AS-74.4192 Elementary Cybernetics

Lecture 9:

About "Artificial Evolution"

HELSINKI UNIVERSITY OF TECHNOLOGY
Department of Automation and Systems Technology
Cybernetics Group

- 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*

A complex system cannot be instantiated once and for all – one has to let it *evolve*

“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 “allocybernetic”, 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

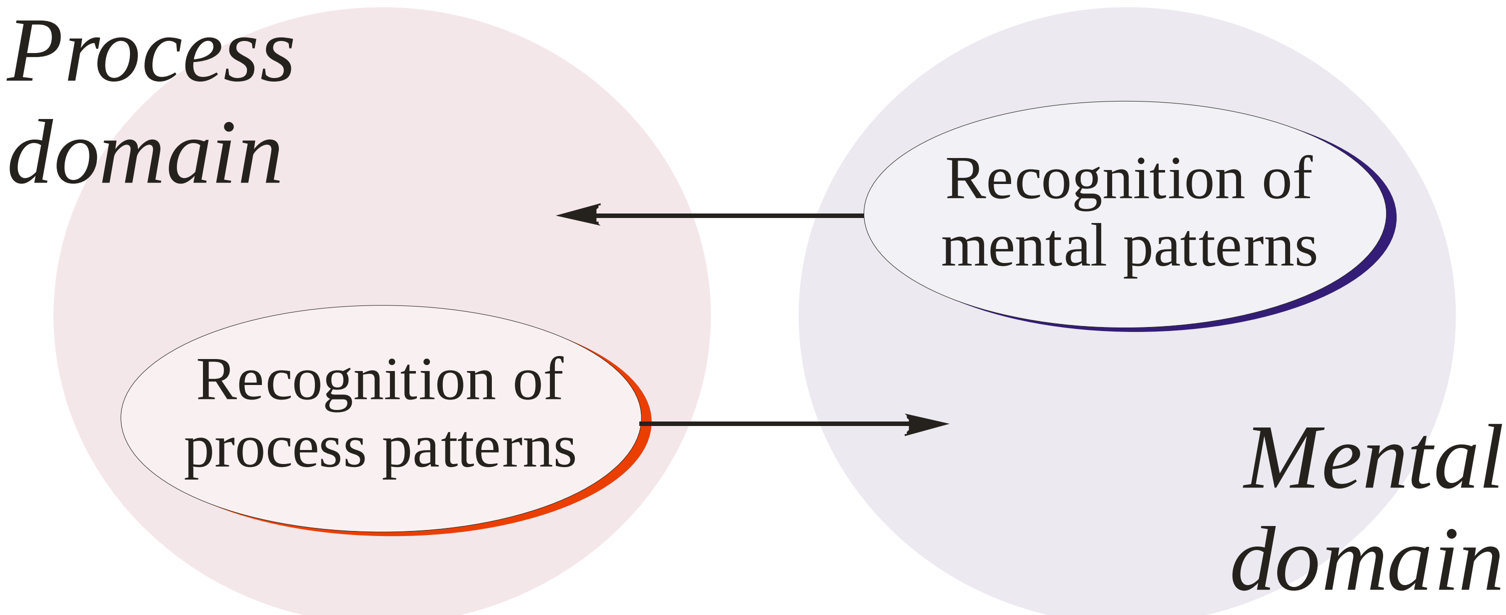
  Is this assumption always necessary?

- 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

Find pressures that push the system in a desired direction!

“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*.

Better balance, less variation – linearity assumption becomes OK?

Restructuring data

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

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

"Process domain"
(inputs)
Not only parameters but reference values, ...

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

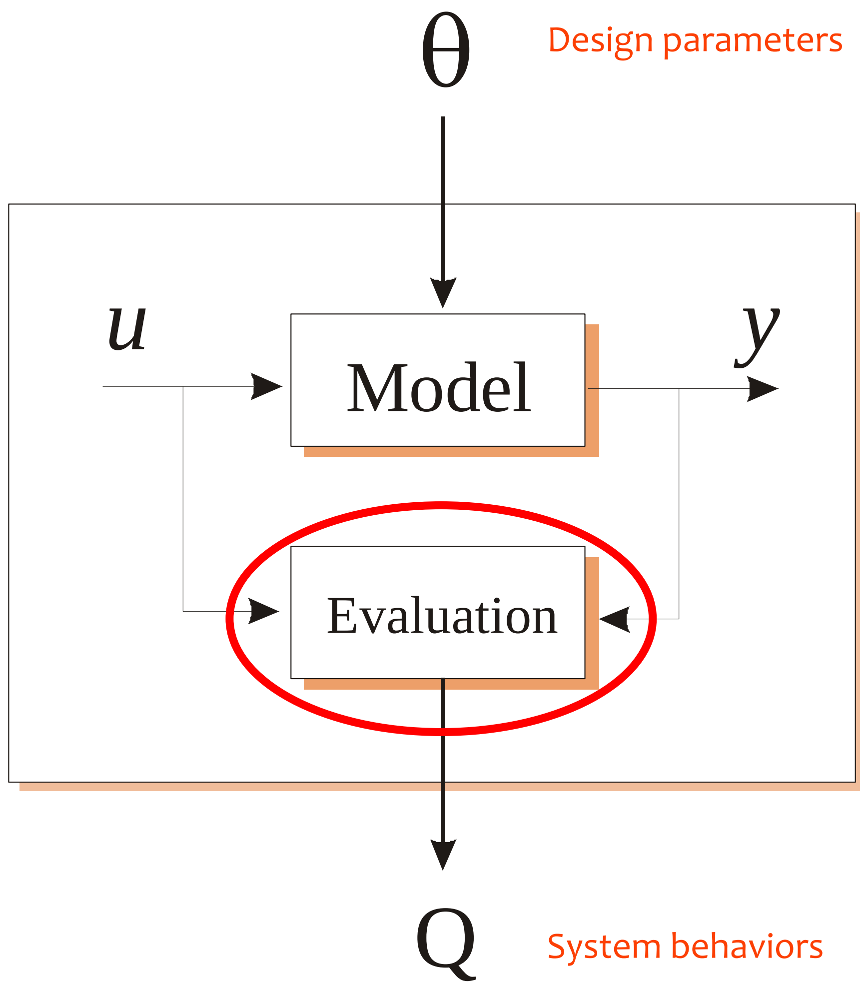
"Mental domain"
(outputs)
Quality characteristics of practical interest

- 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

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

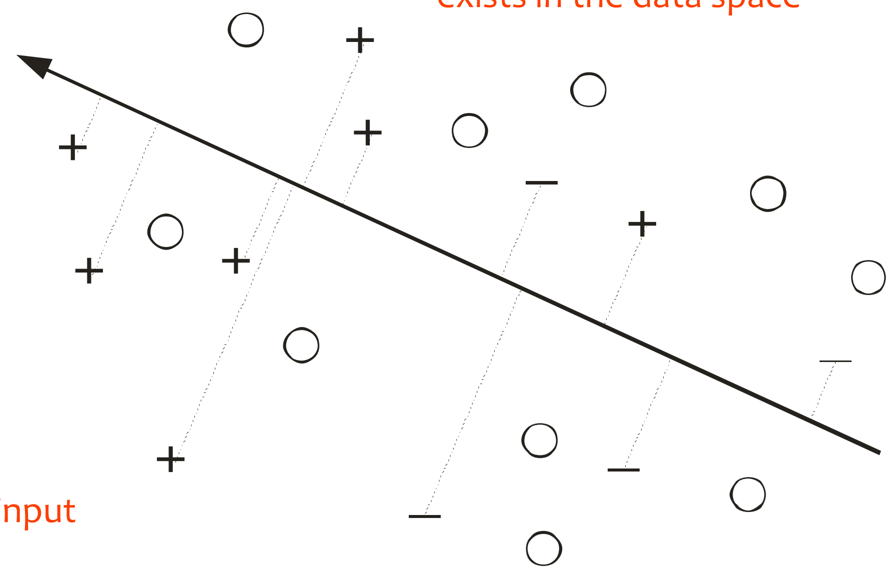
and if the quality measure is scalar,

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

For the estimate one has

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

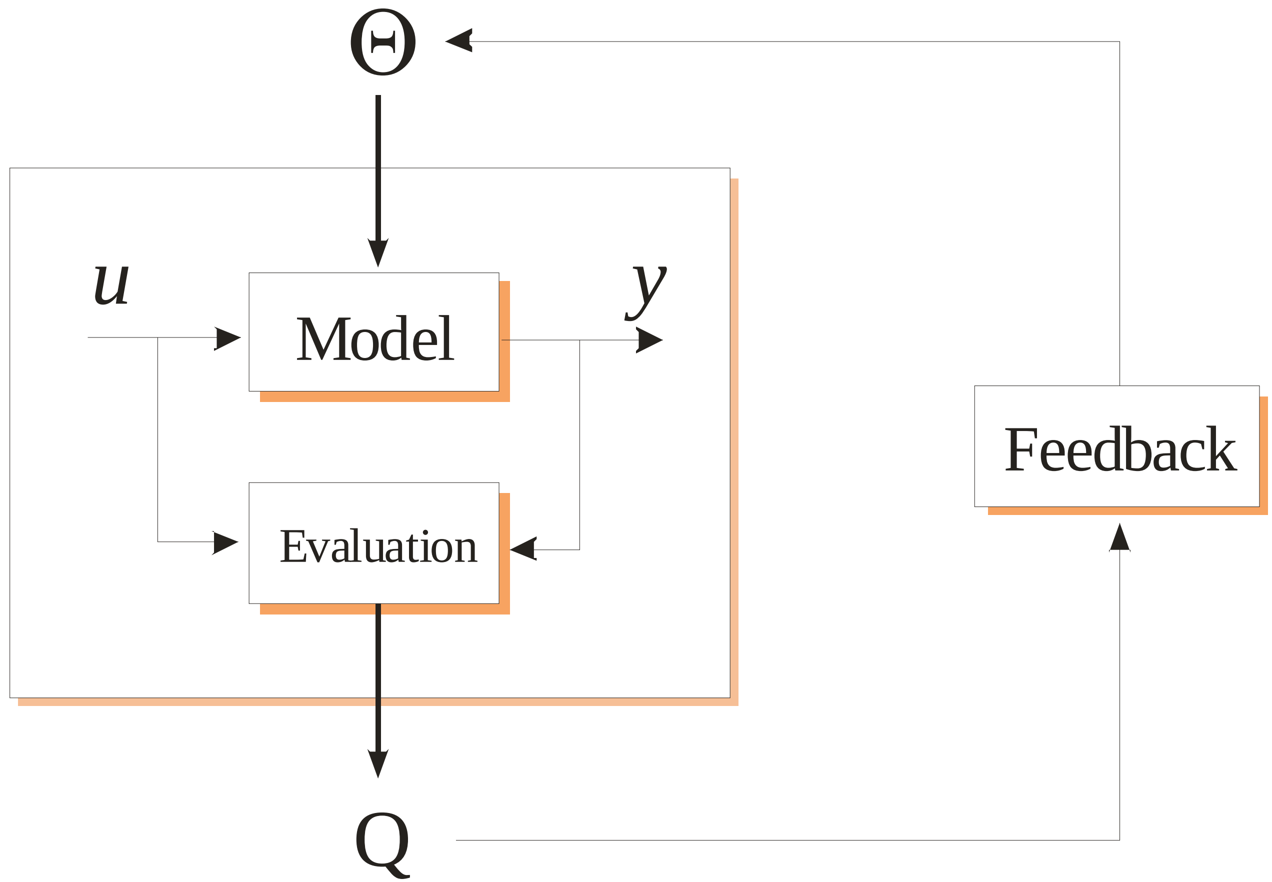
If only one quality measure, only one non-trivial direction exists in the data space



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

Applications

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



Iterative optimization

- Assume that the cost criterion is defined as

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

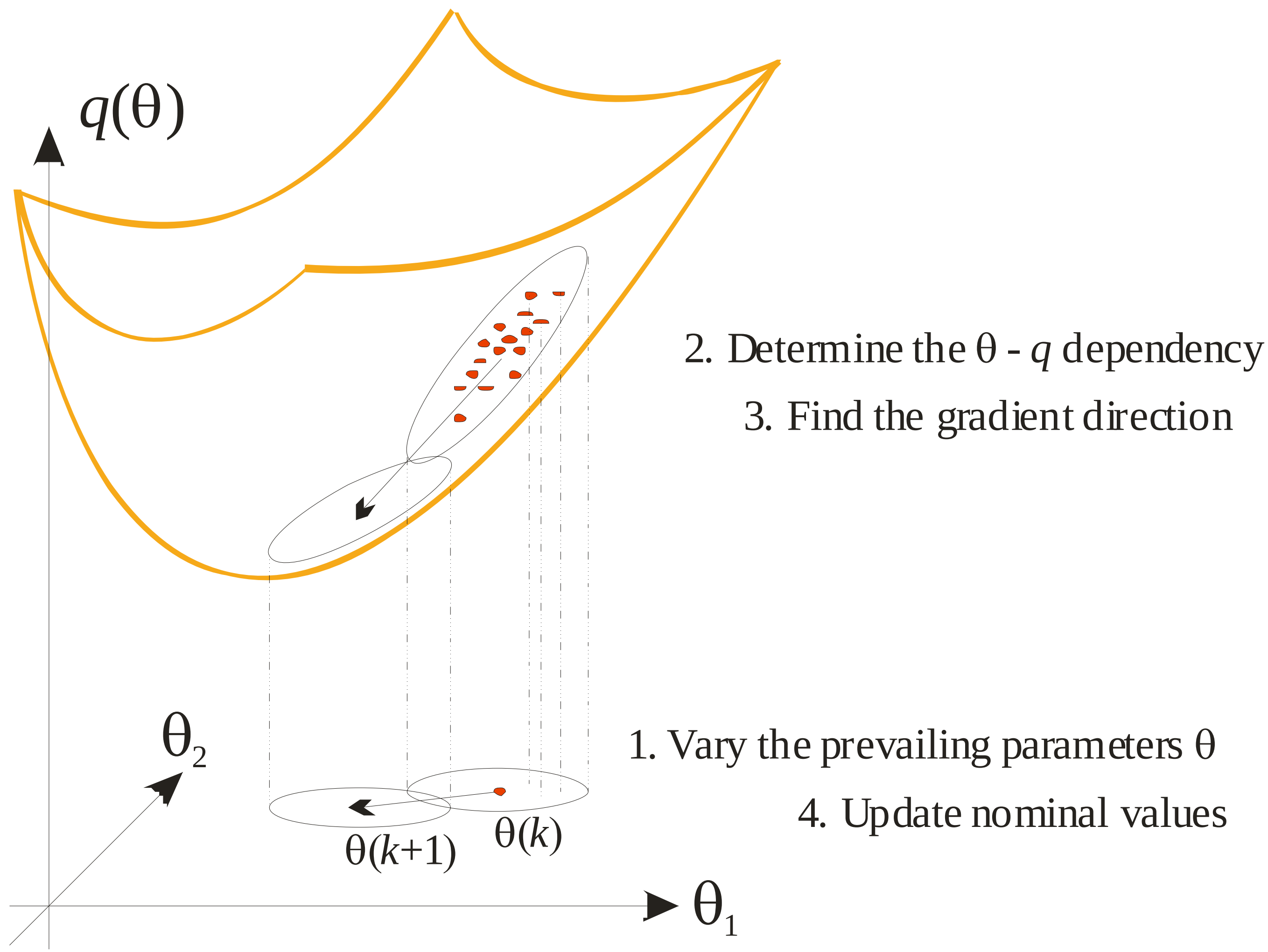
Noticing that

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

one can write the steepest descent algorithm as

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

- Visual version



- 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:

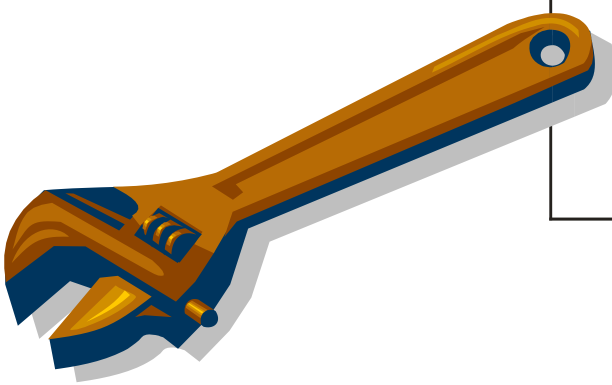
$$y(k) = \theta^T(k) \cdot x(k)$$

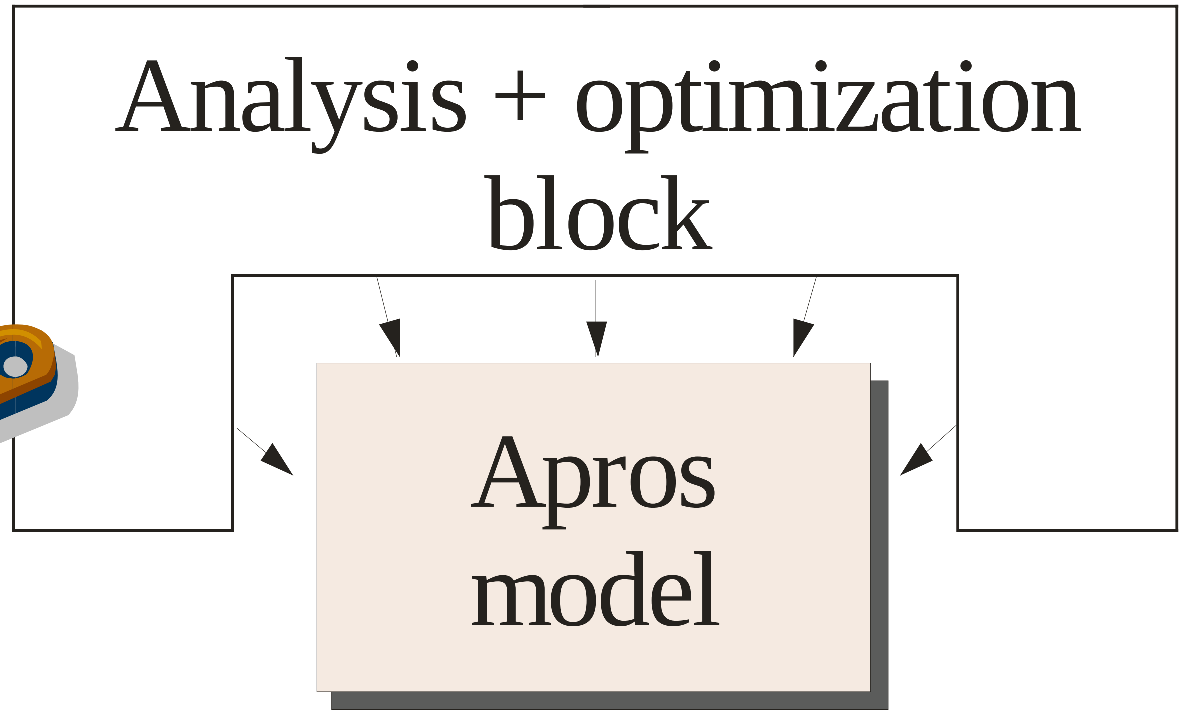
- Now, however, there are two *separate* linear models on different levels:

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

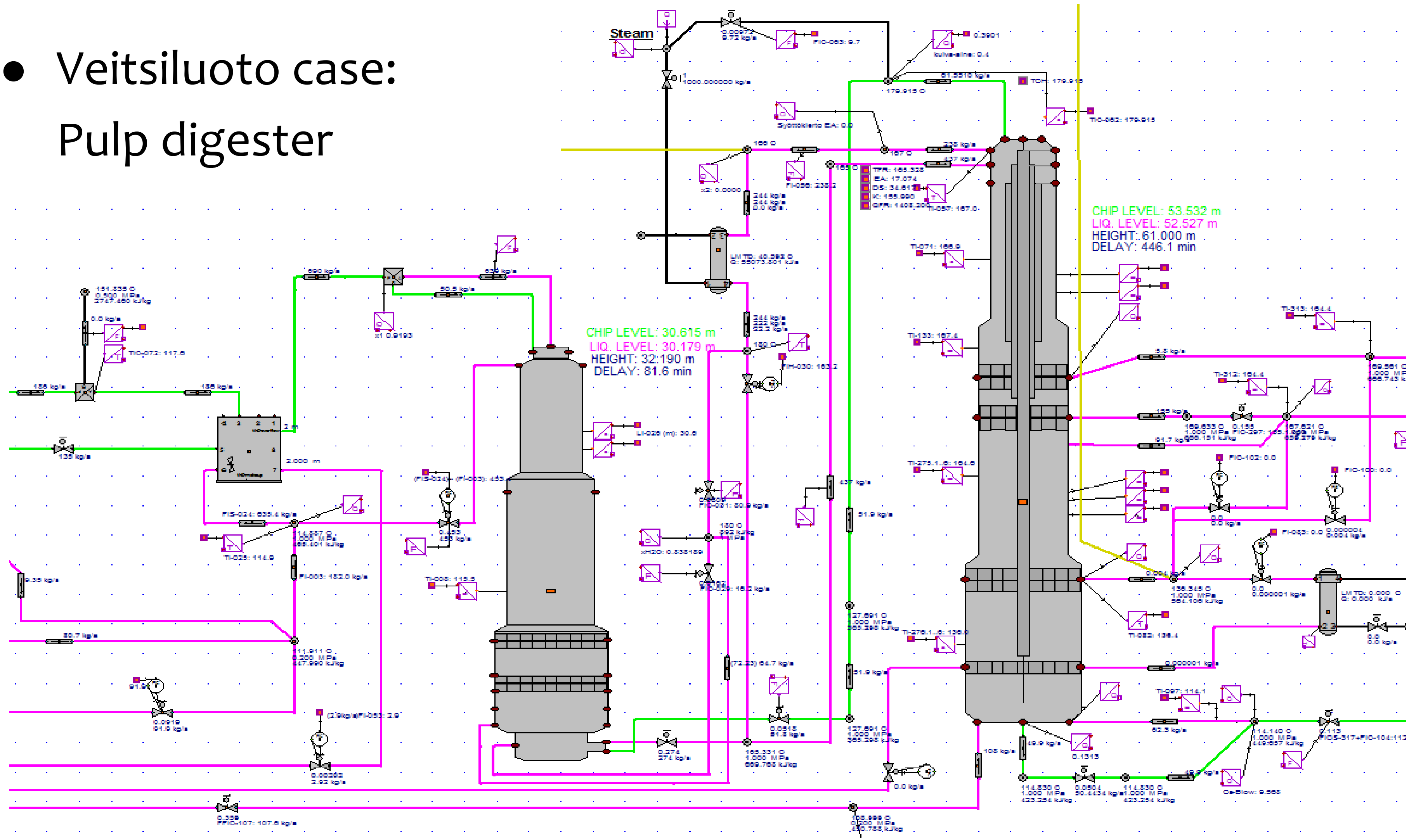
- Explicit distinction between levels makes it possible to reach theoretically simpler analyses.

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





- Veitsiluoto case: Pulp digester

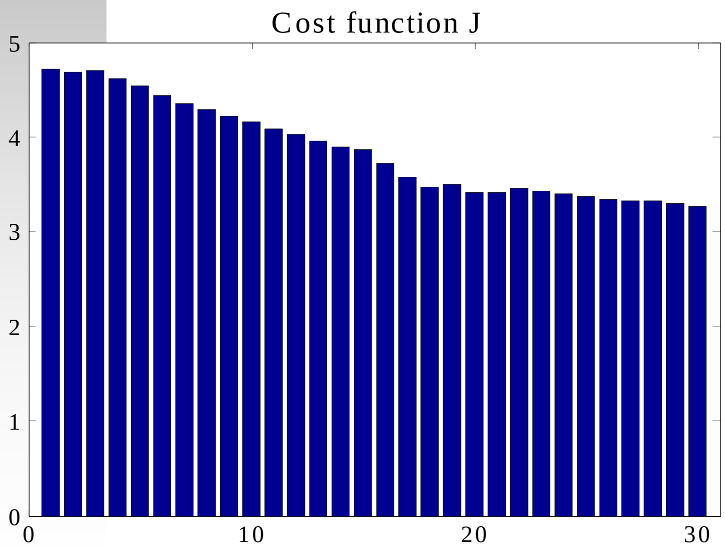


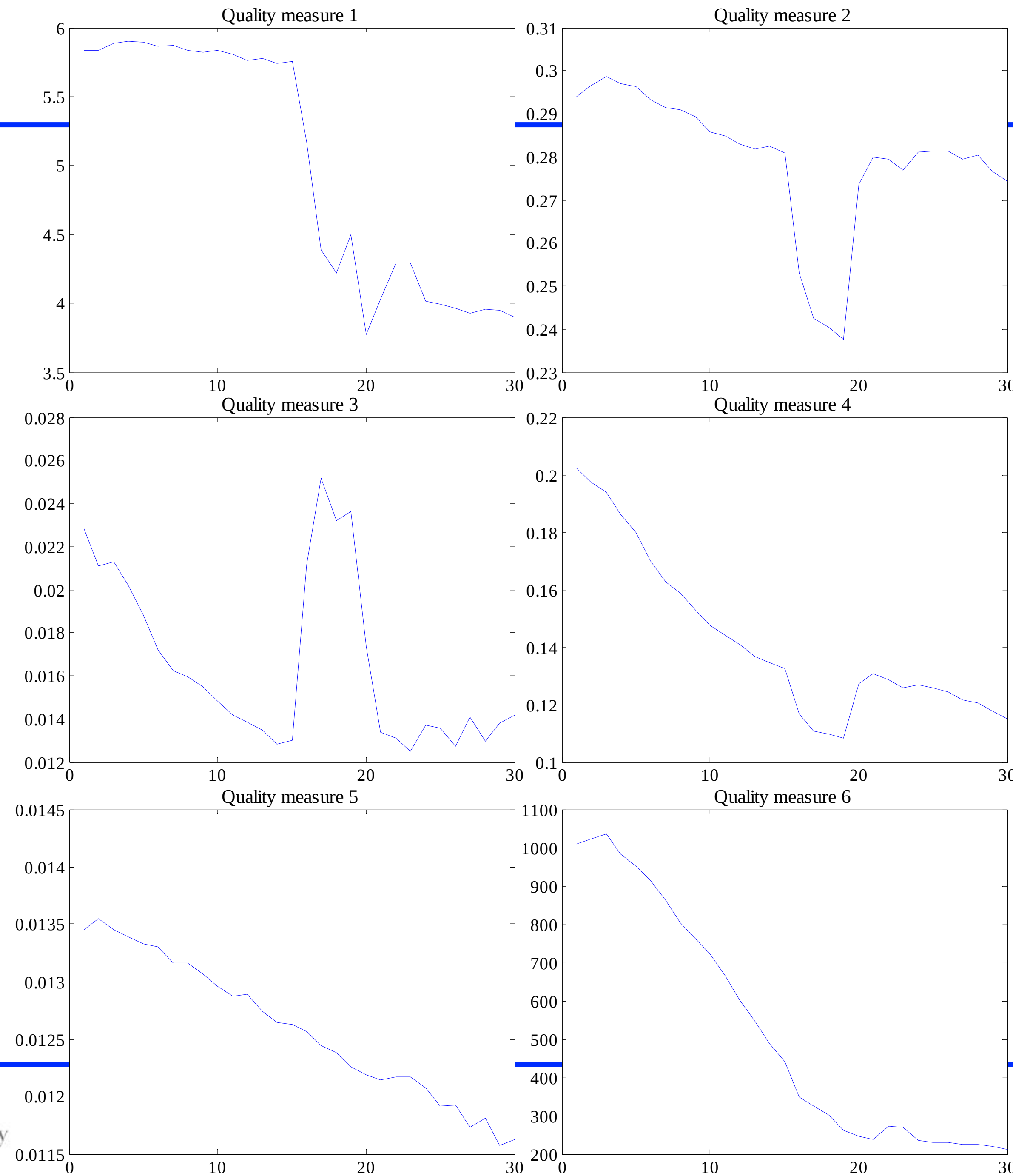
- 20 parameters (7 PI controllers + 2 model based controllers)
- 6 quality measures:
  - q_1: Kappa number in blow
  - q_2: Wash coefficient
  - q_3: Digester liquor level
  - q_4: Digester chip level
  - q_5: Impregnation vessel chip level
  - q_6: H factor
- Cost criteria

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

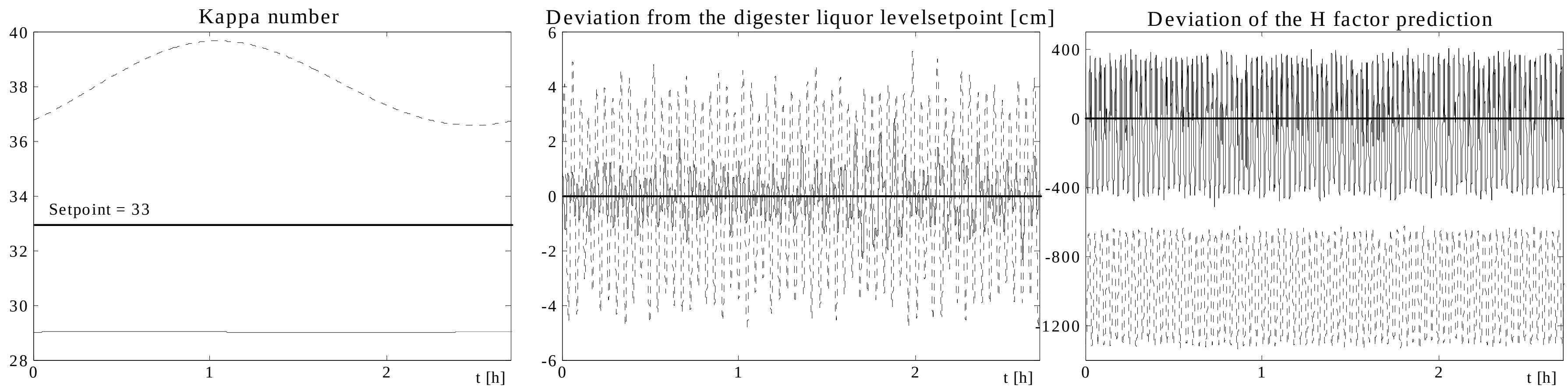
- Optimization based on the PLS model

- Optimization process



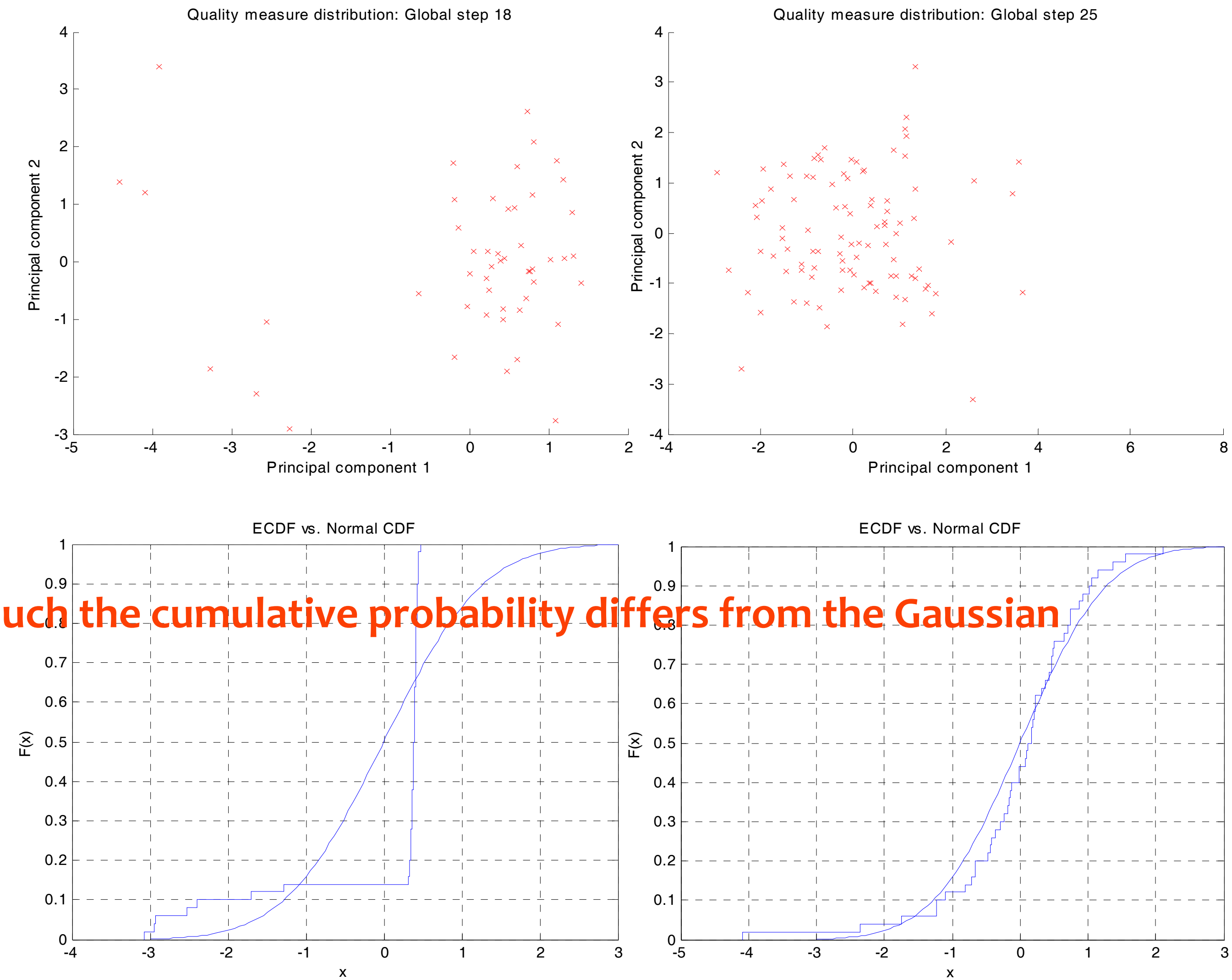


- Results promising – various issues where further analysis is needed ...



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

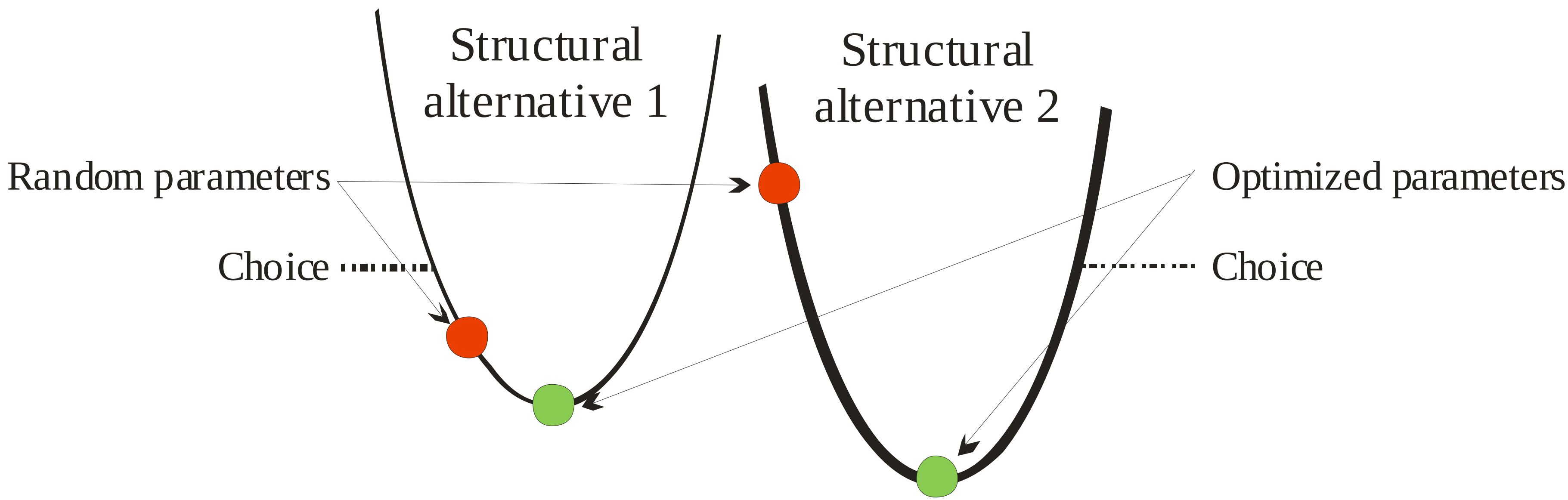
- Test for Gaussianity = check for validity of the linearity asumption



How much the cumulative probability differs from the Gaussian

Further views

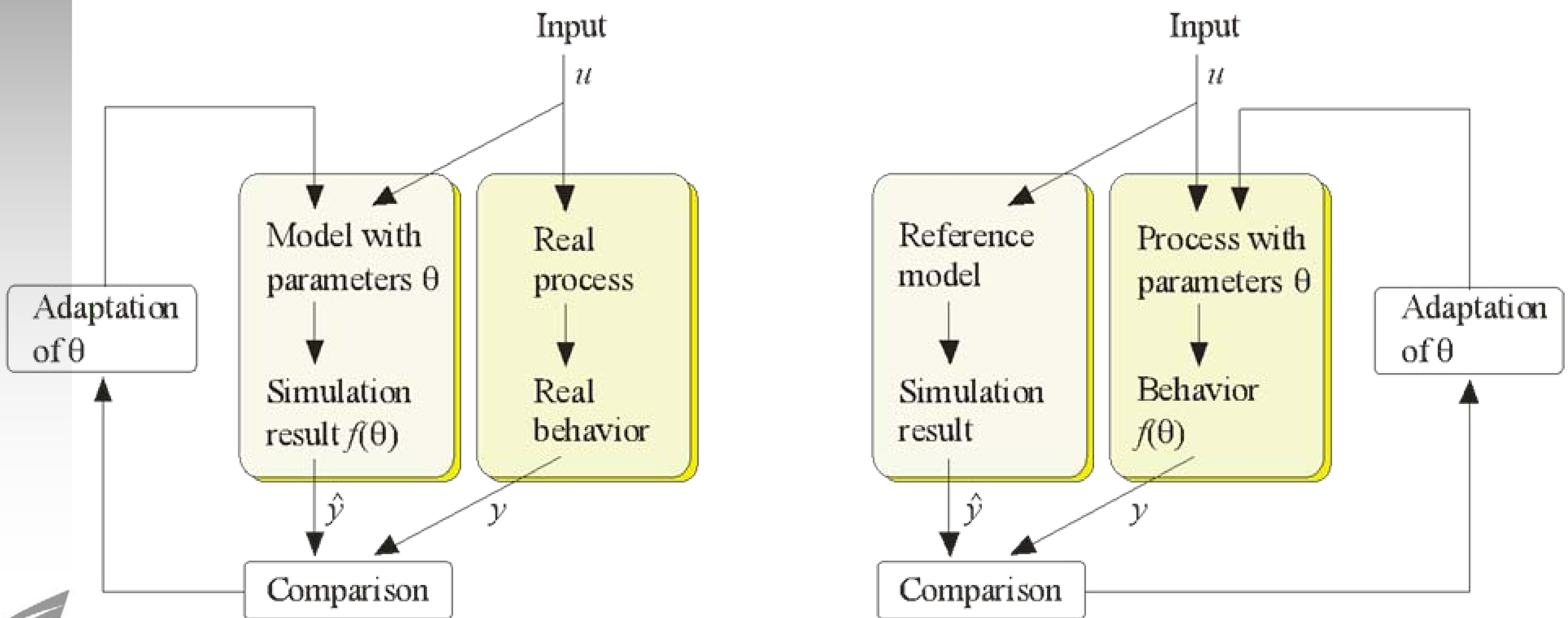
- Gaining intuition on assumptions: What the assumed quality criteria truly *mean* in practice = level of iteration gets higher
- Concrete comparison of structural alternatives:



- 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*

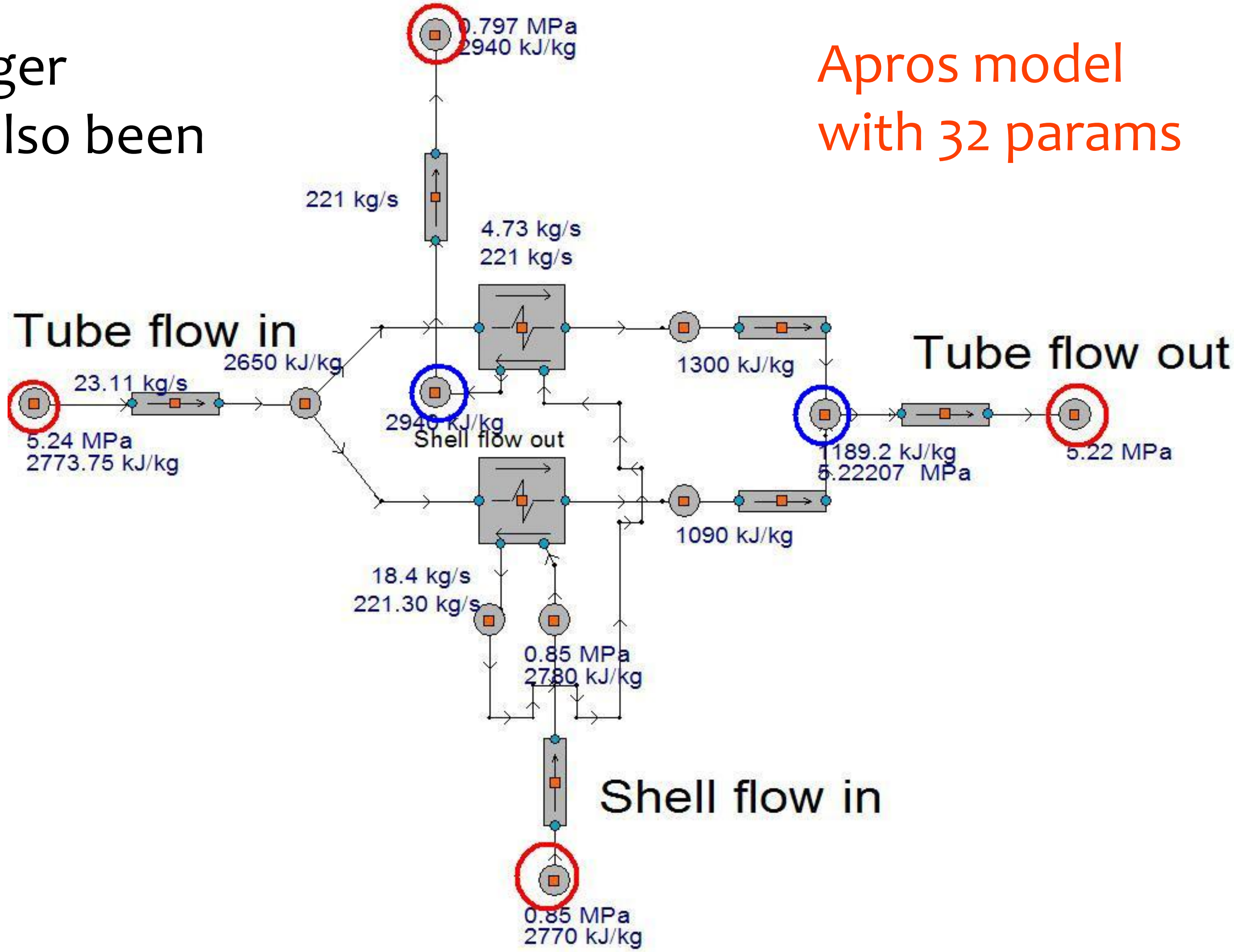
Opposite view

- 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

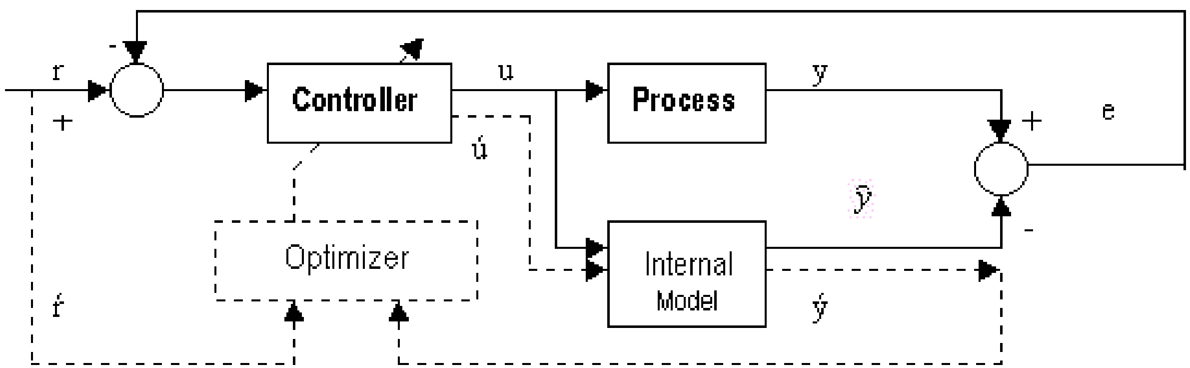
Apros model with 32 params

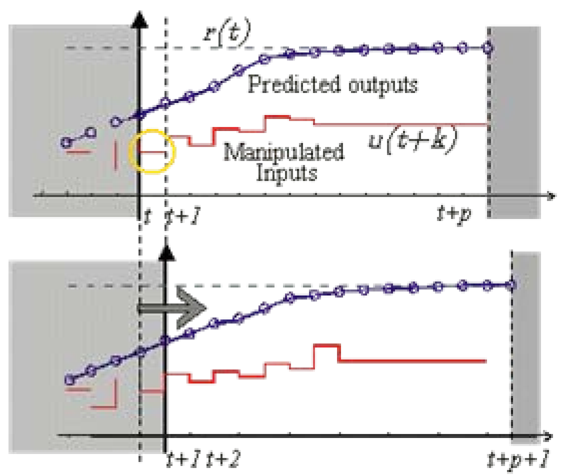


Simulation-based practices

- 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

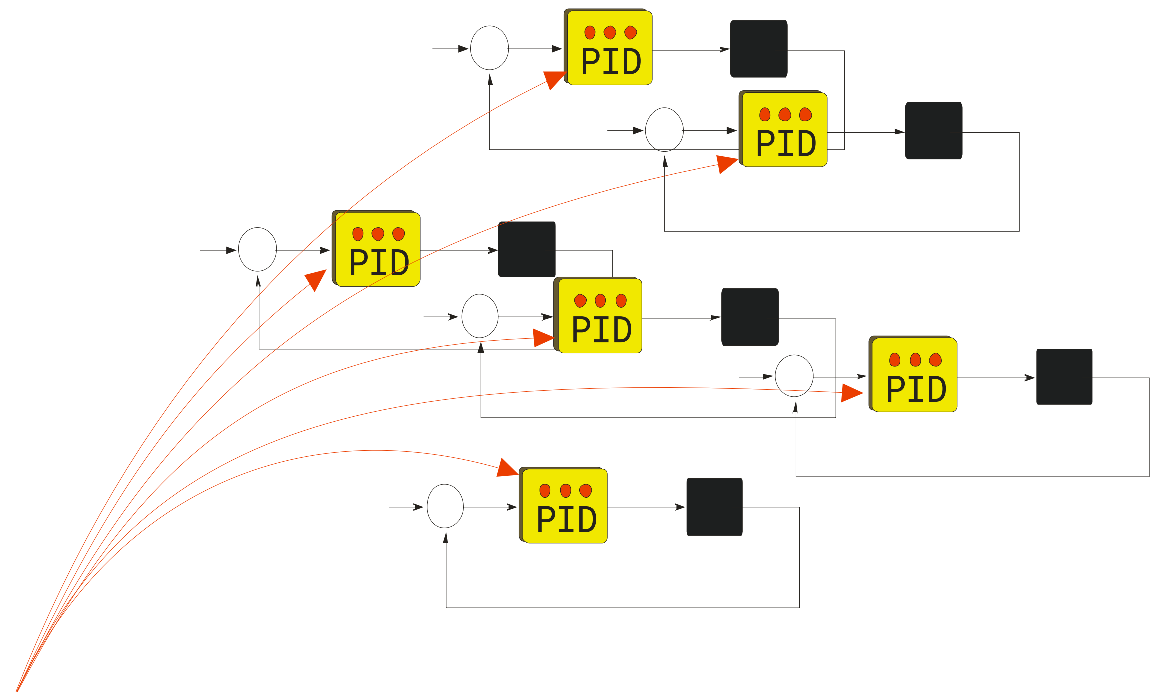
- Again, there is a close connection to traditional practices: Model Predictive Control (MPC) is among those modern methods that have become widely adopted in practice – model is needed to predict process behavior
- Good, efficient models are needed to implement these control schemes





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*



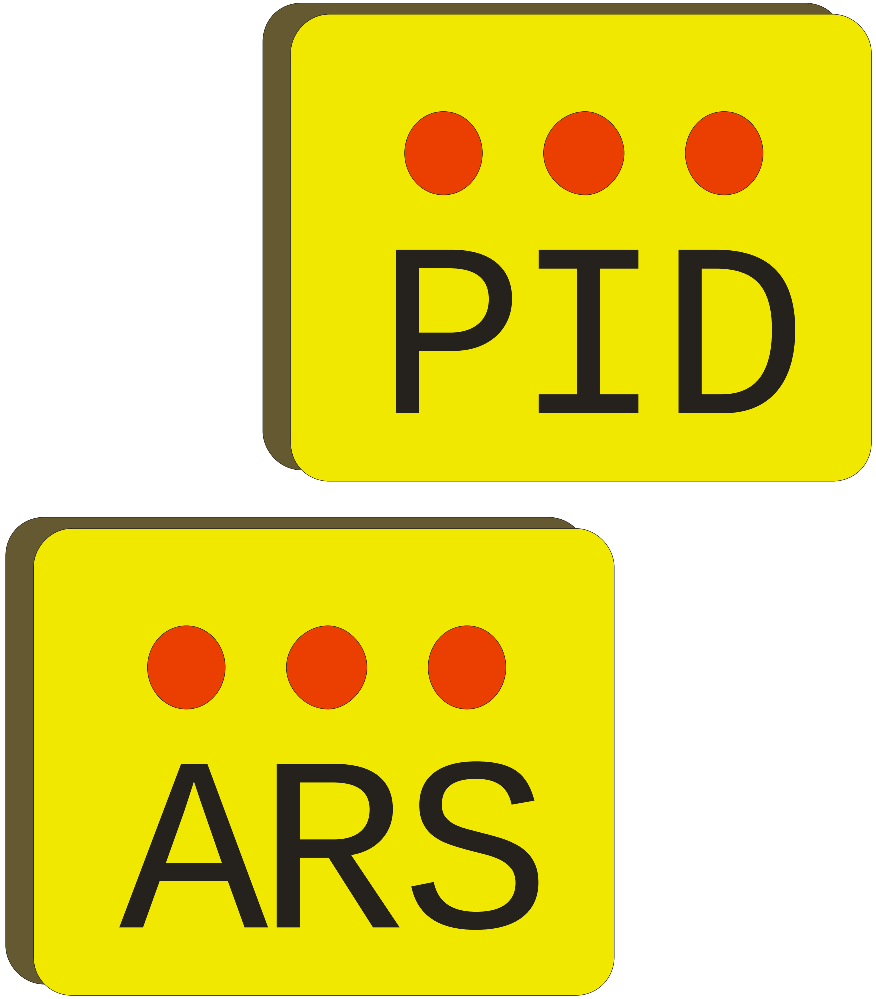
Lower-level controllers tuned in a coordinated manner according to a model where control parameters affect qualities

“Higher-level PID’s”

- Power of PID: *Intuitiveness*
  - **P**roportional action
  - **I**ntegrative action
  - **D**erivative action
- Correspondingly:
  - “**A**ccuracy action”
  - “**R**obustness action”
  - “**S**peed 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"

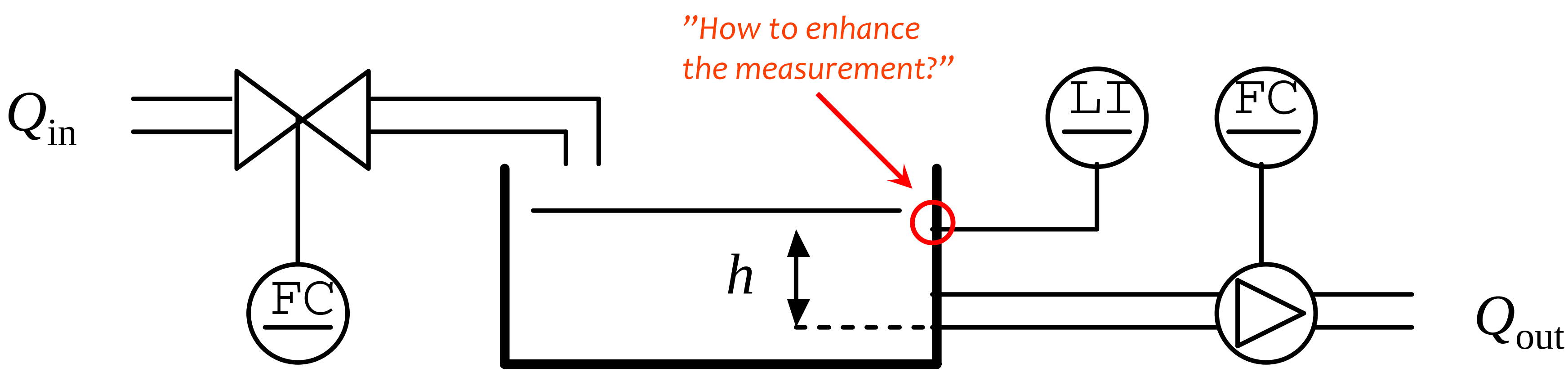
Evolutionary systems typically evolve towards being more and more cybernetic

- 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



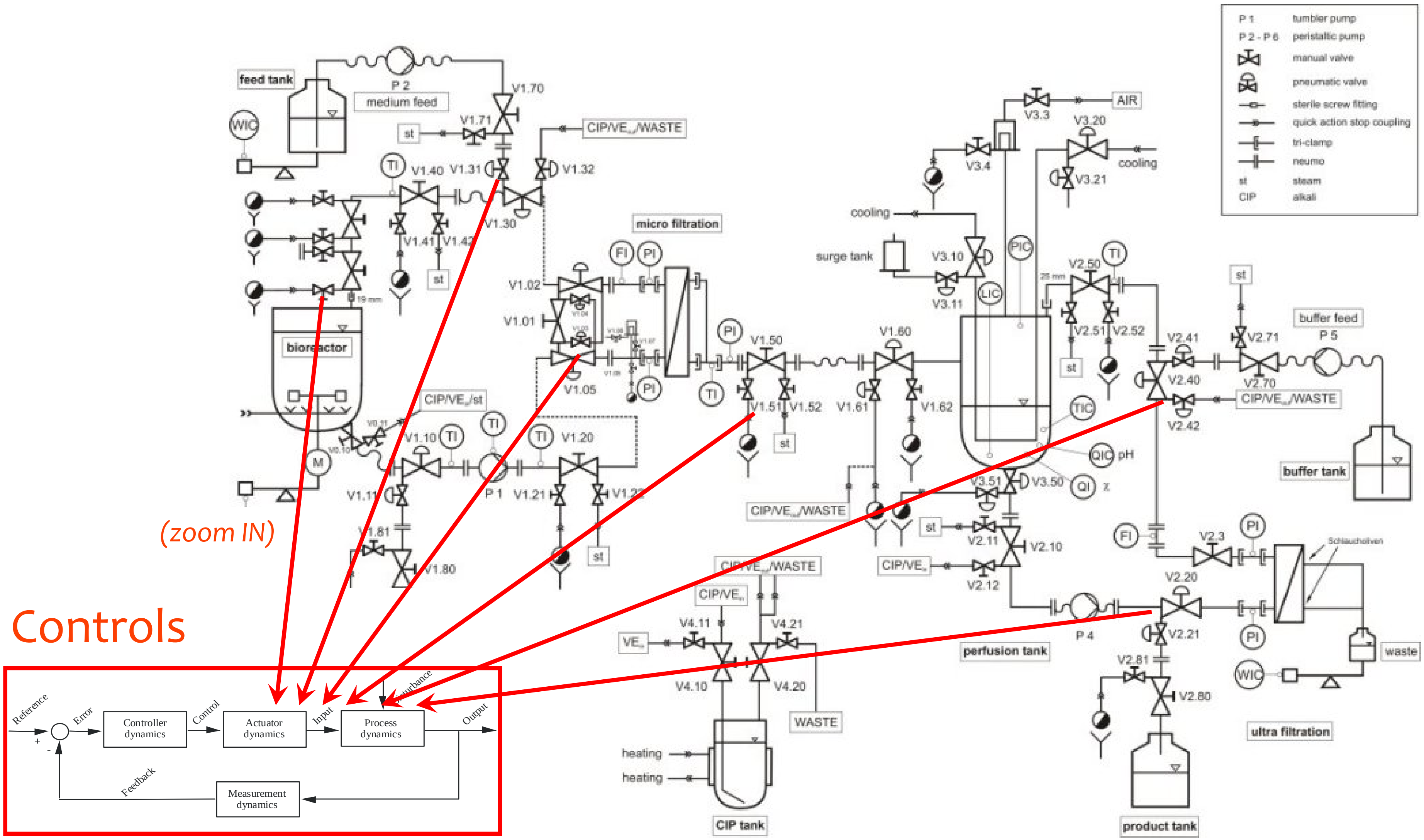
- *Physical level* (formation): Input Q_{in}, output Q_{out}; based on the actual process structure and its energy/matter flows
- *Information level* (metaformation): Inputs Q_{in} and Q_{out}, output h; based on what can be measured and what can be affected
- *Knowledge level* (*metainformation*): Inputs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

Emphasis now

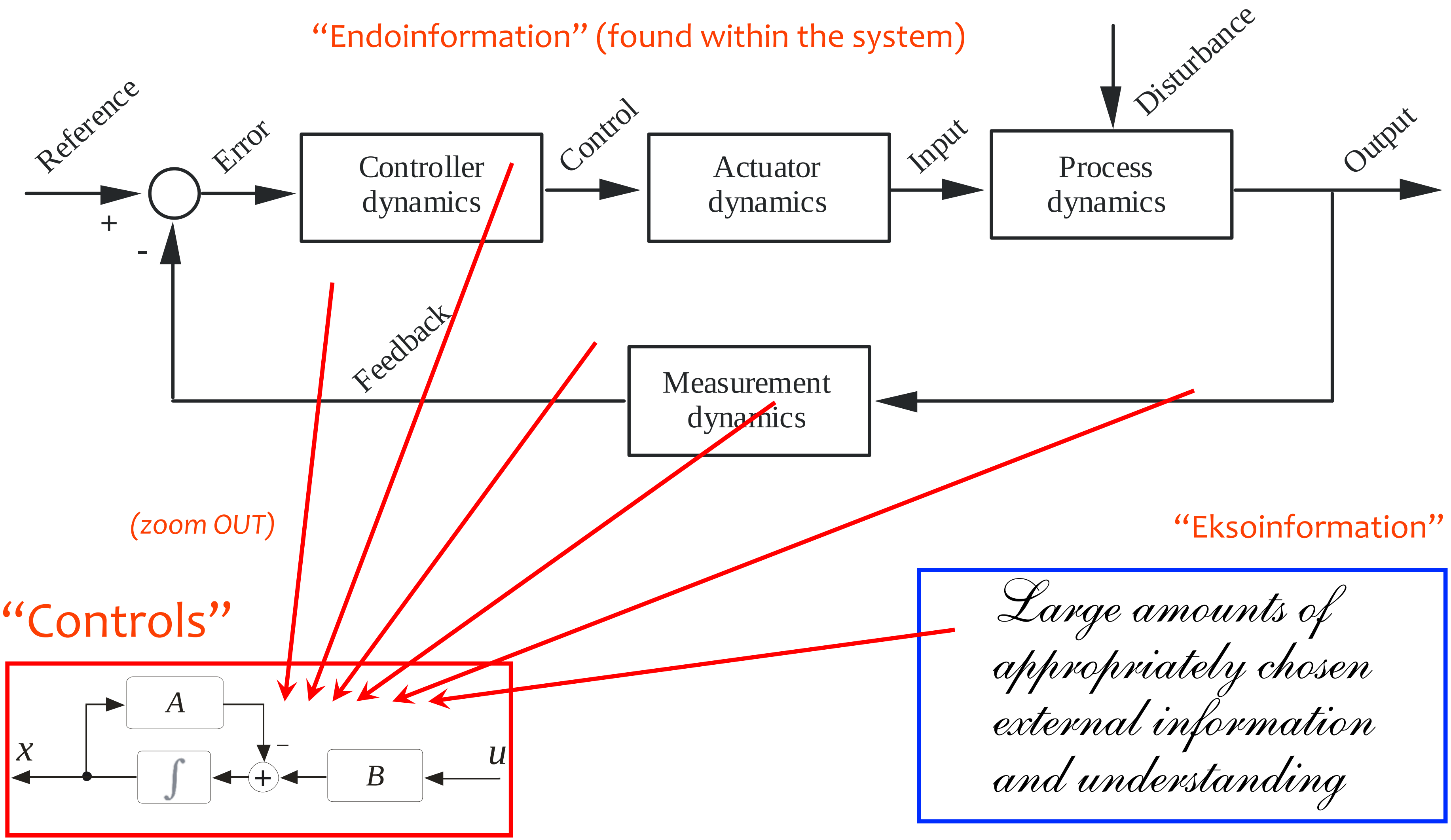
- There are some structural similarities typically found in different levels of system flows
- On the *information processing level*, it is the feedback control loop that is typically found (in some form or another)
- On the *knowledge processing level*, the behaviors can be captured in the cybernetic 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

Key challenge: Find the "degrees of design freedom" among constraints

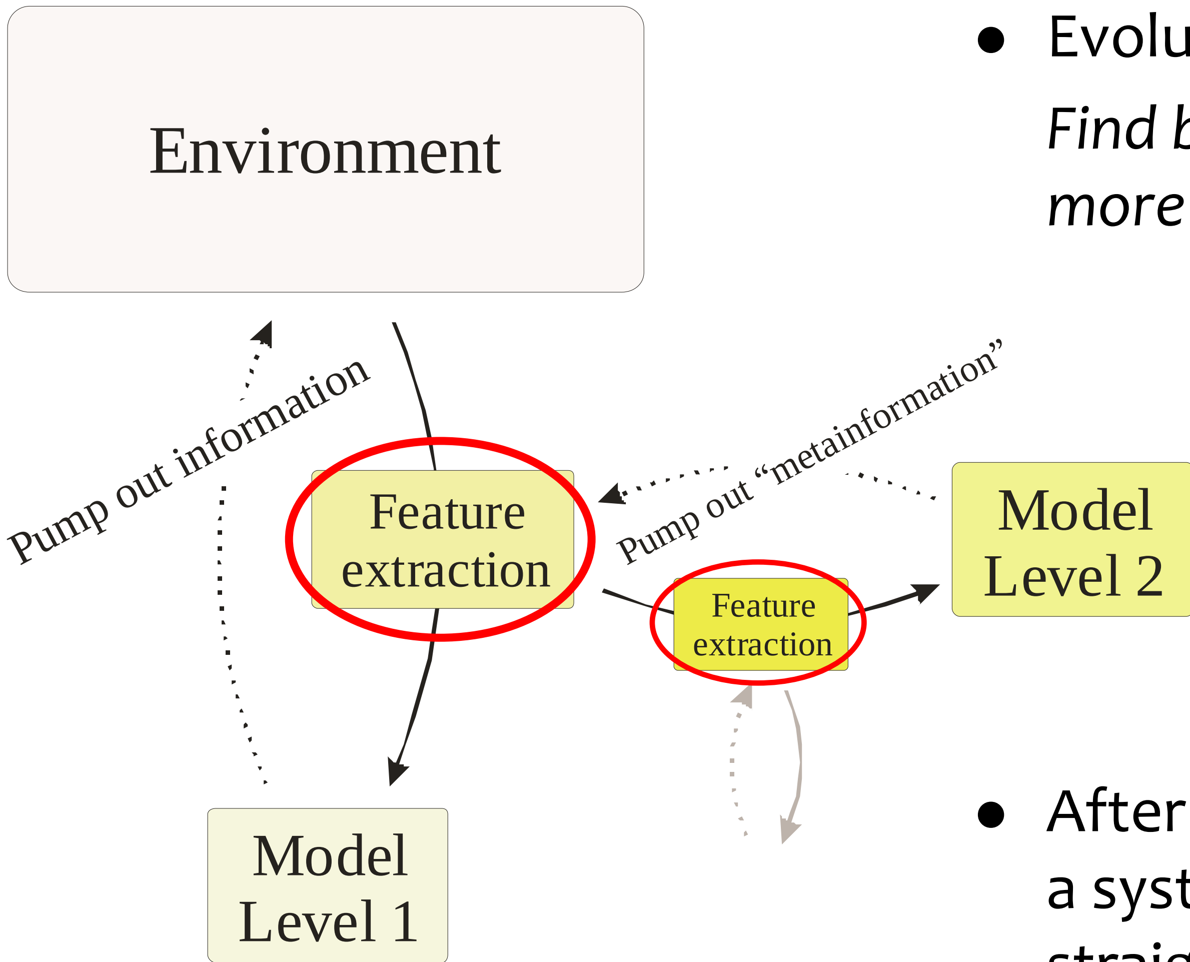
From process flows to information flows ...



… From information flows to "knowhowflows"



Yet another view: Role of semiosis



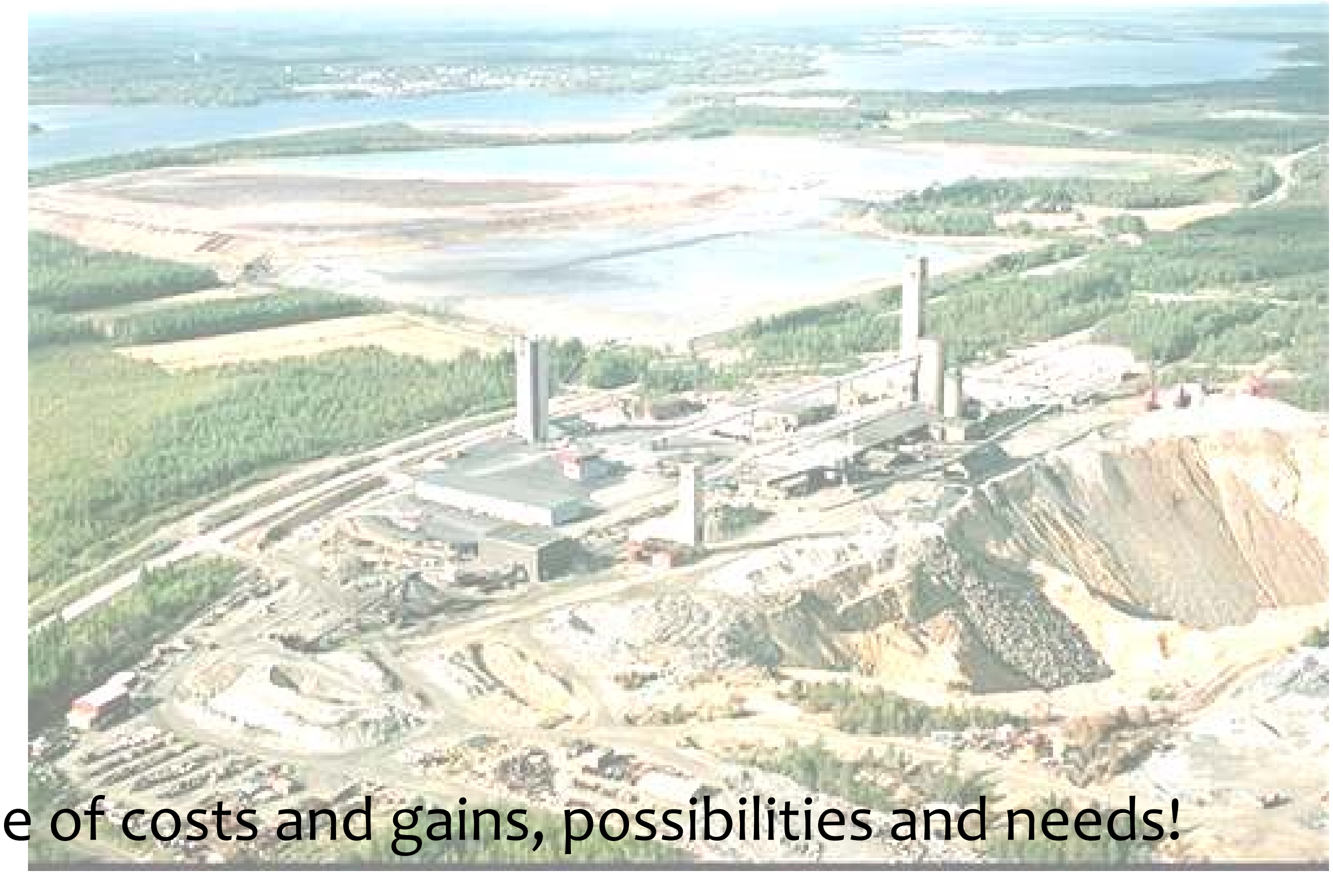
- Evolution goal focused:
  Find better – streamlined – more effective features

- 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*

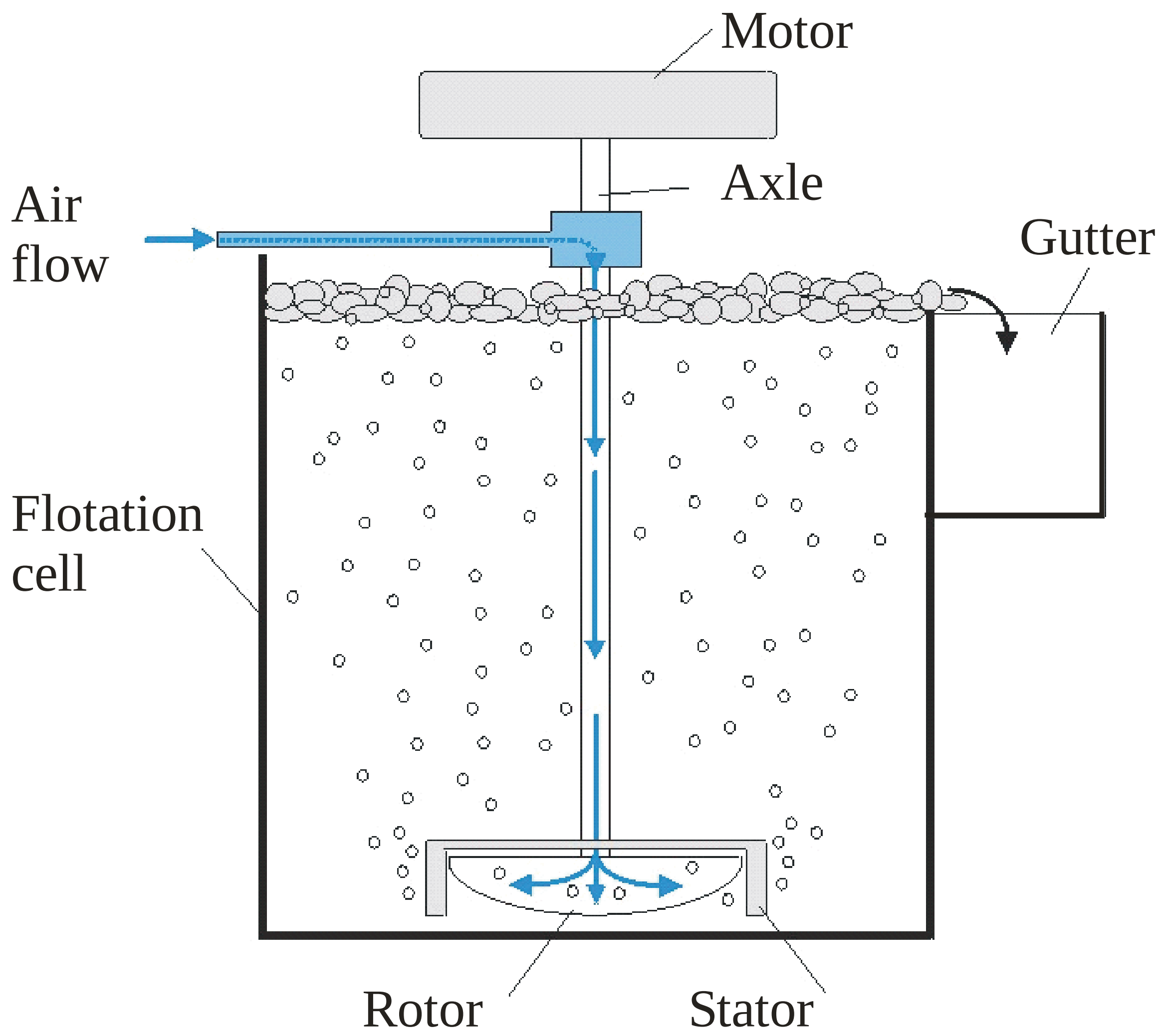
Simple?



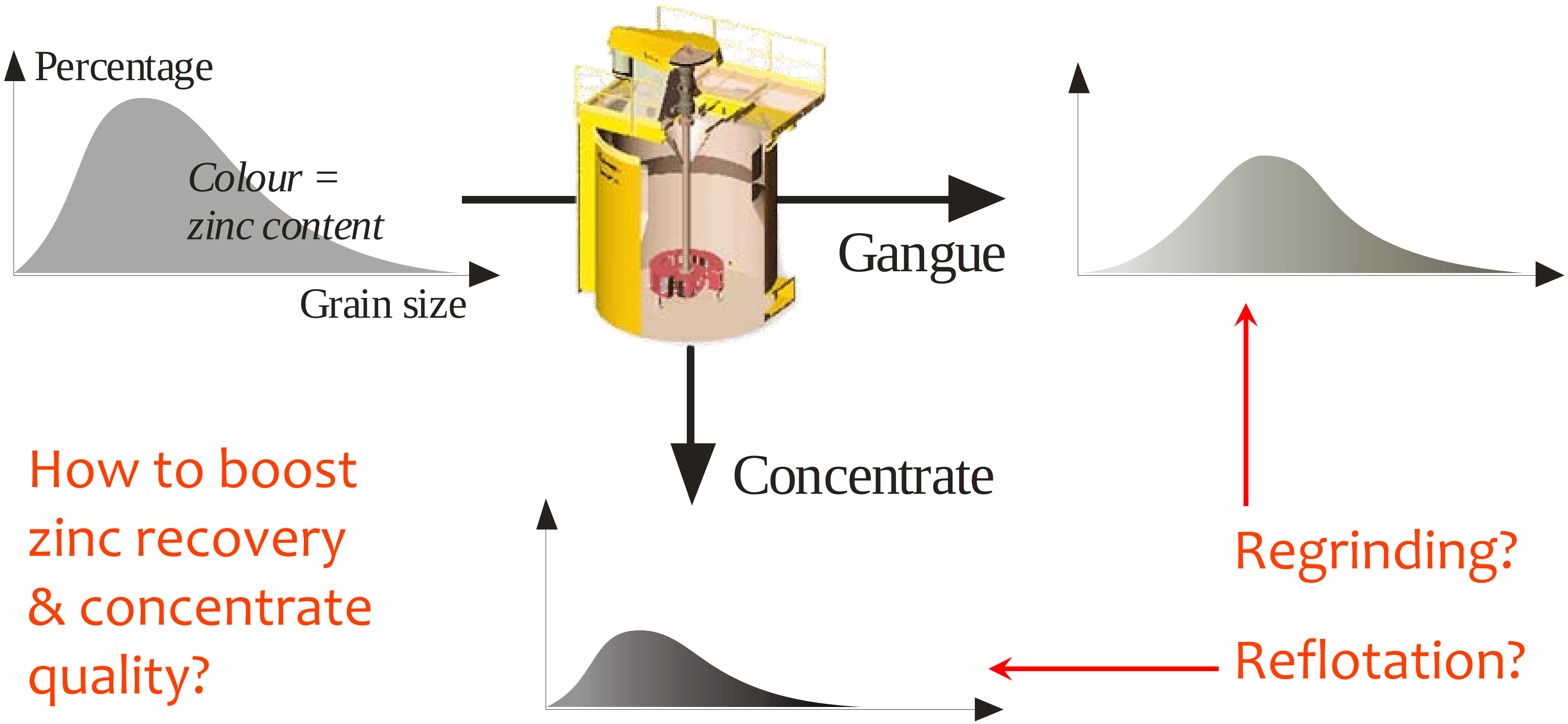
Find the balance of costs and gains, possibilities and needs!

- Flotation cell: Air bubbles bring the hydrophopic mineral grains onto the froth surface
- Simple?

- Increasing understanding makes things more and more complicated…

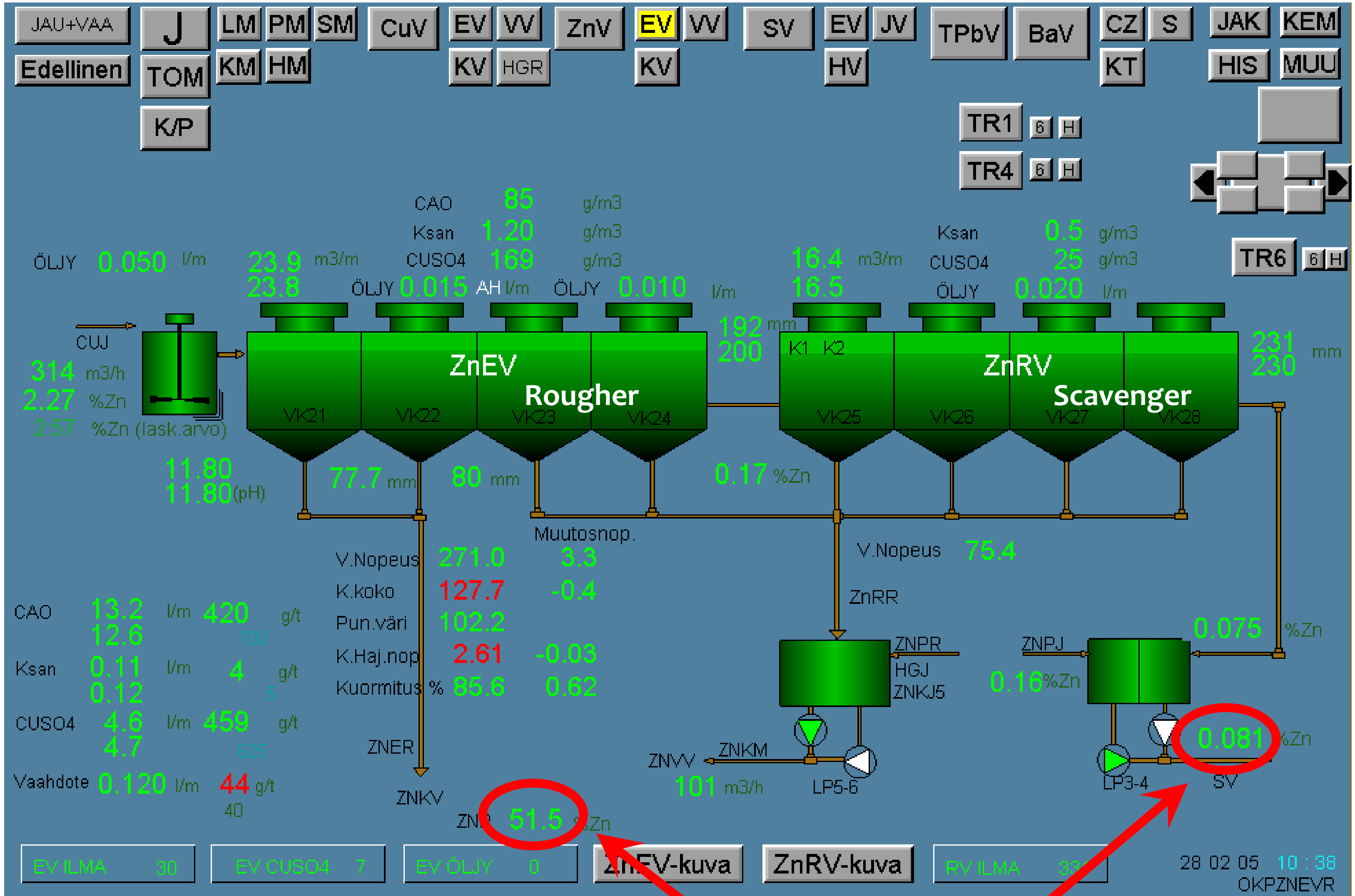


- Closer analysis: How the need for more sophistication in the flotation process emerges



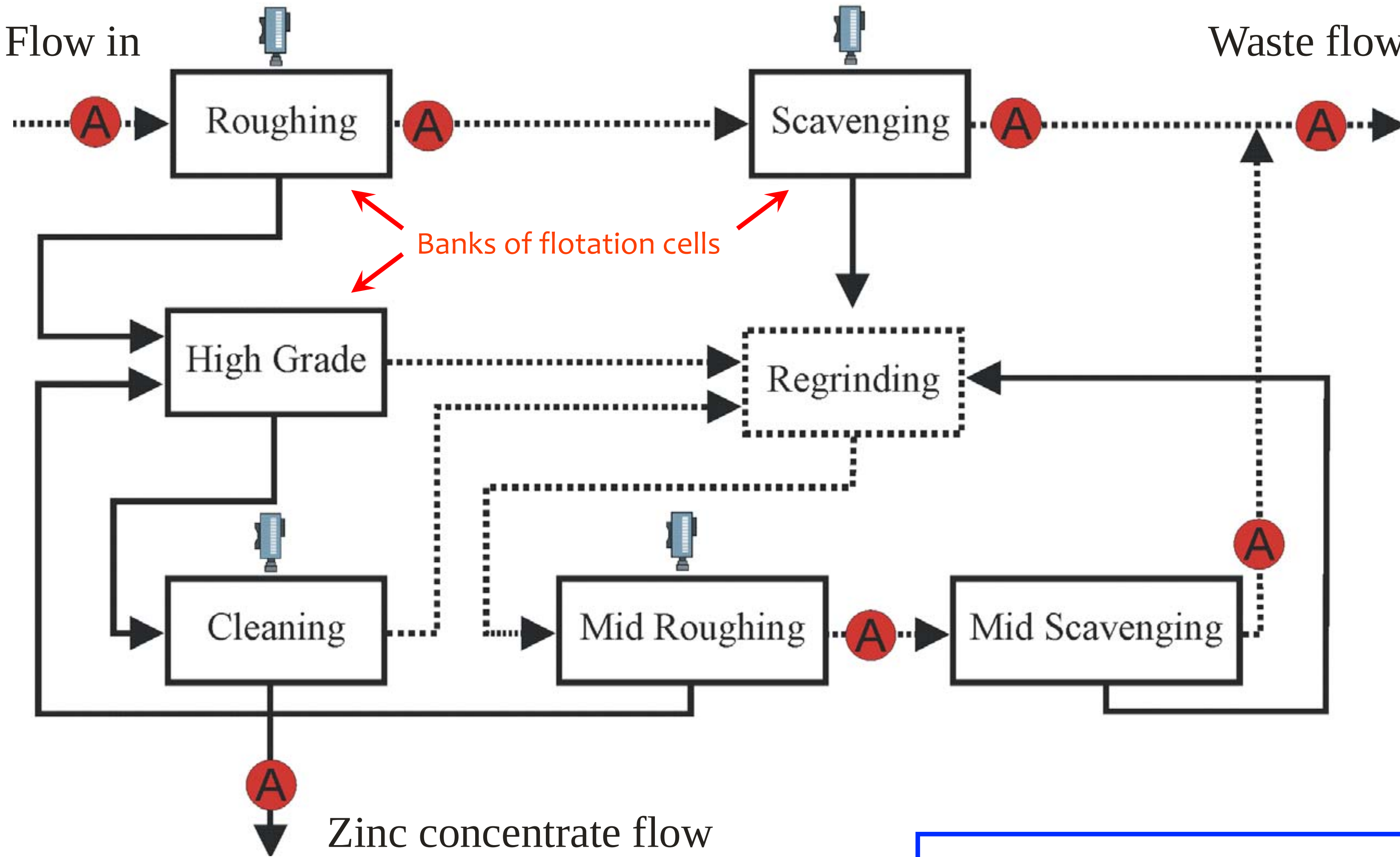
How to boost zinc recovery & concentrate quality?

Optimization between *grade* and *recovery*



Maximize **Minimize**

Zinc circuit



Final structure is "self-organized"!

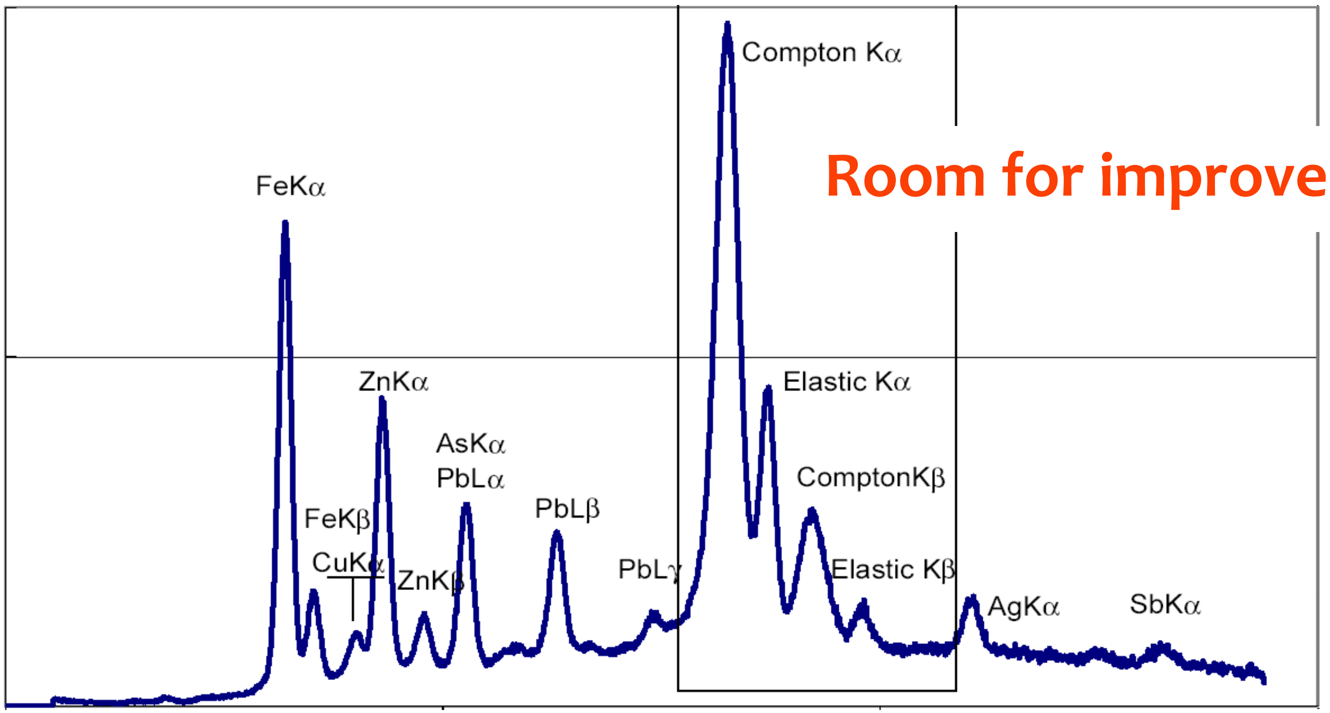
- Flotation circuit designs vary in structure depending on the type of mineral, degree of liberation of valuable minerals, intended grade (purity) of the product, and its value
  - The first rougher stages produce a good grade concentrate, but recovery is only medium, the second rougher stage is designed 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

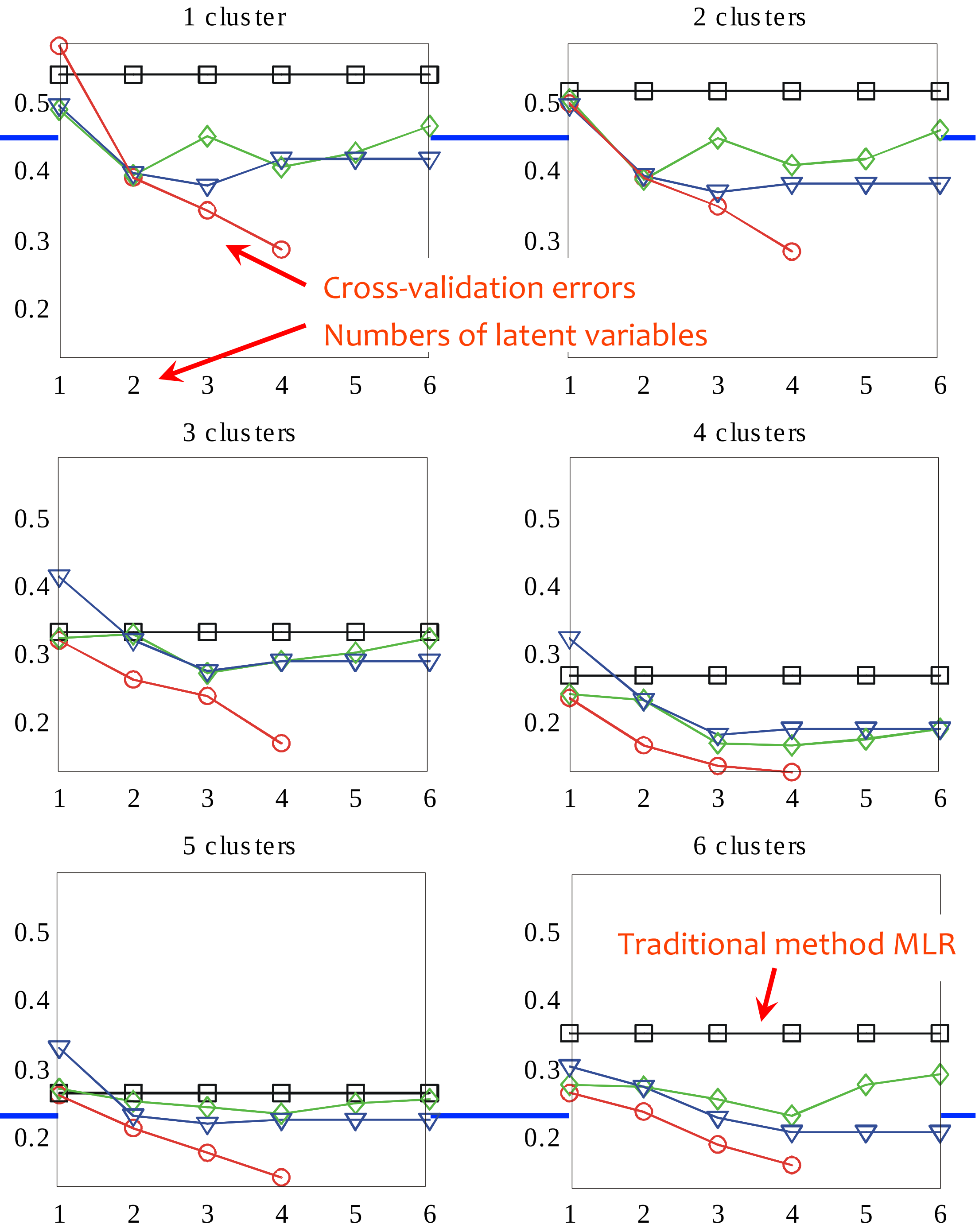
- In principle, spectra are uniquely determined by atoms
- In practice, problems because of uneven slurry densities, imperfect sensing technology, external noise, ...



Room for improvement!

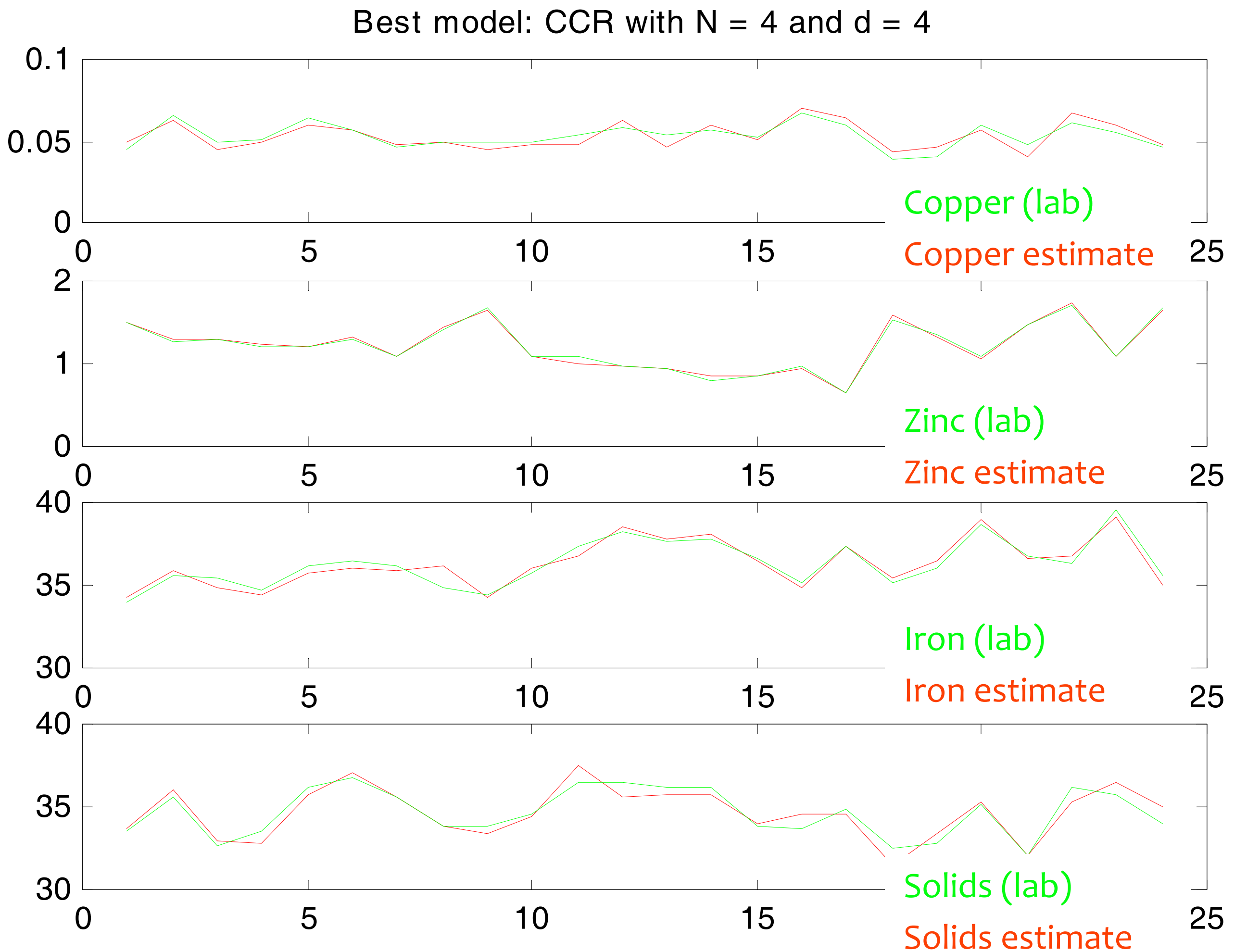
- Calibration model needed from measurements to atom concentrations
- New approaches being developed...
- Statistical multivariate models:

- MLR
- PCR
- PLS
- CCR



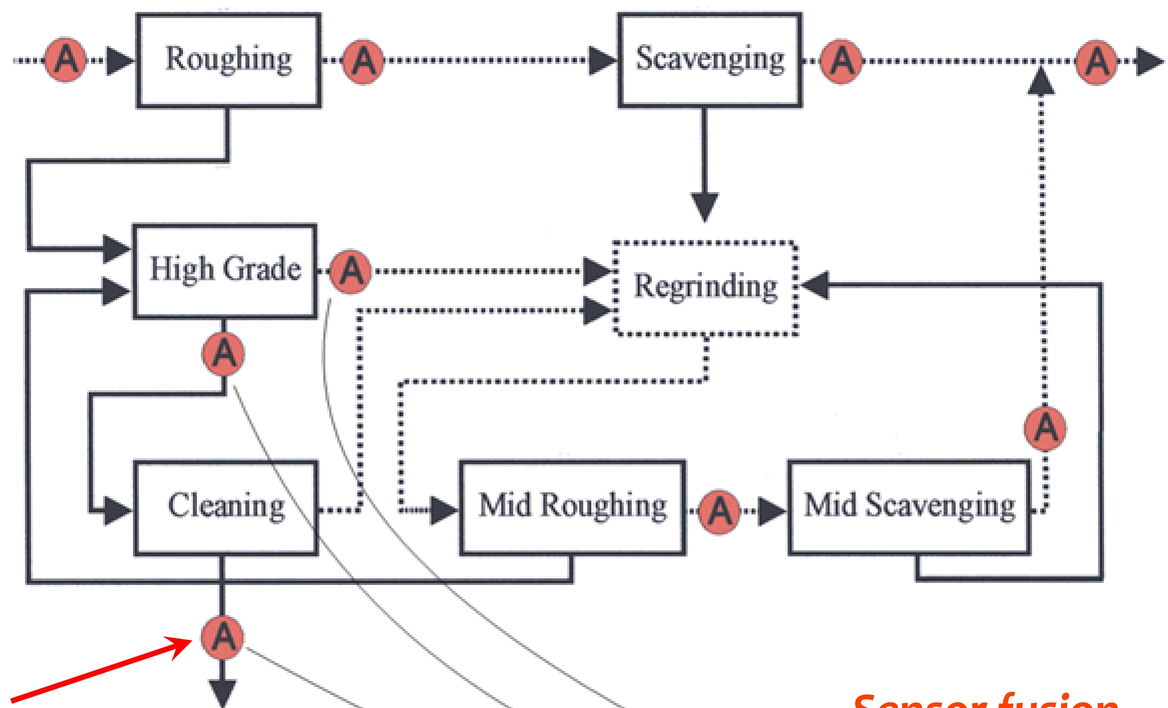
More accurate measurements reached

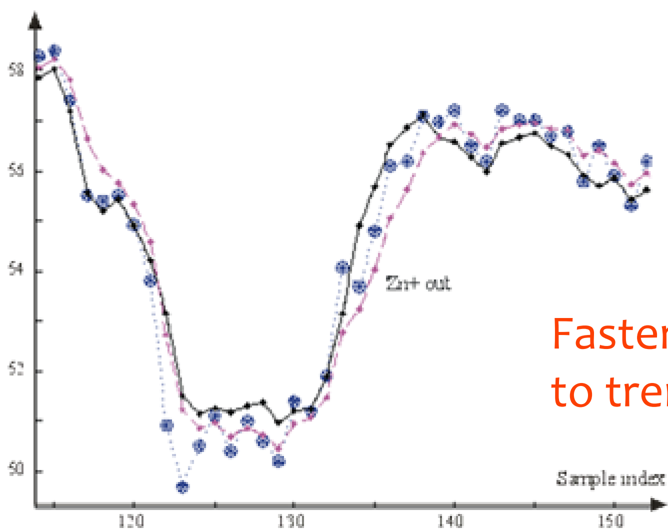
- Estimates OK, but...
- Measuring using X-ray analysis is slow – there is a 20 min interval
- Additionally, the data has to be filtered



Towards "smart devices"

- Correlations between signals can be exploited to reach better estimates





Faster reactions to trends

Sensor fusion

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"Data mining" for mining data

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

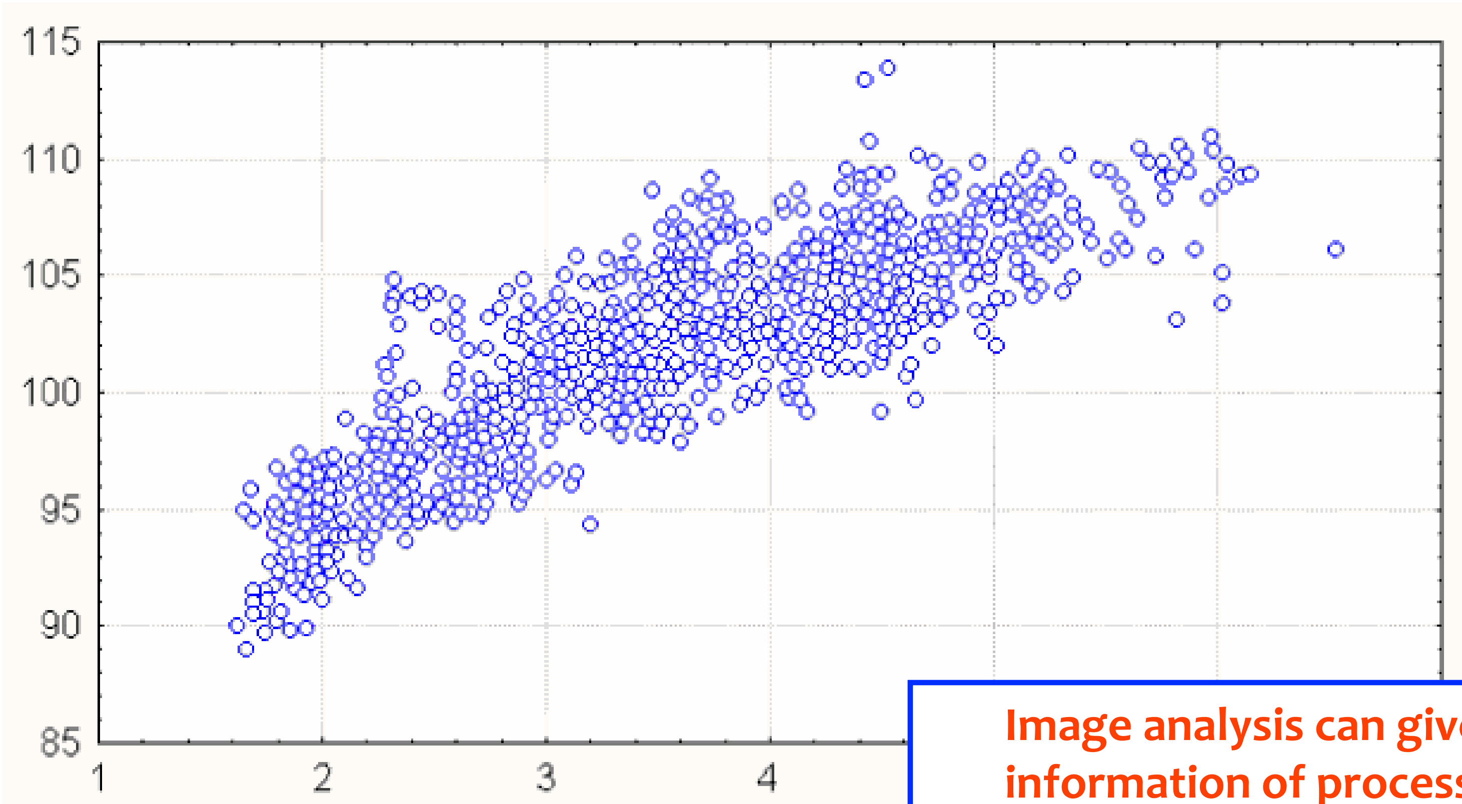
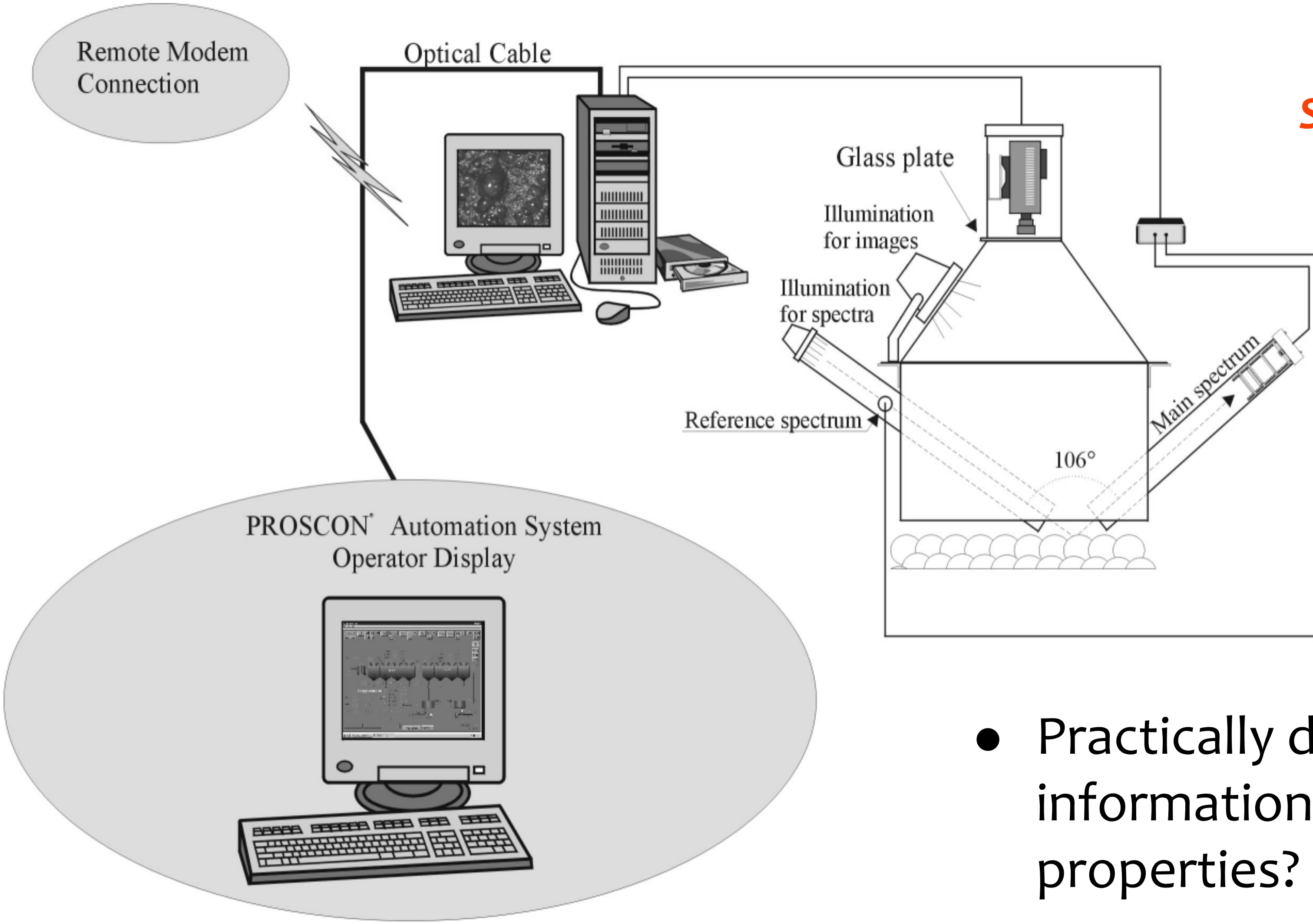


Image analysis can give information of process state also between X-ray analyses – utilize this!?

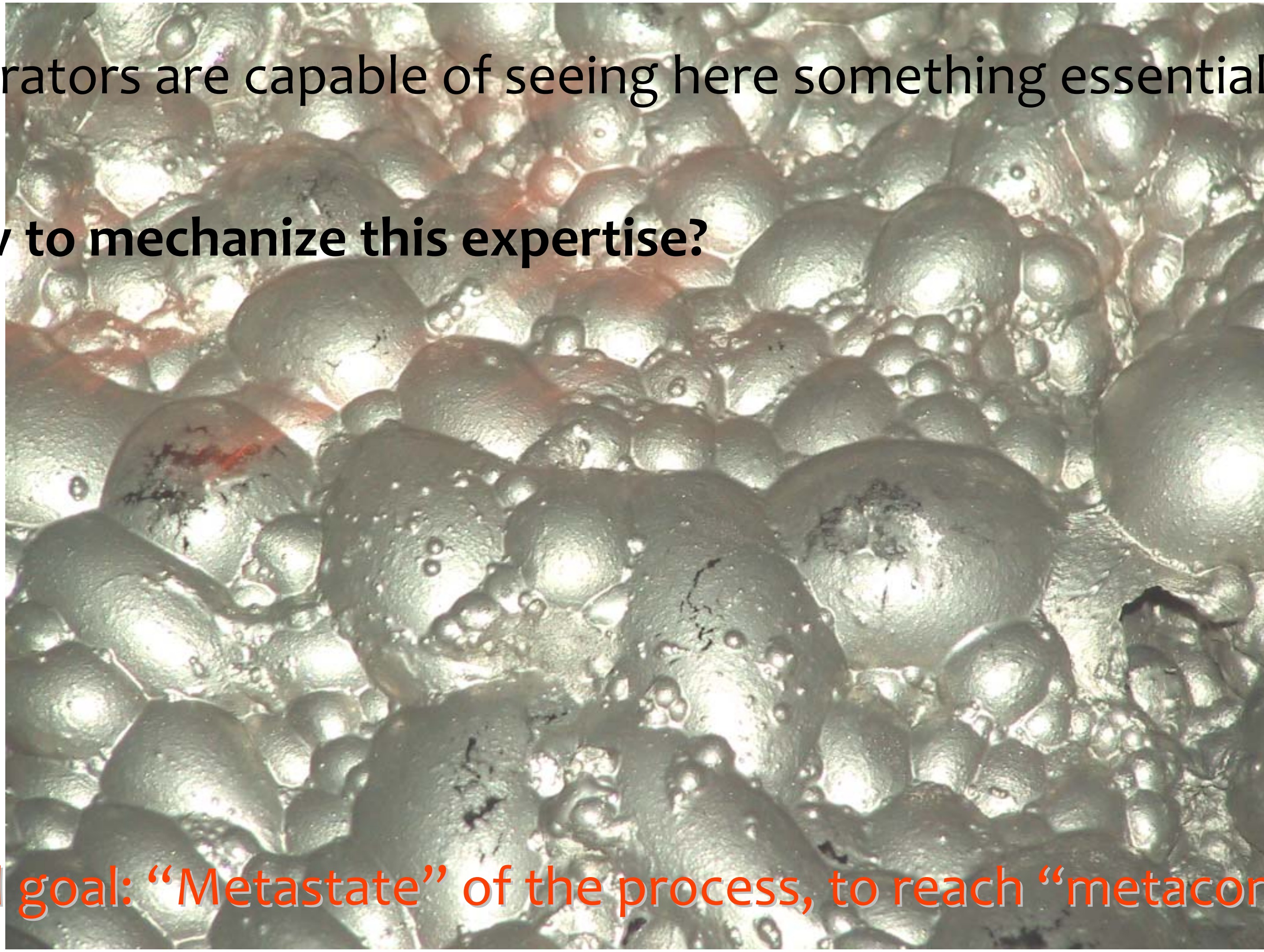
Projects “ChaCo”, “Väsy”, “Äksy”, “Rike” ...



Soft sensors

- 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 *froth thickness* $<$ *lower limit*	Froth collapse situation	–
2.	IF *BCR* $<$ *lower limit* OR *bubble transparency* $<$ *lower limit*	Too “stiff” froth	–
3.	IF *zinc content in rougher tailing* $>$ *upper limit*	Try to optimize	+
4.	IF *zinc content in scavenger tailing* $>$ *upper limit*	...	+
5.	IF *froth thickness* $>$ *upper limit*	Try to condence froth	+
6.	IF *BCR* OR *bubble transparency* OR *bubble size* $>$ *upper limit*	Too “wet” froth	+
7.	ELSE	Finally, try to save reagents	–

“Increase/decrease dosage”

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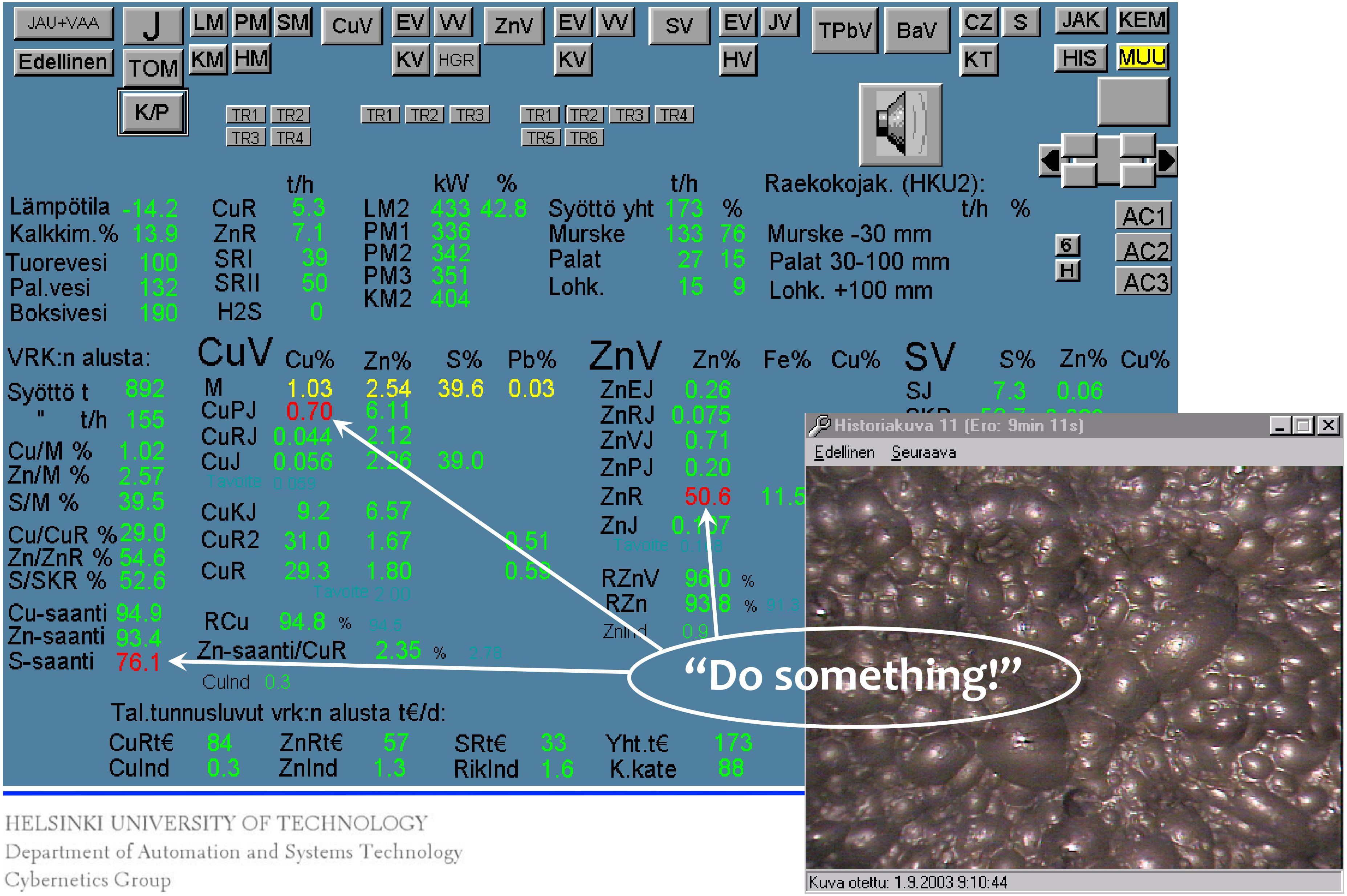
- Marginally stable cyclic behavior effectively maps the dynamic range of the process
- This gives the possibility of gaining information of the process –

  "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



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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...

Not in closed loop

Sensor fusion
& Control

OPERATORS

- 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

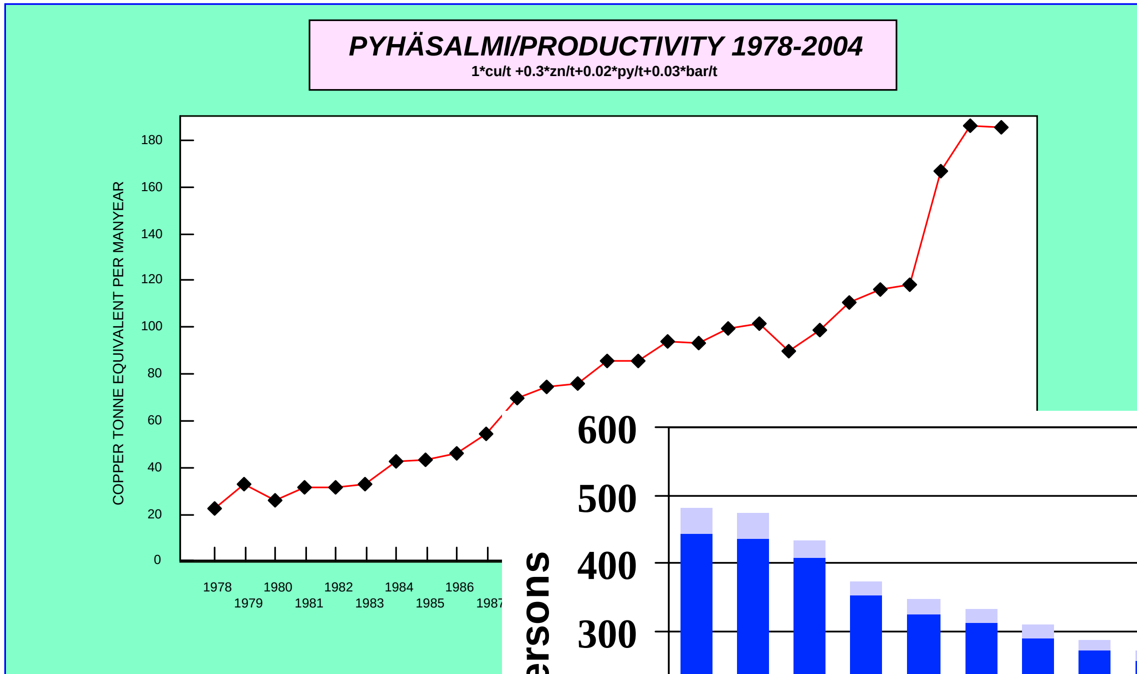
- Cybernetic balance among the needs and possibilities / savings and costs has not yet been reached at the plant
- There exist too many unknown variables and unknown dependencies among them
- And even if there existed knowledge, understanding is not deployed: There is no time/instrumentation to implement; finally, it would be too expensive – there are balances.

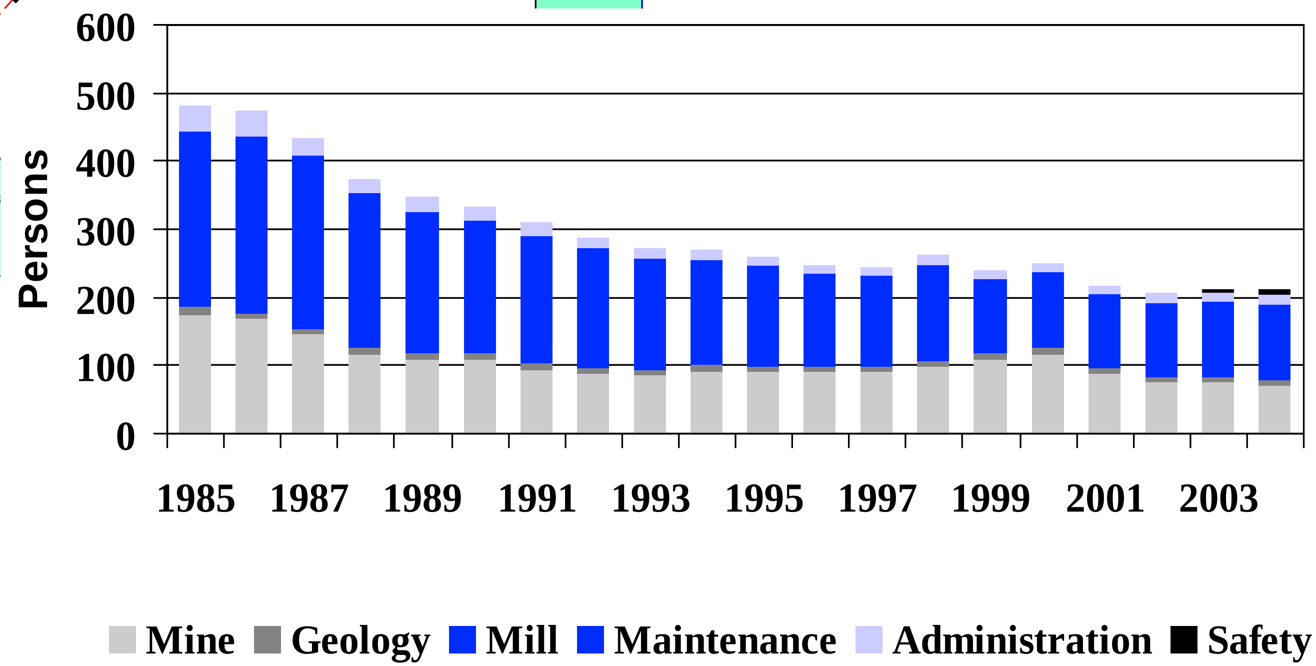
Humans (operators) in the control loop

- 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?

When service, etc., becomes part of the product life cycle, humans become once again important in the feedback loop

“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...