Model Predictive Control for Flotation Plants
Content

- **Technology**
  - Model Predictive Control and its modalities
  - Implementation in cpmPlus Expert Optimizer

- **Economic Process Optimization in Minerals Beneficiation Plants**
  - Goals
  - Technology
  - Project Phases

- **Case Study: Boliden Garpenberg, Sweden**
  - Plant, Modeling, Results

- **Other Advanced Process Control applications**
  - Grinding

- **Conclusions**
Stabilize then optimize

Manual

Production Rate

Automatic using APC

Optimized Setpoint

Benefits due to Optimization

Optimize

Manual Setpoint

Stabilize

Time
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 linear and quadratic terms so as to guarantee convexity
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

- Signal processing
- Measurements
- Estimation of process state variables
  - (MHE, *moving horizon estimation*)
  - State estimates
- Computation of optimal set-points
  - (MPC, *model predictive control*)
  - Set-points
- Postprocessing of set-points

Done in Expert Optimizer

Sensors

Flotation process

ABB 800xA control platform

Actuators

OPC protocol for communication

Require solving an optimization problem
Expert Optimizer – Advanced Process Control Platform
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

\[ J = Q_C \cdot F(x_C, x^{Fe}_C) \]

- 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

Legend:
- air addition
- froth level change
- reagent addition
- X-ray analyzer
- volume flow meter

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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
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

- 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