Copper Production as an Application of Optimization and Scheduling

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ABSTRACT

Copper production in a copper smelter is a process comprised of batch and continuous production tasks. Typically, subprocesses have been operated in a locally optimal way though significant interdepecies exist. In general, copper production presents a harsh environment where production is often disturbed by unforeseen events and frequent maintenance operations. Optimization of production is further complicated by the significantly differing timescales with recycling of some materials. This work presents first the main production tasks related to copper production and then details requirements and procedures in modelling the full task with the goal of producing models suitable for a global scheduling solution. The main scheduling decision variables are detailed and a simplified example of scheduling two converters is included. The scheduling and optimization is to provide operators with advice on timings and resource use to maximize equipment use and production throughput. The solution structure may be viewed as a combination of scheduling and predictive control techniques. By considering material inputs over the complete production cycle, the optimization is to provide improvements especially in impurity control.

1 INTRODUCTION

Copper production is a complex process consisting of many interconnected subprocesses. Following the route of different mineral components through the production chain is a challenging task. Further, copper production presents a harsh environment which is often disturbed by unforeseen events and commonly requires frequent maintenance. Measurement data is often lacking, insufficient, or lags behind the actual process due to the harsh and difficult environment. Copper production includes both batch and continuous production tasks with many tasks of substantially different timescales introducing further complexity.

The main production tasks in copper production are batch tasks. Scheduling, which provides operators with advice on timing and resource use, can be used to improve operation /1/. As schedules often need to be provided quickly or updated often, process models are typically linear or linearized allowing for use of mixed integer linear programming (MILP) techniques. Automating the scheduling of process steps and providing decisions on the use of different material inputs can provide, for example, a better end product, safer operation, and increased throughput.

In this presentation, we briefly describe the process through the main production steps, define the main decision variables for a plantwide advisory system, and describe what modelling approaches and model structures these require. This system is to be applied to improve a Finnish copper production plant. These ideas have been successfully applied to copper making in /2/; in contrast, here we seek to provide a more comprehensive handling of, mainly, the relevant process impurities.

1.1 Process description

In general, copper production can be described as the separation of materials into matte and slag with an objective of having most of the copper in the matte. These materials have different densities and separate such that slag can be removed. Notably, metals are in sulphide form and SO_2 gasses are produced during most stages.

The main production steps in copper production are:

- Mixing of a suitable concentrate mix with silica flux (20–30% Cu)
- Smelting of the concentrate in a flash smelting furnace (FSF). Matte (~65% Cu) is moved to converters and slag is processed further in the slag concentrate plant.
- Pierce-Smith (P-S) converters remove the remaining sulphur and iron through injection of oxygen-enriched air. The plant runs with three converters hot and one in maintenance rotation. Two converters can be at blowing stage at the same time. Air blowing is broken into the slag-making stage, where most of the iron is removed, and the coppermaking stage, where the remaining sulphur is removed. This results in blister copper with a copper content of ~99%. In the slag-making stage, various materials (e.g. silica flux, scrap metal) are used to control temperature and viscosity. The reactionary conditions control how much copper moves to the matte and to the slag. Scrap with a high copper content is used during the coppermaking stage as cooling material to avoid formation of end slag with a high copper content. Converter slag is also processed in the slag concentrate plant and the recycled to the FSF.
- Anode ovens process the blister copper with natural gas to remove any remaining oxygen. The resulting material has a copper content of ~99%. This is cast into anodes and transported for further processing in an electrolysis plant. Any slag produced in this stage is recycled directly to the converters. Spent anodes are shipped back to the copper making plant for use as scrap in the converters after electrolysis.

The main decision variables consist, first, of the timings of different production tasks. These relate mainly to the times and lengths of converter blows. Their timings are constrained primarily by the capacity of the sulphur acid plant which is used to process the generated gasses. The timing of converter use must also take into account the availability of anode ovens close to the conclusion of each batch. Second, decisions on the concentrate mix and the use of different cooling material and other materials, mainly during converter operation, greatly influences the quality of blister copper (i.e. copper produced by the converters), matte and different slags in terms of copper and impurity content. Transfer of materials is performed using shared cranes and has to be carefully considered in a full scheduling solution. Further, the copper content objectives for each stage can be somewhat varied. By considering the complete production chain the influences of each change on other production stages can be better taken into account.

The main motivation of model based online optimization is to increase the actual net production by increasing the efficiency of the smelter. Increasing the net production of a copper smelter will increase the operating profit heavily since the fixed costs will remain the same but income is related to production throughput. Figure 1 describes a typical example of actual yearly net feed rate to a flash smelting furnace compared to the theoretical maximum. Optimization will increase the average production rate when the concentrate feed to the FSF is on. However, it may also decrease the effect of the maintenance stops. This may happen if a production stop is caused by sudden maintenance work in a process unit and other operations are optimized so that full capacity is achieved in the restricting unit as soon as possible after the maintenance work is complete.

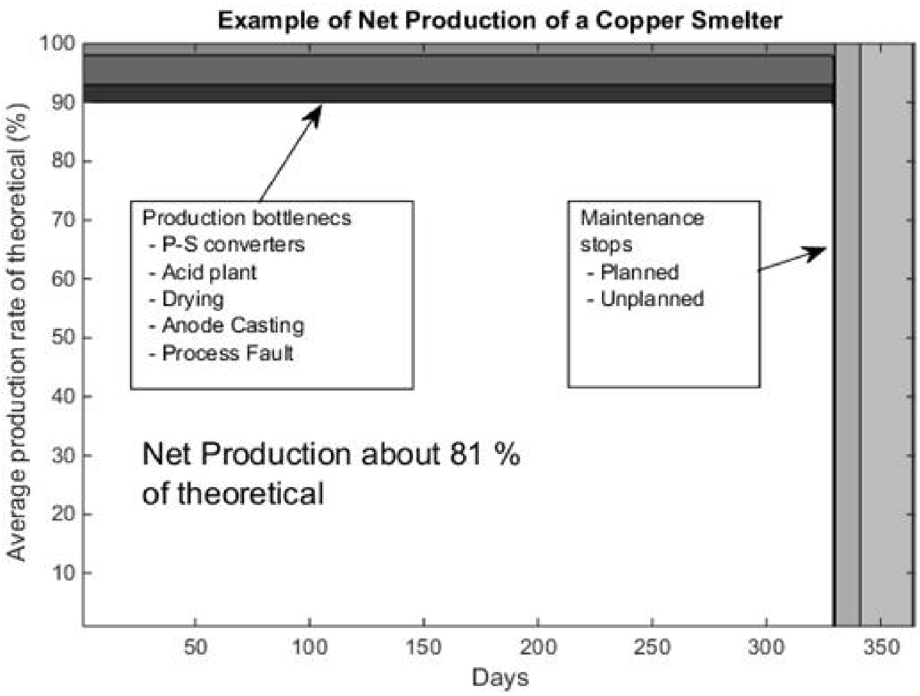

Figure 1. Net production of a copper smelter with influence of production bottlenecks and maintenance

Smooth operation is usually preferred by the operating personnel of a copper smelter. This leads to the feed rate of the FSF occasionally being restricted notably more than is necessarily required by the capacities of the other production units and their optimal scheduling. This may happen especially in process conditions where the actual bottleneck is related to batch operations like anode furnaces, anode casting or P-S converters. This will then likely lead to unnecessary wait times in other the process steps due to an overtly conservative scheduling. Additionally operators may decide that, for example, in the situation when the acid plant has reduced capacity for SO_2 gasses, the feed rate of the FSF is restricted every time two simultaneous P-S converter blows are required. However, in this case it would be possible to decrease the target matte grade of FSF matte lowering the SO_2 produced there and thus increase the time two P-S converters are simultaneously blown. Another task is to control the impurities, such as Ni, As, Sb and Bi, in the anode copper. This can be done by controlling the amount of some secondary materials to FSF and P-S converters, optimizing the concentrate mixture and through some operating practises in the anode ovens and the P-S converters that also affect copper recovery to anodes.

2 MODELLING METHODS

A predictive scheduling and control solution must be capable of estimating the relevant process components as governed by the aforementioned decisions. This requires the careful formulation of mass and energy balances. A model based on the reactionary kinetics, such as /3/, can be used to define the mass transfer rates between matte, slag, and gas flows for different elements. These models should, to a sufficient degree, define the relevant time, temperature, and composition dependencies.

Compositions with the prevailing temperatures define transfer rates from matte to slag. These are generally available for the FSF in literature and have been studied extensively in industry. The transfer rates allow for definition of SO_2 gas production as well which is one of the main bottlenecks for the production. Temperature information is required to keep equipment in good operating states or when, for example, the concentrate mix is defined as it needs to fulfil certain requirements such that additional heating oil is not required. Temperature between batches should also be followed such that converters are not allowed to cool nor heat up too much.

A full model of the reactionary kinetics would provide the dynamic model for mass transfer rates for at least both the FSF and P-S converter. Existing FSF models are to be used in this work. The models related to P-S converters on the other hand have not been as extensively published or used and require first principles based modelling. A first model and simulator based on /3/ has been constructed. Both the FSF and P-S converter models are to take into account impurities which have not typically been measured or modelled. A first measurement campaign has been carried out and its results will be used to augment and validate existing knowledge.

Dynamic models in their basic form are, however, too computationally heavy for the large calculations required in scheduling solutions. For example, many kinetic models make use of Gibbs energy minimizations which in any optimization have to be approximated. For scheduling use, the models should tie the used material amounts linearly to the required batch times. The material amounts should also predict SO_2 production and temperatures.

3 CONVERTER BATCH SCHEDULING EXAMPLE

This section presents an example of scheduling a system consisting of a FSF and two converters which feed their production to one anode oven. A discrete time model is used. Time points $\{t_0, t_1, \dots, t_H\}$ are spaced evenly with $\delta t = t_k - t_{k-1}$ the same for all k. The subscript k is used below to denote the time step. The mass balance of the FSF is defined such that over each time increment a continuous feed $\mu_{F,k}$ is added to the mass volume and when batches start in converter 1 or 2 a predefined amount is removed. The input feed is limited by a maximum and minimum limit and further the difference between consecutive input feed values is limited. This allows for a smoother response than a simple limit on the input feed values. Converter batch starting times are defined with binary allocation variables $X_{C1,k}$ and $X_{C2,k}$ which are set to 1 when a batch starts and zero otherwise. Converter batch sizes are denoted by m_{C1} and m_{C2} and are fixed in this example. The FSF mass balance $M_{F,k}$ is then defined as:

$$M_{F,k} = M_{F,k-1} + \mu_{F,k}\delta t - X_{C1,k}m_{C1} - X_{C2,k}m_{C2}. \quad (1)$$

Though not used here, parameters can be defined for ratios of matte moved to converters and slag to processing.

To illustrate how overlapping operations can be forbidden, converter use is limited such that only one converter is allowed to be in use during the first blow. These times are denoted T_{B11} and T_{B12} for converter 1 and 2 respectively. The full batch time is denoted T_{B1} and T_{B2}. The following constraint defines that only one converter batch may be in production in each converter at a time. For converter 1 this may be written as:

$$\sum_{k'=k}^{k+T_{B1}} X_{C1,k'} \leq 1. \quad (2)$$

Additionaly, converter 1 is not allowed to start a batch if the first blow is ongoing in the second converter:

$$X_{C1,k+T_{B12}} + \sum_{k'=k}^{k+T_{B12}} X_{C2,k'} \leq 1. \quad (3)$$

The anode oven use is handled with the binary allocation constraint $X_{A,k}$. Each anode oven batch takes time T_A. Thus the anode oven is reserved by constraint:

$$\sum_{k'=k}^{k+T_A} X_{A,k'} \leq 1\,. \quad (4)$$

Further, the anode oven batch is required to start at the end of each converter batch:

$$X_{C1,k+T_{B1}} - X_{A,k+T_{B1}} \leq C\left(1 - X_{C1,k}\right), \quad (5)$$

where the constant C is some large positive value. Though not stated here, a constraint is also set to force alternating of converter use and to force the same amount of anode batches as converter batches.

The objective is defined as the sum of mass processed by the converters which maximizes production throughput. Figure 2 depicts the result of an optimization run. In this case the solution is provided in ~60 seconds. A drawback of the discrete time method used here is the large number of required variables and constraints which leads to very large problems. In this example 501 variables were used with about 1500 constraints.

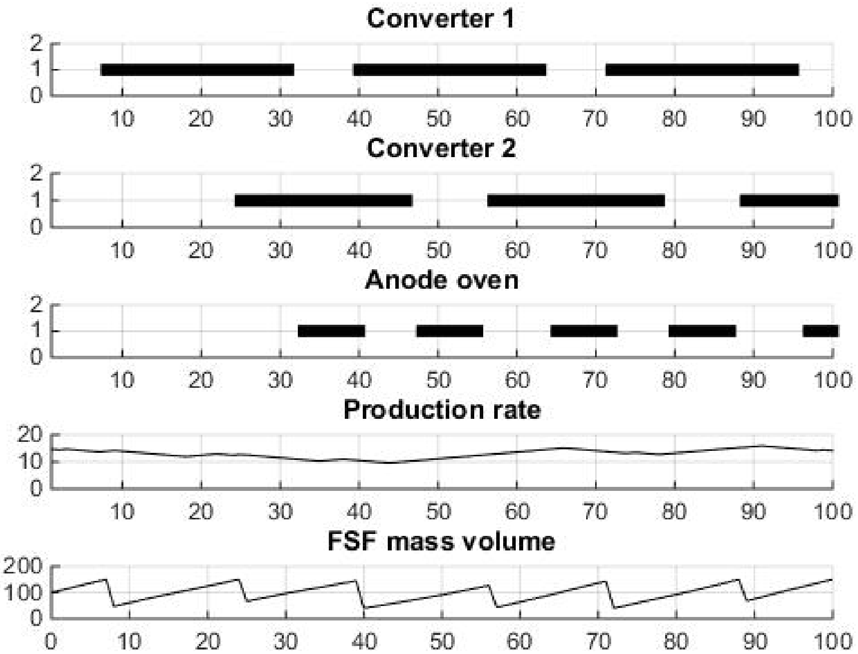

Figure 2. Example of scheduling converter operation and optimizing production rate. Black bar shows when production is ongoing

5 SUMMARY

Optimization and scheduling of copper smelter operations can increase production and provide a better end product. The main decision variables include material inputs in each stage including recycled materials, timings of converter batches and their lengths. The interdepencies in production are to be modelled using first principles models and existing knowledge. Dynamic models are, however, too computationally heavy for the large calculations required in scheduling implementations where updates are needed relatively often and results should be presented to operators quickly. This requires models to be linearized or approximated otherwise. A scheduling example consisting of a smelter, two converters and an anode oven was presented.

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