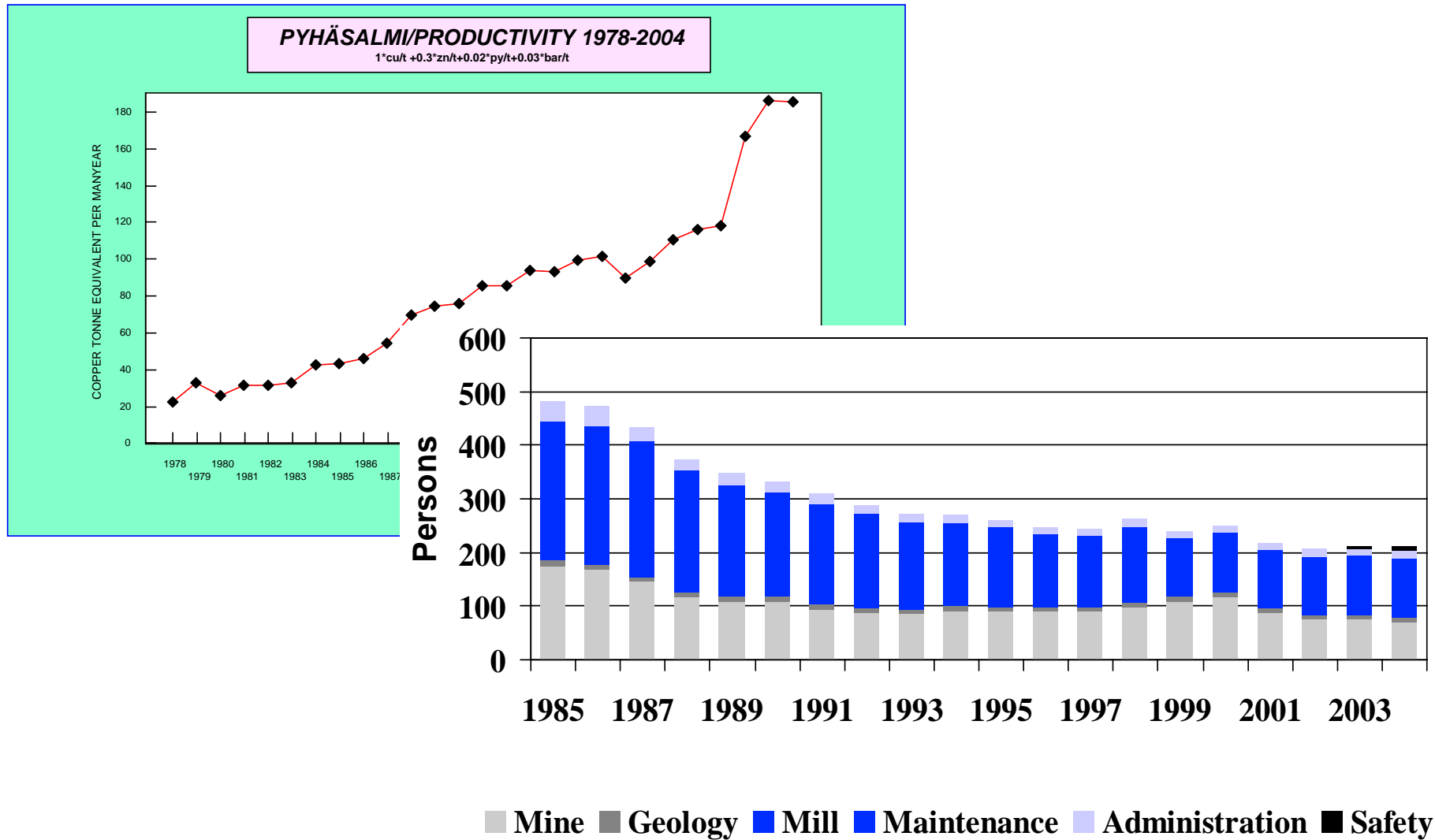


Humans (operators) in the control loop

- Changes/disturbances in the process – operators taking action (adjusting controllers, etc.) constitutes a *higher-level controller* above other controls, keeping system in balance
- Why “human controllers” are good:
 - Humans are flexible and multi-purpose actors
 - Humans are self-learning and have “common sense”, deeper understanding
 - Humans are cheap to employ
- Why “human controllers” are *bad*:
 - Humans are inconsistent and unreliable, expertise cannot be transferred
 - Humans are slow (and the delays vary)
 - Humans are expensive in the long run, and need extra facilities
- Loops with humans are necessarily complex – If possible, humans are substituted with mechanized controllers?



“Evolution” at the plant



Conclusion

- The current plants are globally non-optimal – but locally satisfactorily-behaving – and getting ever better controlled
- Technical evolution is always gradual, as there is inertia: operator beliefs and practices also need to adapt
- The directions of development are very much dependent on the agents – research engineers, operators, directors
 - The larger the package of available conceptual/practical toolboxes, the more there exist variables to select from; there are more degrees of freedom = different analysis/design methods, devices and algorithms available
- Also the society of humans (a cybernetic system) needs to be understood to reach smooth production at the plant
- To understand humans in the loops, **the mechanisms of human cognition need to be understood and exploited...**

