Plant-wide optimization of a copper smelter: how to do it in practice?

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Abstract

Optimizing complex industrial processes, such as copper smelting, accurately has proven to be challenging with traditional methods. The process includes combinations of interlinked continuous and batch unit processes and further many of the control actions require manual actions from the process operators. Changing process bottlenecks and other limitations in real life have meant that the process is not necessarily operated optimally. The traditional closed loop Model predictive control (MPC) methods cannot be used in such applications until the level of automation is increased significantly. To unleash the full potential of the smelter and to meet the future demands for sustainability, efficient plant-wide model-based control is needed. In the first phase such tools can be implemented as advisory systems guiding and supporting the human operators in their everyday decisions. Coordinating Optimisation of Complex Industrial Processes, or COCOP, a project born under the European Union’s Horizon 2020 and the SPIRE initiative, aims to tackle this challenge. In this paper methods under development in COCOP for optimisation of a copper smelter including plant-wide control and unit process advisory tools, are introduced and discussed. The main focus of the paper is in describing the development work relating to the optimisation of the Peirce-Smith unit process.

Introduction

The mining and metals industry has been challenged with the declining productivity and the more complicated ore bodies and feed materials, while it’s getting harder and harder to secure talented workforce and to meet the environmental requirements set by the governments and the neighbouring communities. The processing facilities need to become more efficient in a more challenging business environment. Increasing the level of automation, implementing advanced process control and taking the next big step in digitalization are becoming more and more viable solutions for the industry.
Automation and digitalization have already proven to be beneficial in improving the productivity of industrial operations [1,2]. McKinsey & Company studied the technical potential for automation in United States and in different industries and the results show what many knew already by intuition: the potential for automation is amongst the highest in the mining industry [3]. Based on their study the two of tasks with the biggest potential for automation were data collection and predictable physical work where 21% and 17% of the total working time was used respectively. If we add this with the potential for improving process efficiency with advanced process control the potential savings for the industry are surely in the scale of billions of dollars globally.

The Coordinating Optimisation of Complex Industrial Processes project (COCOP) is a European project under the Horizon 2020 framework and the SPIRE initiative, whose objective is to enable the plant-wide monitoring and control by using model-based, predictive, coordinating optimization concept in integration with local control systems. As such it will enable the process operators to improve their understanding of the plant as a whole and to support their daily work by giving important advices and instructions on how to improve the current process efficiency. The project has two pilot cases, where the COCOP solution will be implemented in practice. This paper focuses on describing the development behind the COCOP’s Copper-smelting pilot case from a technical perspective. [4]

**Copper smelter description**

The general process flowsheet of the copper smelter used for piloting the COCOP solution is presented in the figure 1. The main raw materials are sulfidic copper concentrates that are first blended to feed mixture and then dried before processing. Flash Smelting Furnace (FSF) and Peirce-Smith Converters (PSC) are in the heart of the operation. The FSF is a continuous process where feed mixture is oxidised to copper-rich sulfidic matte and oxide slag with low copper content. The matte and slag are collected to the settler part of the furnace as separate layers and tapped out to ladles batch wise. The PSCs operate as batch processes where the matte is first oxidised in a sequence of slag blowing steps to white metal (mainly Cu$_2$S) and oxide slag is skimmed after each blowing step. This is followed by a copper blow phase where the white metal is oxidised to blister copper. In this phase copper scrap is also added as coolant. Blister copper from PSCs is then fire refined to anode copper in Anode Furnaces (AF). Fire refining in AFs is another batch process including a final oxidation, reduction and anode casting steps. The copper in FSF slag and PSC slag is recovered in slag flotation as slag concentrate, which is then recirculated to the FSF as part of the feed mixture. The slag at the end of the copper blow and after the oxidation step in AF are circulated directly to an empty converter. SO$_2$ rich off-gases from FSF and PSCs are ducted to the acid plant and processed to sulfuric acid.
Control challenge description

The copper smelter includes continuous and batch processes which affect each other. Each unit process has its own operators and own control room. The feed mixture feed rate to FSF and copper content in FSF matte (matte grade) are the main parameters affecting the overall processing. The feed mixture composition is subject to changes. The matte grade affects slag blowing times and the copper-in-slag content in the PSC. Feed rate affects the overall schedule and overall production rate. The circulated slag from AF or from copper blow shortens the required slag blowing times and increases copper content in PSC slag but has a cooling effect as well. The actual bottleneck of the production can change (for example from acid plant capacity to availability of PSCs) which makes it really challenging for the operators to maximize the FSF feed rate against the actual bottleneck of the process.

Maintenance operations on the plant equipment make the optimisation challenge even more difficult. For example, during a 6-hour maintenance break preventing anode casting operations, what should the target feed rate for FSF and the PS converter schedule for the coming hours be until the situation is normalised? Additionally, process operators generally tend to introduce human buffer just to be on the safe side from the process limits, e.g. by lowering the FSF feed rate and delaying the converter batches more than necessary.
There are also other aspects in plant-wide control such as the operators do not necessarily consider ongoing or predicted special conditions in the next processing step. For example, if large amount of slag from an anode furnace is circulated to an empty PSC, the target matte grade in FSF should be lowered for a period to compensate for the effect to the PSC batch. All aspects like this might have a significant effect on the process performance and as such have to be taken into account in plant-wide control.

**Plant-wide optimisation and scheduling of copper smelter**

The overall COCOP idea to copper smelter optimisation is to introduce two level model-based control where the upper level coordinates the unit processes while unit processes are controlled by unit process advisor tools. The coordinative level calculates the future schedule of batch processes for the PSC and AF and the main parameters affecting the overall operations: the feed rate and target matte grade in the FSF. Unit process advisor tools will enable model-based control for the unit processes keeping the process operator in the loop. Both levels will contribute to the optimisation targets: increase production, increase copper recovery and decrease emissions and increase, for example, brick-lining lifetimes. The results of the optimisation algorithm are presented to the operators in visible and understandable way; for example, the future converting schedule can be visualized in Gantt charts, showing suggestions for control parameters and the simulated process status as individual trends.

The coordinative level utilizes simplified process models which only include the mass balance of the main elements. This enables utilization of mixed integer linear programming (MILP) in solving the coordinative level scheduling problem allowing very fast calculation times. Each unit process advisor includes a detailed model with the relevant minor elements and heat balance. State estimation is implemented in unit process advisors and they provide improved state information to the coordinative level. Heat balance optimisation of the FSF is taken into account in the coordinative level indirectly by including a cost to the target function based on FSF state estimation to avoid so low matte grade feed rate combinations that additional fuel would be required in the FSF. Heat balance restrictions of the Peirce-Smith Converters and Anode Furnaces are implemented as constraints to blowing time steps based on the estimated state of the unit processes. Acid plant capacity is implemented as a constraint for produced SO₂ amount. Slag treatment is taken into account indirectly in the target function as a penalty to amount of high in copper slag. A simplified architecture setup is presented in the following figure.
Figure 2: Simplified software architecture

The communication between different layers enable iterative calculation of the plant-wide optimisation with updated constraints from the unit process level. The communication approach of the COCOP solution is introduced in more detail by Kannisto et al (2018) [5].

MILP solution

Few scheduling results for copper production have been previously reported in literature. Heuristic optimization procedures have been used in [6] and [7]. The use of a MILP solution has been previously reported in [8]. Our chosen scheduling solution employs a continuous time mixed batch-continuous MILP solution to optimize the plant schedule. This follows the general form of combining batch and continuous processes from [9]. The mathematical formulation is to be published. The use of a MILP solution enables fast updating of the current schedule and ensures good operability for the users. A MILP solution does not allow the full models for converter stages to be considered but the approach allows the parameters to be updated and schedules to be quickly recalculated.

The converters are operated in parallel where depending on the current state of the plant different stages are not allowed to overlap. A typical converter batch consists of multiple loading stages before a slag blow after which more FSF matte is loaded and another slag blow is carried out. The second slag blowing step is followed by a short unloading stage before the copper blow stage, which is then followed by a final unloading of the blister copper to anode furnaces. Below, a typical converter batch sequence is shown with $L$ denoting loading stages, $SB$ denoting slag-making blows, $UL$ denoting unloading stages and $CB$ denoting the copper blow. Arrows ($\rightarrow$) denote idling stages:

$$\rightarrow L \rightarrow L \rightarrow SB \rightarrow L \rightarrow SB \rightarrow UL \rightarrow CB \rightarrow UL$$
Depending on the capacity of the converter an appropriate sequence is chosen. Operating times of parallel batches are determined by incorporating the following types of constraints.

- Logistical constraints which ensure the converter aisle cranes are available for transfer of material between processes.
- Sequencing constraints ensuring subsequent processes are available when needed. These also ensure parallel operations use shared resources in a feasible manner.
- Volume constraints of the different units disallow certain operating sequences. Production rates are constrained by the minimum and maximum capacity of the FSF.

In situations where the capacity of the acid plant is restricted, the scheduling can pause the copper blow for the duration of the parallel slag blow. The production rates of the FSF and the lengths of the different processing stages are optimized using continuous variables though some stage lengths and parameters are set as constants for the optimization.

Figure 3 shows the result of an optimisation over 7 converter batches with a case where anode furnace operations are not a bottleneck. Here, the problem has 307 variables, 664 inequality constraints and 7 equality constraints. The solution time is about 2.2 seconds. The problem was solved in Matlab with Matlab’s solver. Here the first 24 hours are shown. Notably, converter 2 is paused during the copper blow of the latter batch to allow for the first slag blow to be carried out in converter 3 where the acid plant capacity would have been over its limit.

![Figure 3: MILP optimized converter schedule and matte mass in FSF settler](image)
Unit Process Advisors

The unit processes considered in the COCOP solution are the FSF, PSC and AF. The focus in this paper is in the PSC Process Advisor development, especially in the modelling and control of the slag blowing step of PSC processing where the optimisation is more challenging. Each Unit Process Advisor may also be used individually without integration to the plant wide control. FSF Process Advisor has been introduced several years ago under the name Outotec® Process Advisor for control of FSF operations [10,11]. Nowadays FSF Process Advisor is widely used in control of FSF processes all around the world with numerous success stories reported [12,13]. As an addition to model based control of the FSF, FSF Process Advisor can be utilized in feed mixture blend planning from different concentrates, which plays a central role when calculating suitable future operating parameters for FSF and suitable future matte production rates affecting the PSC and AF schedule. FSF Process Advisor can be integrated to the coordinative optimisation concept of a copper smelter.

PSC Process Advisor

PSC Process Advisor helps the operators to optimise the converter operations by introducing control suggestions for the next slag blowing steps. These include suggested silica flux amounts, blowing times, oxygen enrichment and revert amounts. The overall optimisation targets are to reduce copper content in slag and increase the life-time of bricks by improved temperature and slag chemistry control and optimised blowing times of different processing steps. The main principle is to control slag blowing times so that most of the slag is removed before Fe-% in matte (white metal) decreases below 2 wt-% as after that the copper content in slag increases rapidly and some metallic copper will start to appear in the slow-cooled slag. The other targets are to have optimal Fe/SiO₂ ratio in slag to have a low slag liquidus temperature and to have suitable temperature (just ~20 °C above the slag liquidus temperature) at the end of a blowing step. Sometimes the above cannot be reached due to the start conditions meaning a longer than optimal blowing time must be accepted to be able to increase the temperature. It can be assumed that improved temperature control will decrease attrition of the bricks increasing the time between re-linings. It is also expected that improved blowing time control will reduce copper losses to slag.

The PSC Process Advisor is implemented in Outotec® Advanced Control Tool (ACT) platform and utilizes a process model implemented in Outotec HSC Sim dynamic unit. The required precondition for the implementation is that the smelter can provide local online access to the process data (through OPC connection for example). In addition to the standard flow, pressure, level and temperature measurements, this includes information from the overhead cranes and laboratory analyses.

The PSC Process Advisor includes a crane data handler unit that interprets the crane data and sets the correct material inputs and outputs to converter models. It also provides a smoothed state estimation calculation of input FSF matte composition and temperature. This is used because the matte
analyses are provided with differing delays and not all the ladles are usually analysed. When a new analysis is received the state estimate of past matte composition is updated and the ongoing PSC batches are recalculated with the updated input matte composition and the temperature of past matte ladles.

Modelling of PSC converter

The PSC process has been modelled with HSC sim dynamic unit where material is stored in ideal mixing tanks. In the model, within a certain time step, a portion of material reacts and the outcome is returned to the mixing tanks. There may be several parallel reactions in the model. The PSC model contains tanks for matte phase, molten slag phase, solid slag phase, blister phase, unreacted solid material phase, build-up on the refractory wall and the refractory layers. The heat transfer between the tanks is taken into account in the model. One benefit of utilizing HSC sim models is that the model automatically keeps the mass and heat balance.

The reaction unit in PSC model utilizes Gibb’s energy minimisation calculation to enable fast calculations. Target kappa functions (Me-% in matte / Me-% in slag) and (Me-% in blister / Me-% in slag) were identified based on previous knowledge and analysis from test batches as function of Cu-% and Fe-% in matte or oxygen-% in blister copper. Activity coefficients formulas were identified as functions of Cu-% and Fe-% in matte or oxygen-% in blister, temperature and slag Fe/SiO₂ ratio to reach target kappa, i.e. Me-% in matte / Me-% in slag, functions based on analyses from test batches. This gives adequate data fits when the minor element shares are not varying a lot.

One of the challenges has been in modelling of the heat balance when converter is cooling down during waiting and heating again up during blowing. Usually at the smelters there can be relatively long waiting times between the batches. Anode slag and oxide slag from the end of the copper blow step are also often charged to an empty converter. If no auxiliary burners are in use, the converter will cool down and the circulated slag will start to solidify. After the matte ladles have been charged and the blowing is started, the temperature increases and solid slag will start to dissolve to the molten slag produced from the oxidation reaction.

To include slag solidification to the model, liquidus temperature calculations for the slag were carried out with MTDATA 6.0 software package [14,15]. Thermodynamic parameters for this chemical system were obtained from MTOX 8.2 database for oxide and sulfide systems [16,17]. The calculations were performed at different Fe³⁺/Fe²⁺ and Fe/SiO₂ ratios. Copper oxide content and minor metal oxides (PbO, ZnO, NiO and CoO) were selected according to average dependencies from Fe³⁺/Fe²⁺ and Fe/SiO₂ in the analyses from the test batches. Elements originating from silica sand flux, like Al₂O₃, CaO, K₂O, Na₂O and MgO, were placed in constant relation to SiO₂. Based on the calculated liquidus temperatures and which phase was the primary solid phase, formulas were fitted to the liquidus temperatures of spinel, olivine and tridymite phase as function of Fe₂O₃/Fe, Cu₂O and Fe/SiO₂. This procedure could be improved by varying some minor components also freely. The fitted formulas were then used in the model to implement slag solidification and melting. The melting is implemented as follows: if the simulated slag temperature is lower than calculated liquid-
dus temperature, slag material is transferred from molten slag to solid slag phase, and, if higher, the opposite way.

Simulation results

Figure 4 presents simulated inner temperature and brick temperature in layers during a converter batch including waiting time between the batches. Figure 5 presents masses of a converter batch where the left curve represents masses of matte, blister, slag and scrap, and the right curve is a zooming to the slag mass. Figure 6 presents simulated compositions. In the simulation, circulated end slag and anode furnace start to solidify before the first slag blowing step and there remains some solid slag (as magnetite) during the whole operation due to lack of silica flux and low temperature due to relatively long waiting times. The simulation also shows there has been blister copper already during the slag blowing step due to reaction between matte and circulated slag, which means that the copper losses to slag have been high. In such conditions the process performance could have been improved if FSF matte grade had been lower.

Figure 4: Simulated temperatures over a converter batch including waiting time. Line 1 represents the inner wall temperature, line 2 the material average temperature, line 3 the middle wall temperature and line 4 the outer wall temperature.
Figure 5: Simulated masses during a converter batch. Left curve: matte (1), blister (2), slag (3) and scrap (4). Right curve: slag (5), solid slag (6), silica flux (7) and front wall slag (8).

Figure 6: Simulated compositions during a converter batch. Left curve: matte Fe % (1). Top right curve: % Cu (2), Fe/SiO2 (3) and Fe3O4/Fe (4). Bottom right curve: % Cu (5), Fe/SiO2 (7) and Fe3O4/Fe (6).

Giving control advises for PSC converter

The PSC Process Advisor does not require operator interactions, but the control calculations are triggered automatically from events like matte ladle measurements. Control calculations are also performed beforehand utilizing the schedule of the future incoming matte ladles from the coordinative controller. The control suggestions like amount of silica flux, amount of reverts and blowing time for the next slag blowing step can be visualised in the existing DCS screens. Additional dedicated user interfaces are made with Outotec ACT to be able to follow the simulated values in more
detail. The PSC process advisor presents simulations as a soft sensor for parameters that are not measured like the amounts of matte, slag and blister copper, Fe-% in matte, Fe/SiO₂ ratio in slag, temperature and the slag liquidus temperature. The tool also covers the relevant minor element contents throughout the processing and finally in blister copper.

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