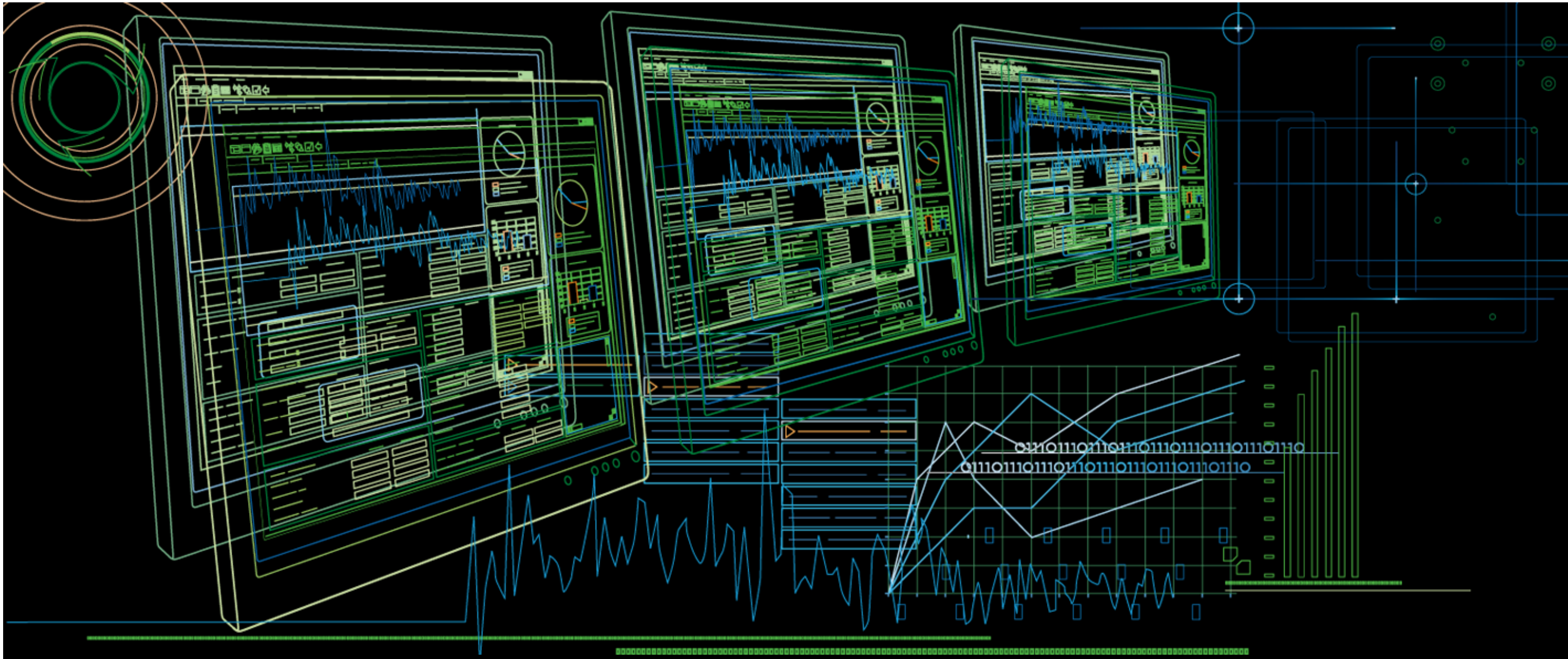

Michael Lundh (ABB), Sebastian Gaulocher (ABB), Henrik Lindvall (Boliden), Eduardo Gallestey (ABB)

Model Predictive Control for Flotation Plants

Content

- Technology
  - Model Predictive Control and its modalities
  - Implementation in cpmPlus Expert Optimizer
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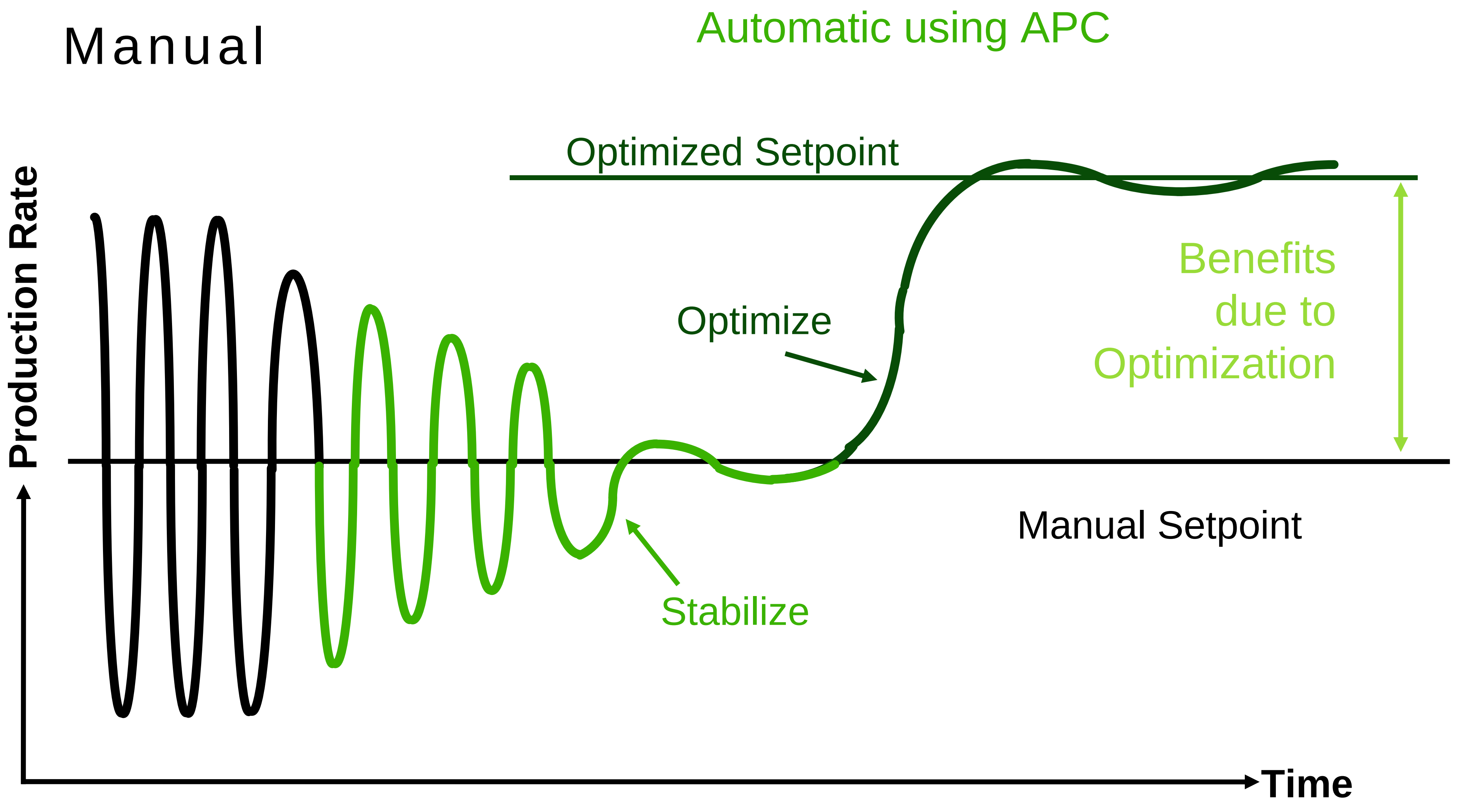
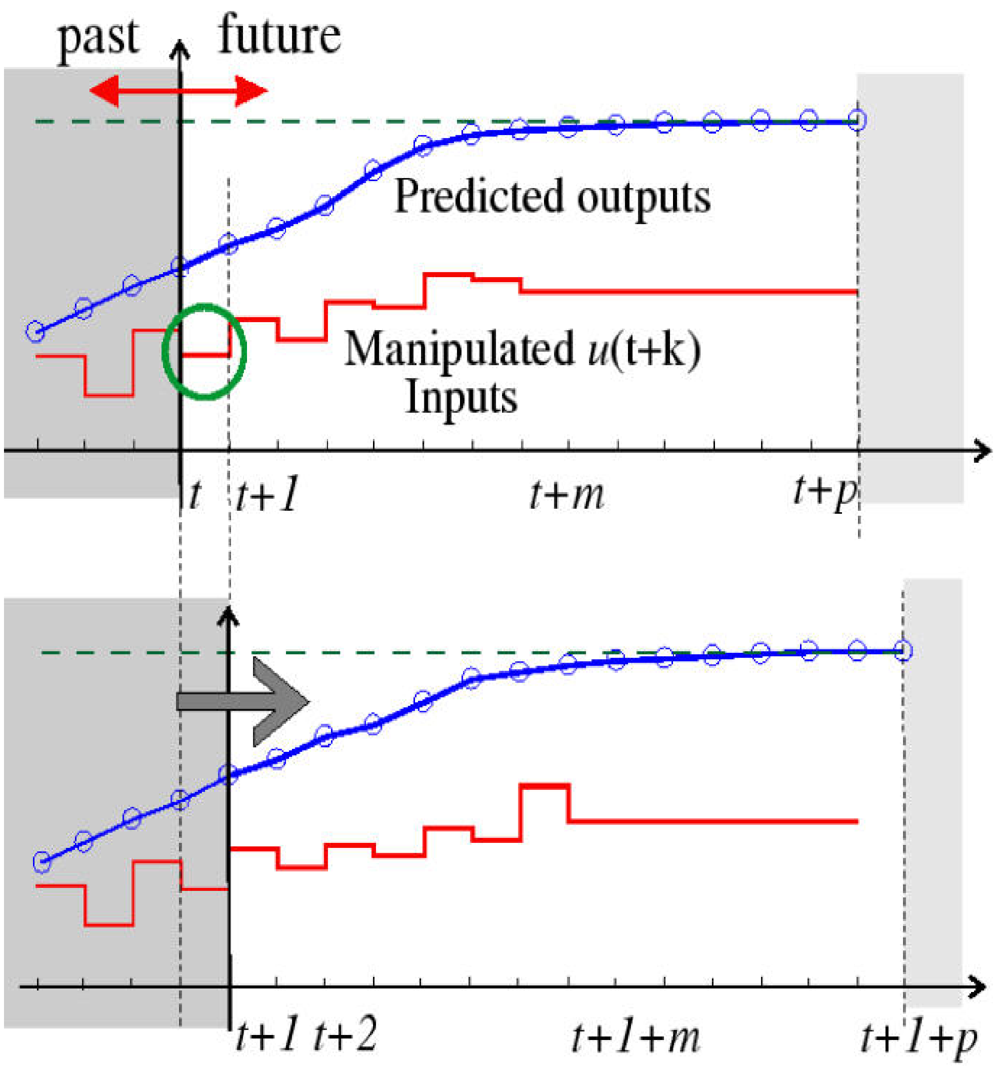
Stabilize then optimize



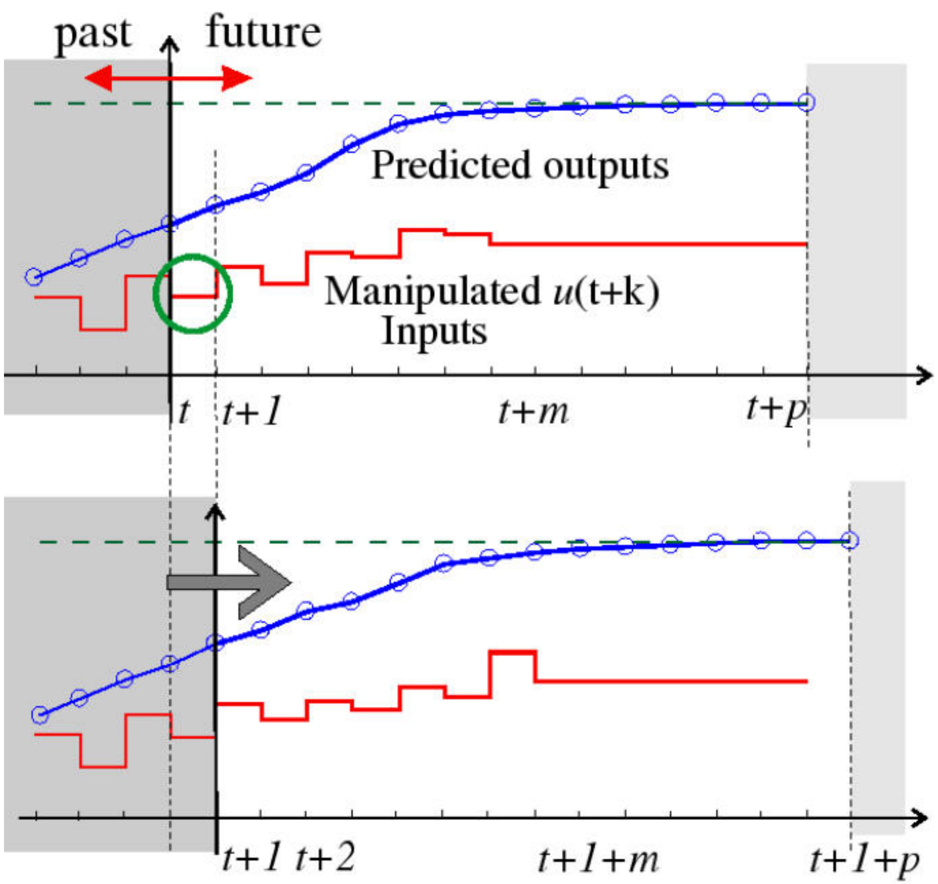
Model Predictive Control (MPC)

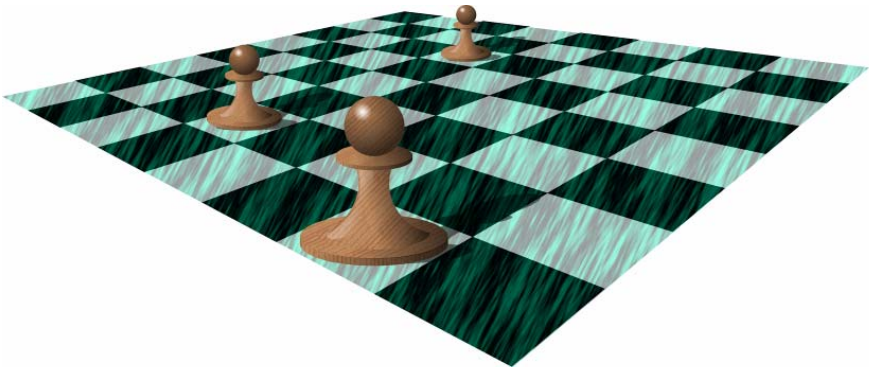


- Main ingredients are
  - Plant model
  - Objective Function
- Model used to predict system behaviour some steps into the future
- Cost Function used to decide which is the best strategy
- Requires solution of optimization problem at every sampling time
- Cost function is normally a sum of of linear and quadratic terms so as to guarantee convexity

Model Predictive Control (MPC)

1. Evaluate position (=measurement) and estimate system state
2. Predict sequence of future moves (mathematical algorithm, optimization) and select the best
3. Implement the first move (new actuator set-point)
4. Restart after the opponent moves (process reaction)





- Constraints are considered (allowed moves)
- A cost function drives the decision process (e.g. improve quality of the position)

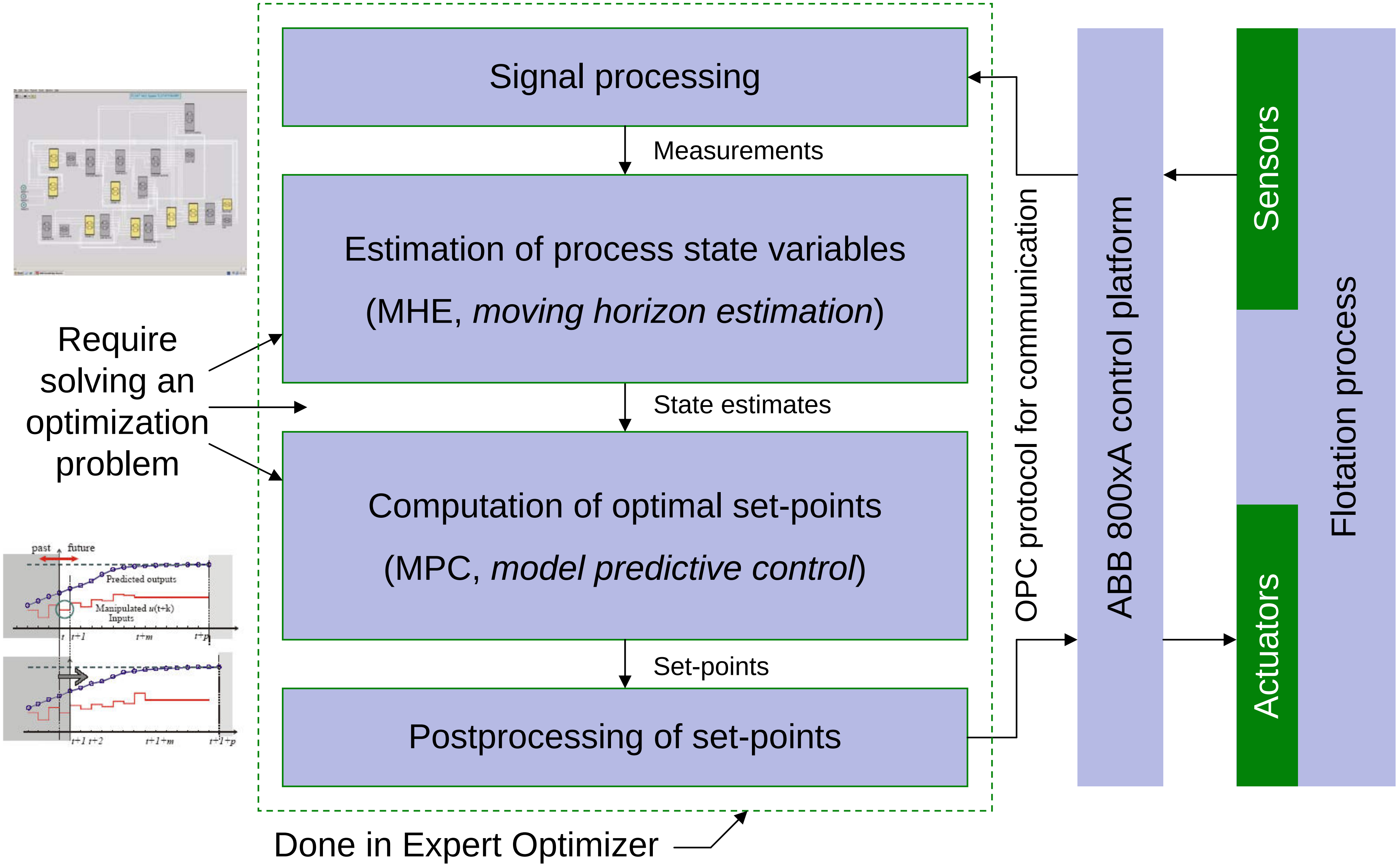
Modelling for Model Predictive Control
First Principles and/or Black Box Models

- Models are not necessarily high fidelity models
  - Comprise only magnitudes relevant for the control tasks
  - Often contain information related to gains, time constants, and time delays
  - Must predict only relevant time horizon as given by process time constants
- Two modelling paradigms
  - "First principle models": attempt to describe the relationships via equations based on process knowledge. Selected parameters are adapted online
  - Black Box models: models are generated by looking at plant data. Variables must undergo "excitation" for algorithms to work successfully

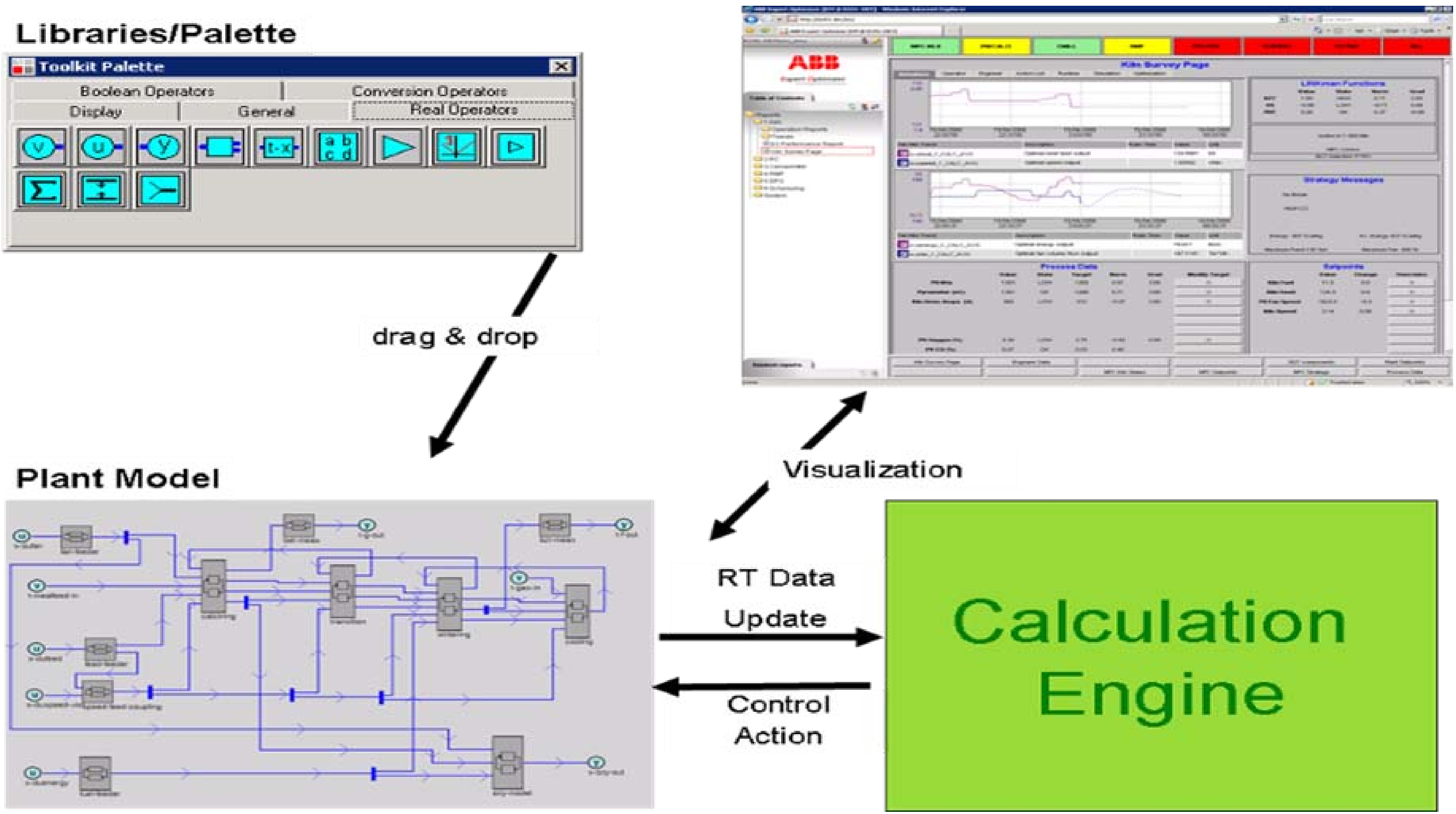
Expert Optimizer: ABB's advanced process control platform

- Successor of "Linkman" (Fuzzy Logic), but enhanced with Neural Networks and MPC technology
- DCS independent
- More than 300 installations worldwide
- Global Fuels Conference Award for "most innovative technology for electrical energy savings"

Implementation in Expert Optimizer



Expert Optimizer – Advanced Process Control Platform



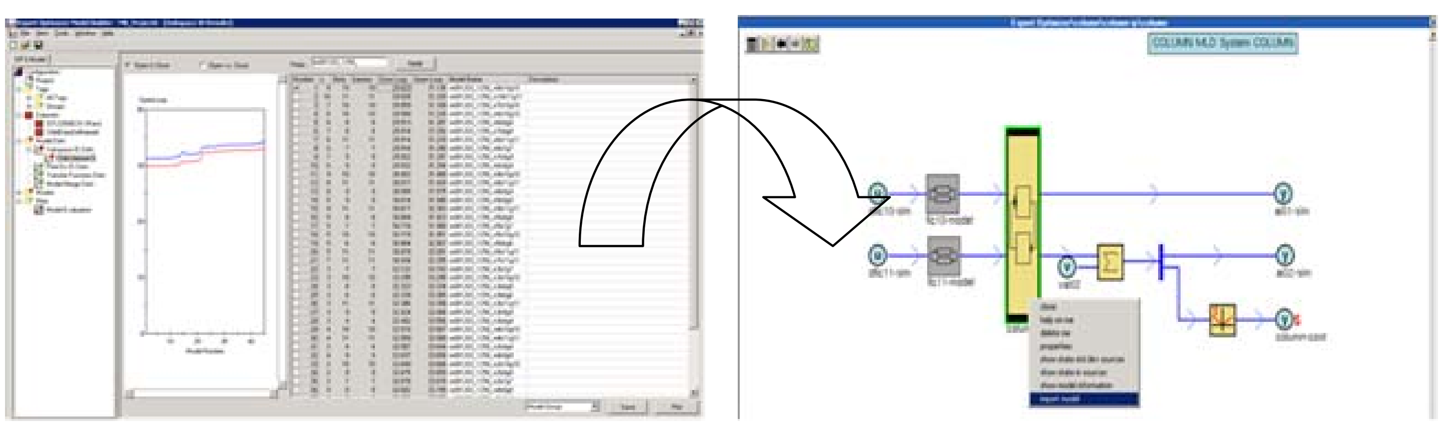
ABB

Model Predictive Control in Expert Optimizer

First Principles and/or Black Box Models

- Supports both modelling approaches
  - Model building by connecting blocks from a standard library or importing custom made ones
  - Cost function also designed in this form
  - Nonlinear models also supported
- Infrastructure for Black Box identification
  - Environment for handling data import and data set manipulation
  - Subspace identification for model generation
  - Model export with subsequent import in runtime environment

Offline | Real Time Environment



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Flotation: where are we and where do we want to go?

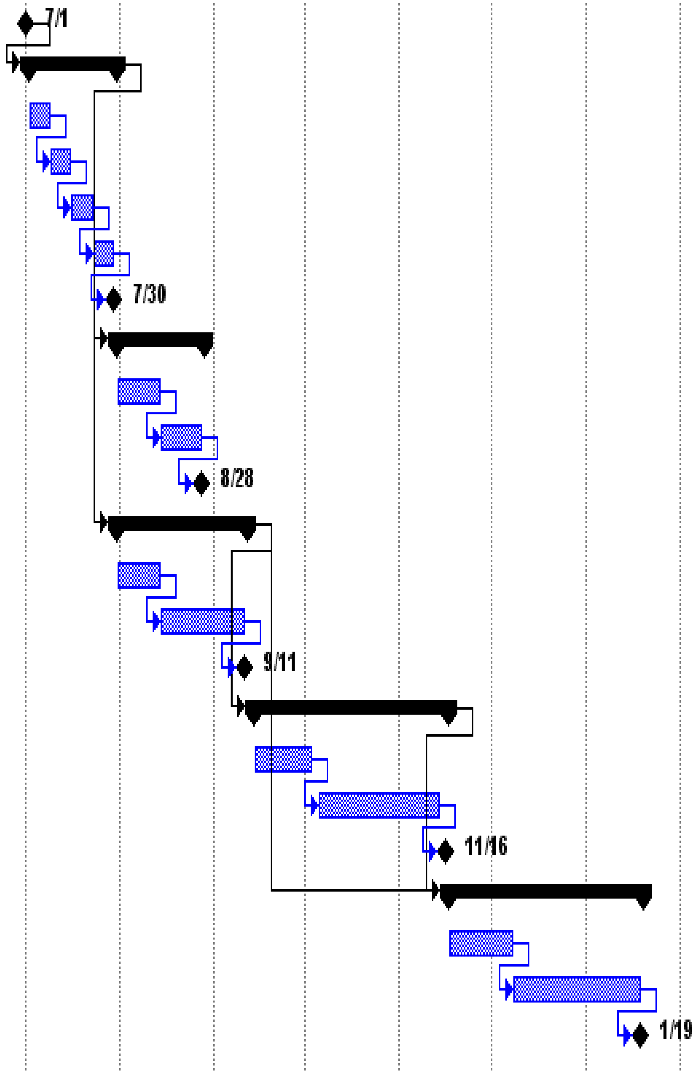
State of the art

- Manual control, intricate due to
  - dynamics (e.g. recirculating flows),
  - frequent feed variations (quantity and quality), and
  - operator shift changes
- No circuit-wide automatic control widely established

Objectives

- Maximization of plant output
- Observance of minimum concentrate grade
- Reduction of chemical reagent use
- Prevention of costly unplanned plant stops by respecting operating range of plant

Beneficiation Plant Project Phases



Feasibility Study

- Tech/Econ Feasibility Analysis
- Project Execution Plan
- Commercial and Technical Offer

Phase 1: Basic Automation Level

- Sensors and Actuators Assessment
- Loop Tuning and Monitoring

Phase 2: Circuit Level Control

- Strategy Configuration
- Commissioning

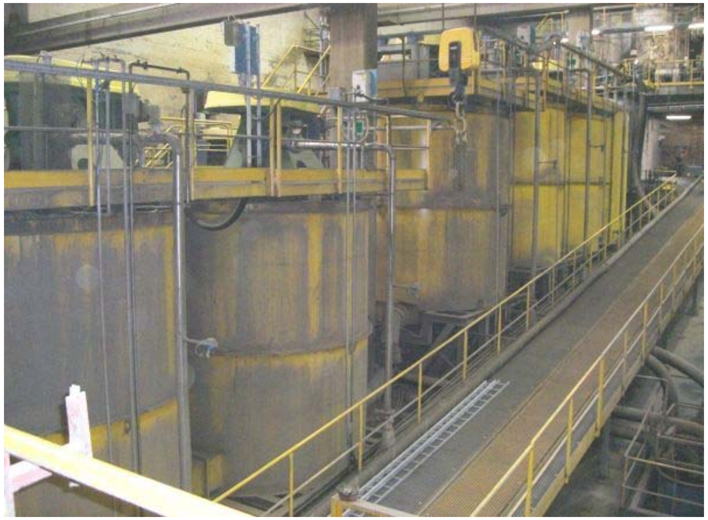
Phase 3: Flotation Optimization

- Civil Work
- Commissioning

Phase 4: Setpoint Optimization

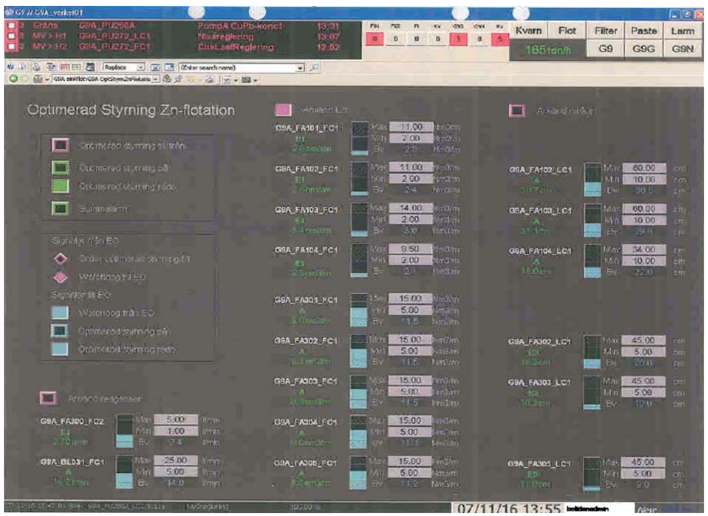
- Strategy Configuration
- Commissioning

Expert Optimizer for Circuit Level Control



- Objectives
  - Better control of the cell levels in the entire circuit
- Technology
  - Adjusting the valves between cells, using measurements of the cells levels
  - Multivariable control problem, solved using MPC technology
  - Model considers coupling between cells and the effect of actions with the valves on the entire circuit
- Benefits
  - More production
  - Better process stability
  - Quality as specified

Expert Optimizer for Flotation Circuit Control



- Objectives
  - Highest possible feed rate
  - Guarantee product quality spec.
  - Increase recovery
  - Reduce reagent usage
  - Prevent froth collapse or overfrothing
- Techniques
  - Model Predictive Control
  - Models
    - Froth Model
    - Slurry Model
    - Coupling between Cells
- Manipulated Variables
  - Reagents, Air Supply, Froth Depth
  - Cell Froth/Slurry Levels!

Next Step: Economic Process Optimization

$$J = Q_C \cdot F(x_C, x_C^{Fe})$$

- What have we achieved so far?
  - MPC controls concentrate and tailings to desired set-points.
  - However, not obvious which set-points to use.
- Method to find best set-points to maximize the value of the production.
  - Assume it is possible to control the flotation process to desired set-points
  - The value of the production depends on the amount of produced mineral, the purity of it, and its market price.
  - Static model of the flotation process as constraint for the optimization

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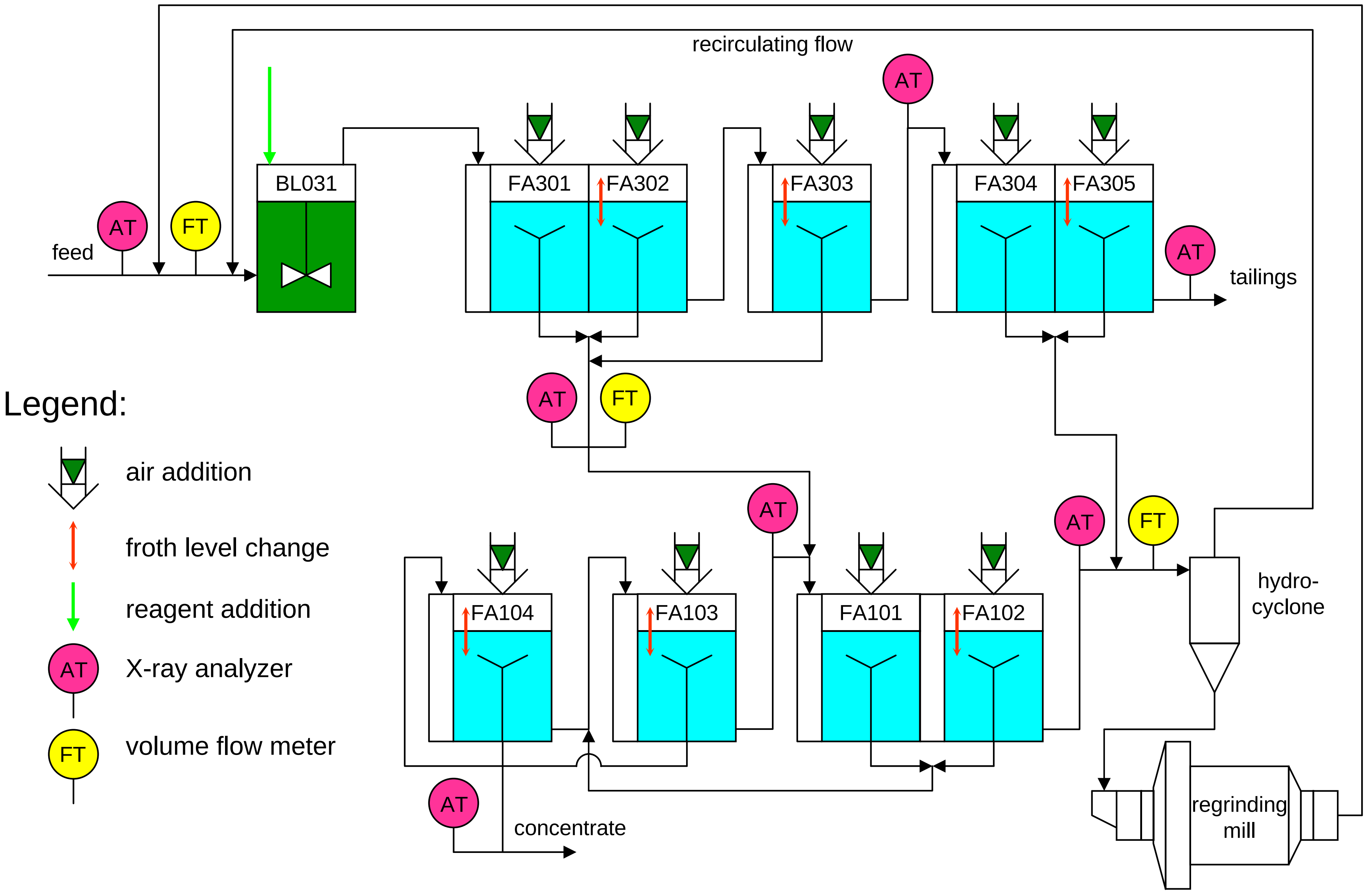
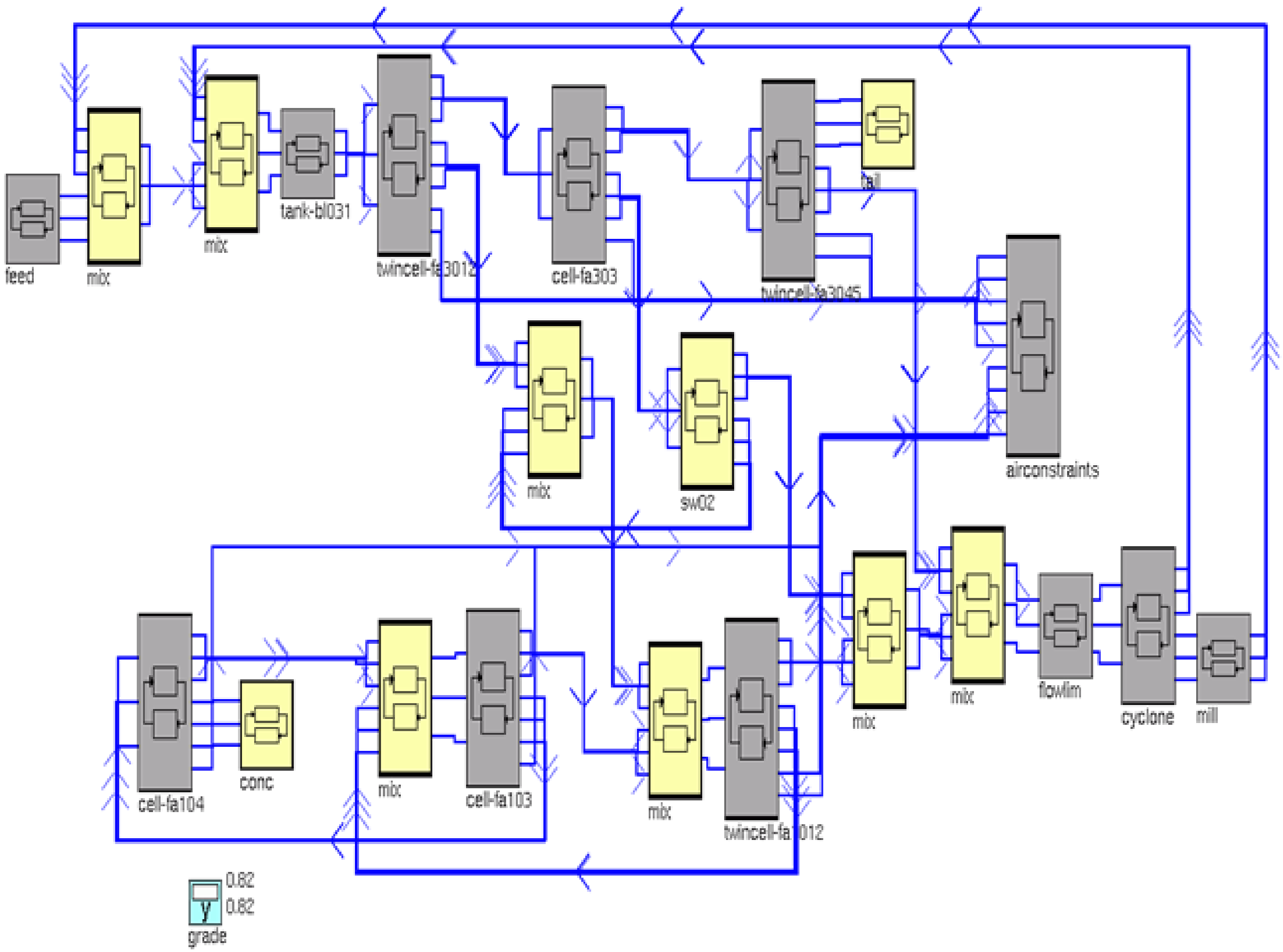
Customer Case: cpmPlus Expert Optimizer in Flotation

- Customer – Boliden, Sweden
  - Optimisation of Floatation Cells in Zn
  - Aim – Achieve better recovery at given grade
- Approach
  - a) Model using historical data
  - b) Model derived from first principles
- Manipulated Variables
  - Cell level control
  - Air Supply
  - Froth Level
  - Reagents

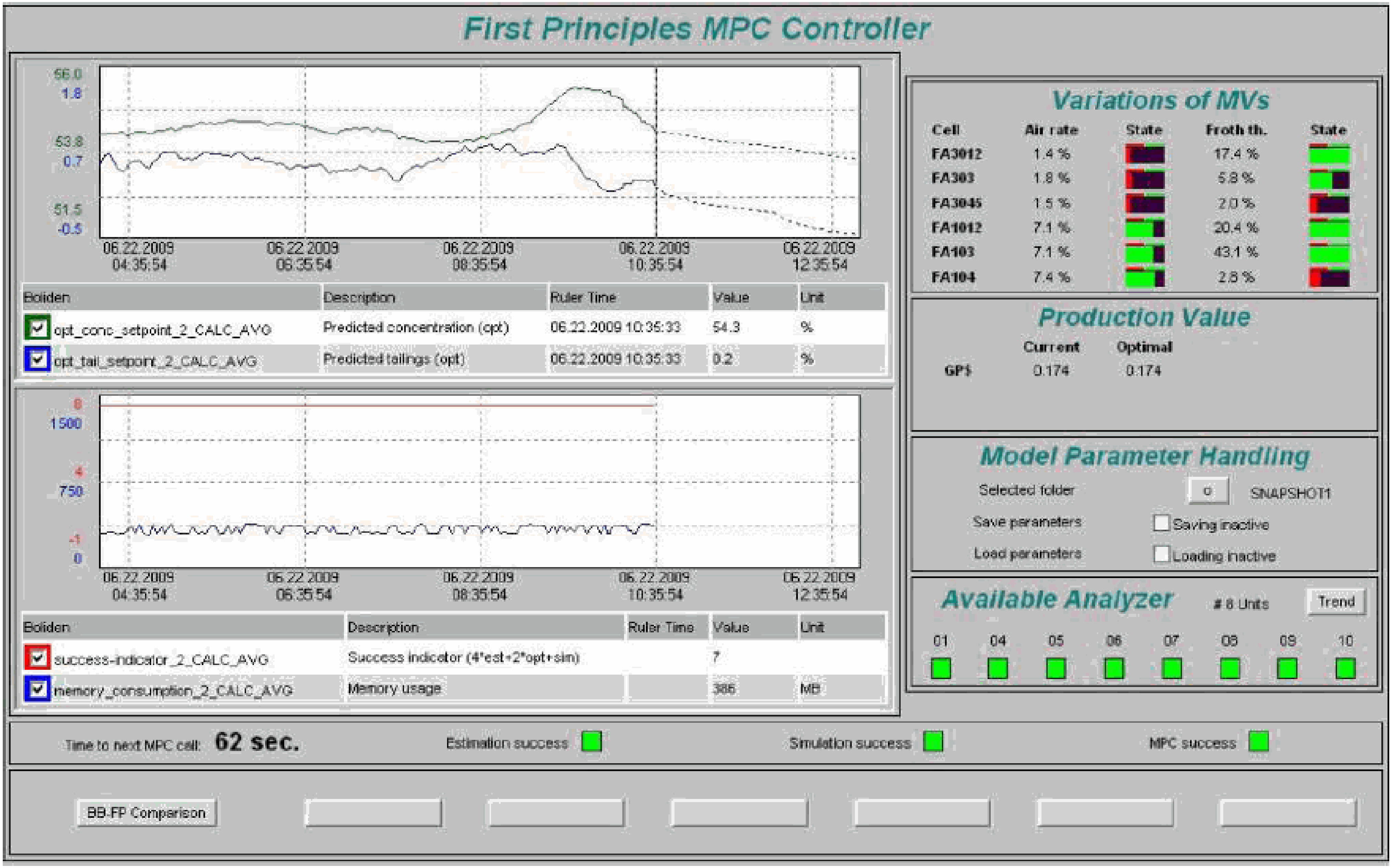
Manipulated and measured variables of a circuit



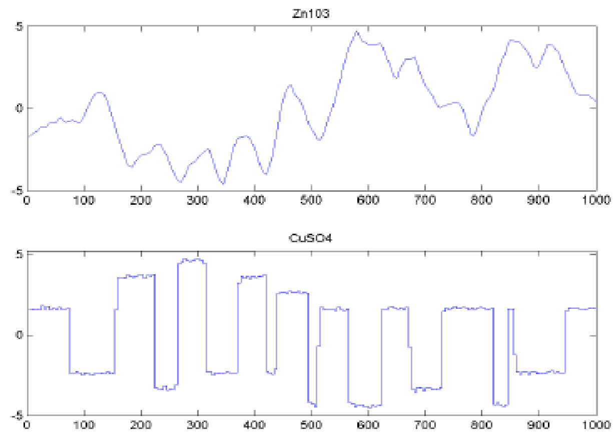
Controller Configuration in Expert Optimizer

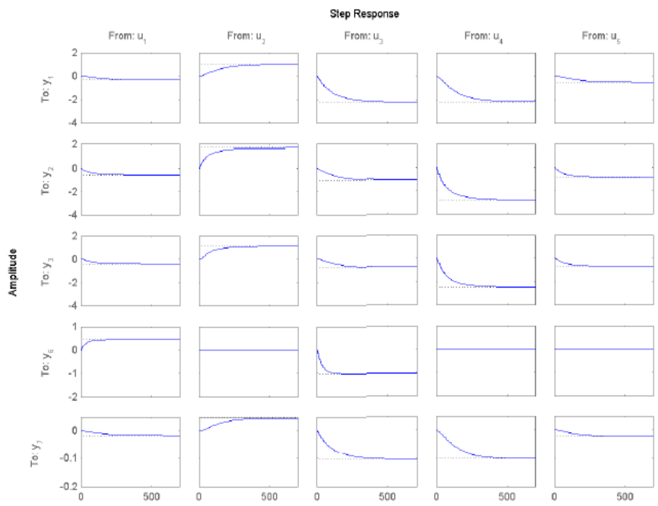


Thin Client User Interface in cpmPlus Expert Optimizer



Grey/Black Box Modeling approach





- Experimental phase:
  - What is done:
    - Plant actuators are moved in controlled manner
    - Reaction of process is recorded
  - Objective
    - Excite relevant process variables so that process dynamic becomes visible
  - Constraints
    - Plant conditions, cost and safety
- Modeling phase:
  - Selection of appropriate slices of data
  - Model generation
  - Delicate iterative process

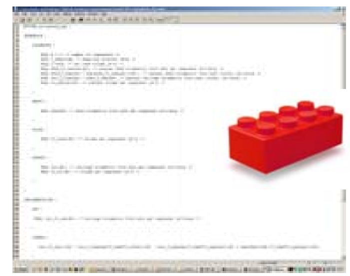
Linearised first-principle approach

The process model is

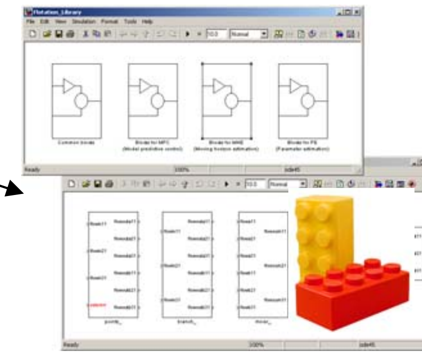
- Mechanistic (“first principles“)
  - Mass and volume balances
  - Pulp-to-froth transfer model
  - Variables: volumes and volume flows of relevant fractions
- Linearized about an operating point
- Generic and modular (component-wise):
  - flotation cell, mixing tank, …
  - analyzers, volume flow meters, …

→ Objectives:

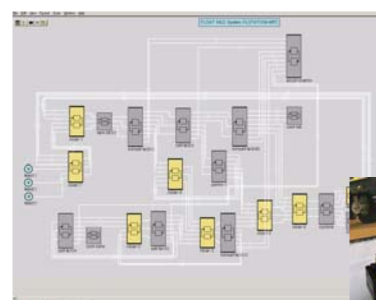
  → maintainability, reuse



Component model

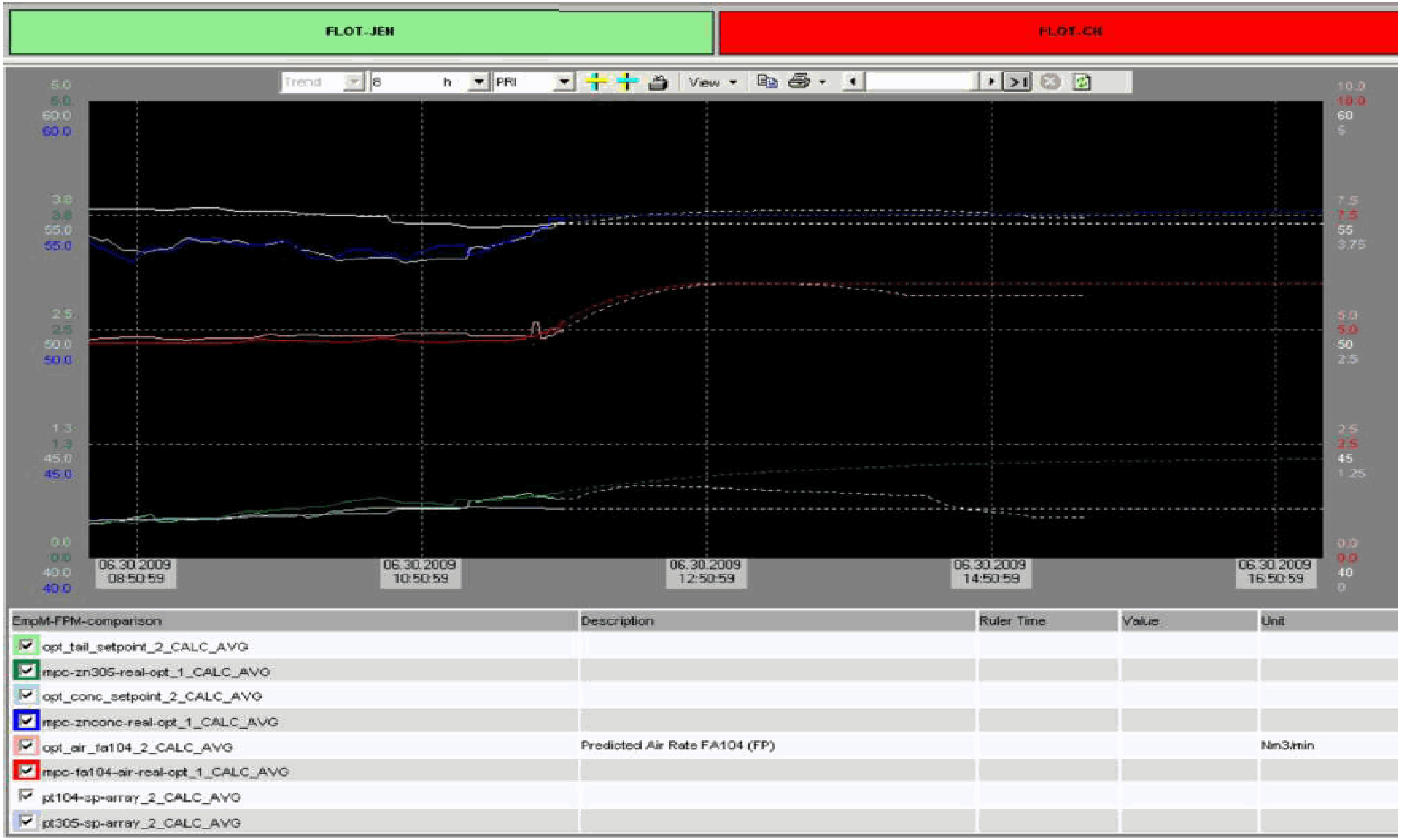


Component library



Circuit assembly in Expert Optimizer

Black Box versus First Principles

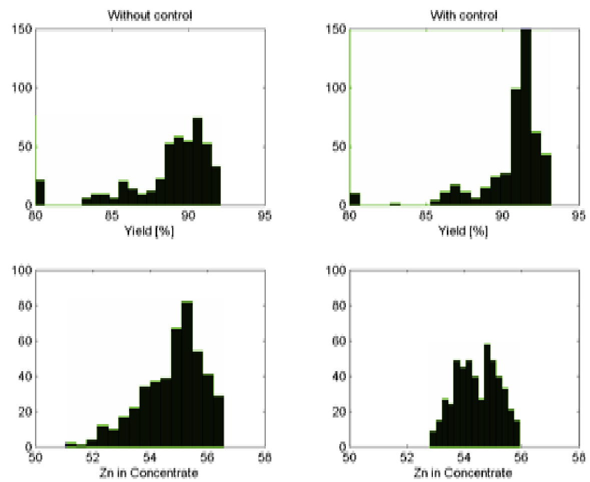


Steady State Model for Setpoint Optimization

$$J = Q_C \cdot F(x_C, x_C^{Fe})$$

- Value of the production depends on the amount of produced mineral, the purity of it, and its market price.
- Value function reflects the plant management objectives
- Static model of the flotation process as constraint for the optimization

cpmPlus Expert Optimizer delivers higher yields



	Input Zinc		Concentrate	Tailings	Yield	AE for Zn
	ton	%	%	%	%	%
On total	98385	7.17	53.57	0.55	90.61	88.34
Off total	121676	7.89	53.77	0.66	89.40	87.32
On 1 day	71000	7.66	53.53	0.58	90.60	88.28
Off 1 day	82826	8.07	53.58	0.71	88.74	86.52
On 2 days	22465	6.66	54.36	0.50	91.43	89.78
Off 2 days	27380	7.40	54.81	0.57	90.08	88.80

- Black Box approach currently more successful
- Several months on-line testing and comparison with existing manual strategy
  - One to two days on, then one to two days off, etc.
- Value
  - 1% Higher Yield
  - More consistent Zn concentrate
  - Improvement is at least one percentage unit
  - Millions worth

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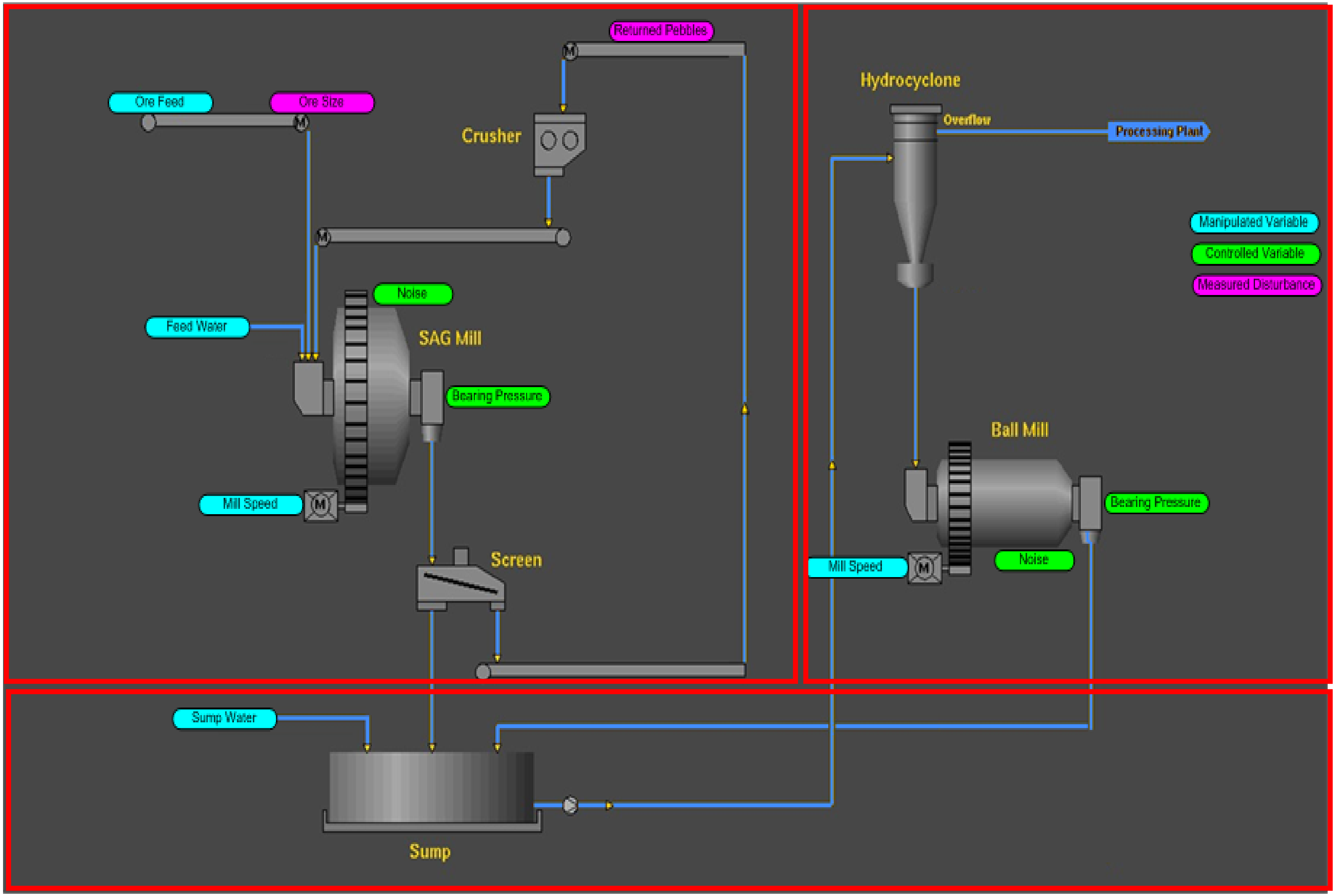
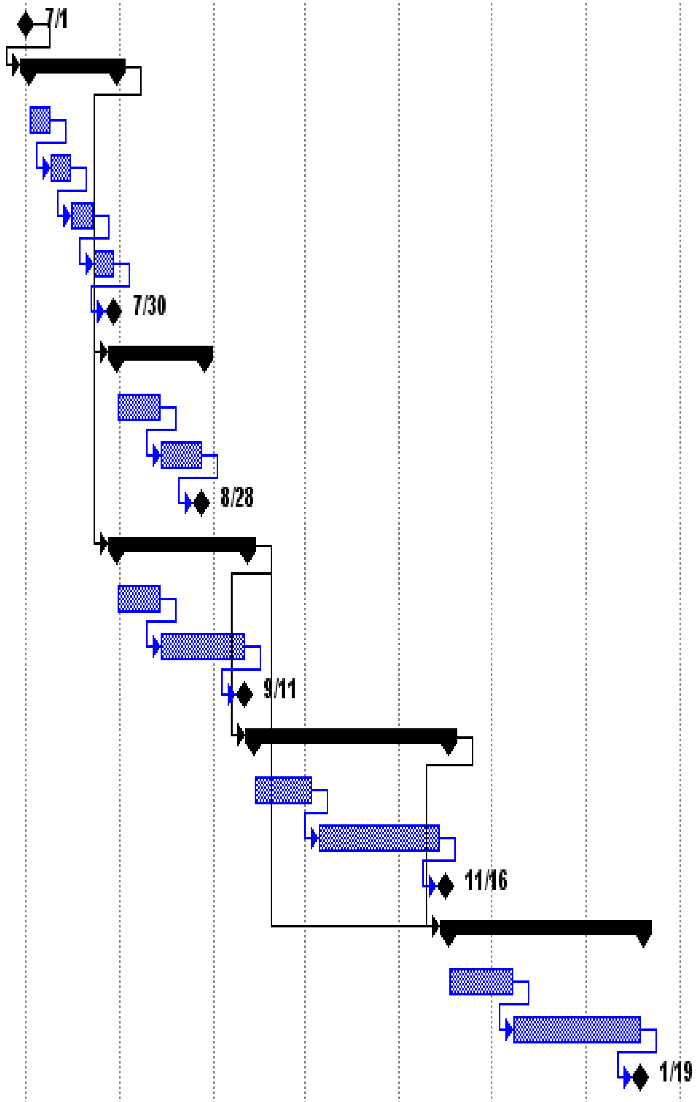
Grinding Circuit Optimization



Grinding Plant Optimization

- Customer Value
    - Better grinding efficiency
    - Protect mill from ball impacts and thus mechanical damage
- Project Data
    - Execution in 3 phases
        - Base Loops
        - Individual Mill Stabilization
        - Coordination thereof via setpoint optimization
    - Total duration 6 months.
- Technology
    - Modular approach
    - Simultaneous and timely manipulation of
        - Ore Feed Rate
        - Mill Speed
        - Slurry Density
    - to achieve
        - Power and Bearing Pressure inside targets
        - Reduced quality variability

Grinding Plant Project Phases



Feasibility Study

- Tech/Econ Feasibility Analysis
- Project Execution Plan
- Commercial and Technical Offer

Phase 1: Basic Automation Level

- Sensors and Actuators Assessment
- Loop Tuning and Monitoring

Phase 2: SAG Mill Control

- Strategy Configuration
- Commissioning

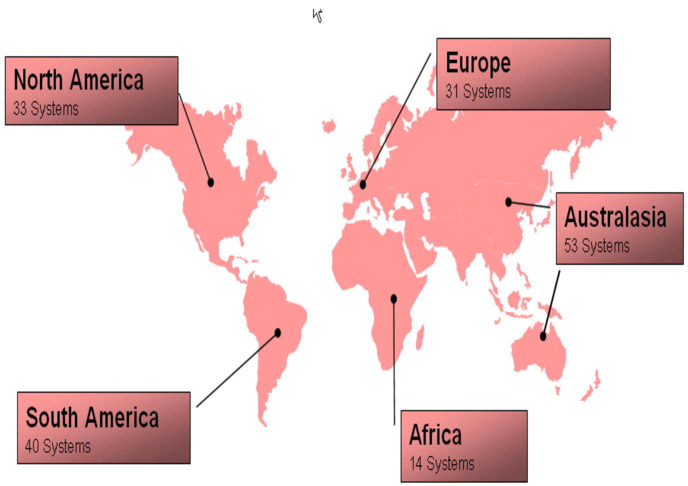
Phase 3: Ball Mill(s) Control

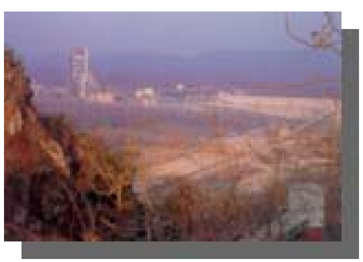
- Strategy Configuration
- Commissioning

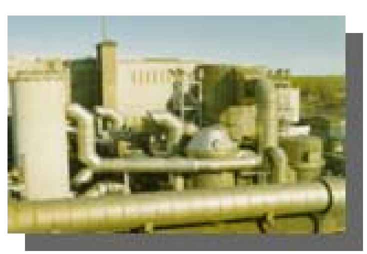
Phase 4: Grinding Circuit Optimization

- Strategy Configuration
- Commissioning

Customer Value with cpmPlus Expert Optimizer







- Value we deliver to customer
  - Increased Output **3% to 5%**
  - Reduced Fuel Consumption **3% to 5%**
  - Reduced Emission Levels **3% to 5%**
  - Reduced Electricity Consumption **3% to 5%**
  - Reduced Quality Variability **10% to 20%**
  - Reduced Refractory Consumption **10% to 20%**

- Customers
  - Oil & Gas
  - Pulp & Paper
  - Minerals, Metals
  - Industrial Power

Power and productivity
for a better world™

ABB