System dynamics and discrete event simulation of copper smelters

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Abstract

Discrete event simulation (DES) is an appropriate framework for the plant-wide analysis of copper smelters. These smelters apply a common set of chemical reactions: copper-iron sulfides are blasted with oxygen-enriched air, sending the iron into a slag phase and the sulfur into the offgas. Moreover, conventional copper smelters exhibit similar operational dynamics: a smelting furnace operates continually, feeding into an alternating set of converters that produce batches of blister copper. The thermochemical and operational commonalities of copper smelters are integrated within the DES framework. This serves as a common basis to begin evaluating the system dynamics of individual smelters. For complex problems, the simulation framework should be developed in phases, incorporating feedback from different personnel who have complementary perspectives. Sample computations are provided in this paper based on the Hernán Videla Lira smelter, whose production is constrained by meteorological conditions.

Minerals & Metallurgical Processing, 2017, Vol. 34, No. 2, pp. 96-106.
An official publication of the Society for Mining, Metallurgy & Exploration Inc.
https://doi.org/10.19150/mmp.7510

Key words: Copper, Smelting, Converting, System dynamics, Discrete event simulation

Introduction

World copper production is approximately 18.5 million t/y (Brininstool, 2015), worth $80 billion a year. Out of this total, 75 percent comes from the pyrometallurgical processing of sulfide minerals (Fig. 1), which occurs in copper smelters. The remaining 25 percent is from the hydrometallurgical treatment of oxides and complex ores (Rotuska and Chmielewski, 2008), which uses solvent extraction and electrowinning.

The current paper describes the pyrometallurgical processing, recognizing that the underlying thermodynamics and kinetics are well known (Degterov and Pelton, 1999), with the notable exception of minor element transport, such as arsenic (As), antimony (Sb), bismuth (Bi), silver (Ag), gold (Au). The latter is an ongoing area of research, as smelters are faced with increasingly complex ores (Devia, Wilkomirsky and Parra, 2012; Swinbourne and Kho, 2012). This paper focuses on the system dynamics of copper smelter operations, which has received considerably less attention than the chemical thermodynamics and kinetics.

Smelter engineers and managers may contribute to the sustainability of their plant by improving their understanding of operational system dynamics. Indeed, we have prompted smelter improvement projects (Navarra, 2016; Navarra et al., 2016; Navarra and Mendoza, 2013) simply by adapting methodologies that are commonly used in other sectors. These previous works incorporate principles from computer-integrated manufacturing (Groover, 2000) and theory of constraints (Dettmer, 2007), featuring the use of discrete event simulation (DES).

DES is commonly used to analyze manufacturing systems (Mourtzi, Doukas and Bernidaki, 2014), but is relatively new to copper smelters (Coursol and Mackey, 2009; Mourtzi, Doukas

Paper number MMP-16-060. Original manuscript submitted May 2016. Revised manuscript accepted for publication December 2016. Discussion of this peer-reviewed and approved paper is invited and must be submitted to SME Publications Dept. prior to Nov. 30, 2017.

and Bernidaki, 2014; Navarra, 2014; Navarra and Mucciardi, 2015). DES can represent the changing conditions of a smelter using an adaptive time scheme, in which the simulated clock advances in discrete steps from one event to the next. This provides an efficient framework to evaluate operational policies, such as scheduling practices (Navarra, 2016) and alternate modes of operation (Navarra, 2014). It has also been used to evaluate plant layout and logistics (Wheeler and McGinty, 2015), and to quantify the operational impact of an equipment upgrade (Navarra and Mucciardi, 2015).

On a fundamental level, copper smelters are described by the oxidation thermodynamics of molten sulfides and slags (Sohn, Kang and Chang, 2005; Fan et al., 2006). An additional level of detail is provided by chemical kinetics, permitting the efficient design of furnaces (Coker, 2001b). Thermodynamic and kinetic principles are thus used to optimize the interior workings of individual unit operations.

The system dynamics of copper smelters is an additional level of analysis that is like “another kinetics.” For instance, a poorly designed reactor may not provide effective contact between incoming streams, thus hindering the reactions: this is inefficient chemical kinetics. Analogously, the poor coordination of equipment, such as furnaces or material conveyors, may cause a production slow-down: this is inefficient operational dynamics. Chemical kinetics occurs within the smelter equipment, whereas operational dynamics occurs among the equipment.

The current paper presents DES as an adaptable framework for copper smelter analysis, which can encapsulate the system dynamics of copper smelters, in addition to the underlying thermodynamics and kinetics. Often, the most revealing aspects of a DES model are due to multidisciplinary efforts that extend the thermochemistry into a wider-reaching context. Also included is a description of a particular application developed in collaboration with the Hernán Videla Lira (HVL) smelter, whose rate of production is constrained by meteorological conditions.

Copper smelter operations

Smelting, converting and refining. A copper smelter forms a hub within the copper value chain (Fig. 2), linking the mining sector to the diverse sectors of construction and manufacturing. The smelter receives sulfide concentrates from several mine sites to produce copper anodes, which are then transferred to an electrorefinery that produces copper cathodes. In many cases, a copper smelter is integrated with a local mine or electrorefinery, in addition to rail or port facilities.

The sulfide concentrates arrive at the smelter in the form of

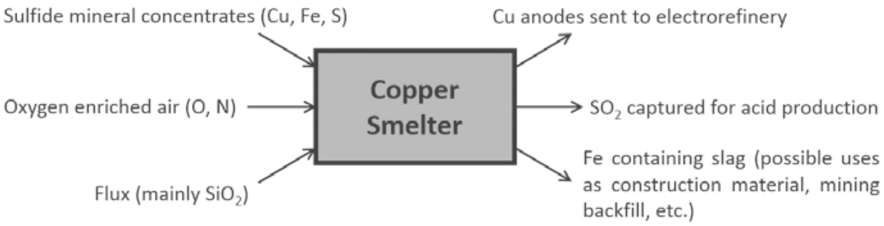

Figure 1 — Pyrometallurgical processing of copper-bearing sulfide mineral concentrates.

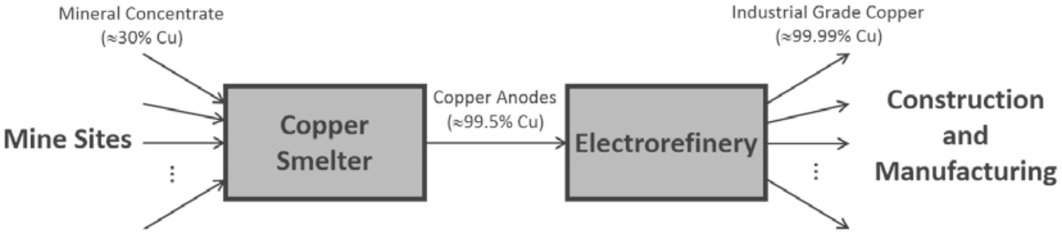

Figure 2 — Copper value chain.

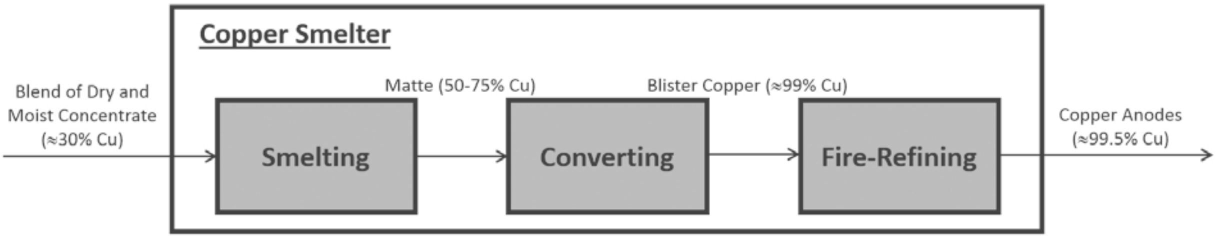

Figure 3 — Unit operations within a copper smelter.

moist powder. The moisture prevents the powder from being blown away during transport, and reduces the risk of explosive reactions. The minerals are dried at temperatures ranging between 400 °C and 700 °C (Talja et al., 2013). In certain plants, the elevated temperatures are combined with in-flowing air, leading to superficial reactions, known as roasting (Devia, Wilkomirsky and Parra, 2012). This diminishes unwanted impurities, such as arsenic and antimony.

The concentrate may include chalcopyrite ($CuFeS_2$), pyrite (FeS), bornite (Cu_5FeS_4), chalcocite (Cu_2S) and smaller amounts of silicates and other sulfides. Inside the smelting furnace (Fig. 3), this feed is melted and reacted to form molten matte, which is held above 1,200 °C (Mackey and Campos, 2001; Pérez-Fontes et al., 2007). This matte is a mixture of iron sulfide (FeS) and copper sulfide (Cu_2S), and is subject to two stages of oxidation: (1) the slag-blow, which eliminates FeS, followed by (2) the copper-blow, which releases a crude form of copper known as blister copper. For a more complete illustration of the copper value chain, Fig. 3 can be merged with Fig. 2 into a single diagram, following the example of Davenport et al. (2002a) that includes schematics of various furnaces and other technologies.

The slag-blow begins in the smelting furnace and is completed within the converting stage (Fig. 3). Ideally, it is described as:

$$2FeS_{(Matte)} + 3O_{2(Blast)} + SiO_{2(Flux)} \rightarrow (2FeO \cdot SiO_2)_{(Slag)} + 2SO_{2(Offgas)} \quad (1)$$

The iron is thus captured as slag that floats above the matte. However, a portion of the iron reports to the slag as unwanted magnetite (Fe_3O_4) instead of the low-viscosity fayalite ($2FeO \cdot SiO_2$). This can be controlled by adjusting the flux composition (Cardona et al., 2012; Davenport et al., 2002b) — that is, the balance of silica (SiO_2) and calcium oxide (CaO) and other stable oxides. In addition to slag viscosity, the flux composition affects the transport of minor elements, including As, Sb, Bi, Ag and Au (Kyllo and Richards, 1998). Minor elements notwithstanding, it is preferable for the slag to have low viscosity, so that it may be effectively skimmed away from the surface of the bath. After the iron has been removed as slag, and the bath contains less than 1 weight percent Fe, the converting stage is completed through the copper-blow, resulting in molten blister copper:

$$Cu_2S_{(Matte)} + O_{2(Blast)} \rightarrow 2Cu_{(Blister)} + 2SO_{2(Offgas)} \quad (2)$$

The slag-blow and copper-blow are both exothermic and will tend to overheat the smelting and converting vessels. In some plants, the temperature within the smelting furnace may be controlled by regulating the balance of dried versus moist concentrate (Fig. 3). Moreover, the blast nitrogen has an important role as a convective coolant, particularly in converting (Navarra and Kapusta, 2009), as it enters the bath at roughly 50 °C and leaves at over 1,200 °C. To some extent, the nitrogen convection can be replaced by introducing a portion of cold feed into the converting process, along with the molten matte.

Following smelting and converting, the blister copper is roughly 99 percent pure, containing less than 0.03 weight percent sulfur (S) and less than 0.8 weight percent oxygen (O) (Davenport et al., 2002b). However, this material cannot be successfully cast into anodes. Solidification would cause a drop in S and O solubility, hence the expulsion of sulfur dioxide (SO_2) bubbles that would form blisters. The blister copper is therefore treated in a fire-refining furnace (Fig. 3) that has two stages: (1) an oxidation stage, which removes the last of the sulfur as SO_2 gas but actually increases the oxygen content, and (2) a reduction stage, in which a hydrocarbon gas such as natural gas eliminates the oxygen as it forms an outgoing mixture of carbon monoxide (CO) and carbon dioxide (CO_2) gas (Davenport et al., 2002d).

The pyrometallurgical processing is completed as the fire-refined copper is cast into anodes. The subsequent electrolytic refining recovers trace amounts of gold and silver, and eliminates the harmful impurities that hinder the industrial properties of copper.

Conventional copper smelters. Copper smelters usually have one, or at most two, large smelting furnaces, which feed into several converters. The converters are arranged side by side, operating in parallel to produce batches of blister copper (Fig. 4). These conventional copper smelters typically have one to three refining furnaces, feeding into an anode-casting system (Kapusta, 2004).

There are roughly 100 of these conventional copper smelters, representing 60 percent of global copper production. These smelters tend to face similar operational problems, so the insight gained at a particular smelter is often directly relevant to other smelters. It is especially critical to determine how much of the slag-blow should be performed in the smelting furnace versus converting (Navarra et al., 2016). This division is defined by the grade of the matte — that is, the weight percentage of copper — leaving the smelting furnace.

Within a conventional copper smelter, cranes travel up and down the converter aisle (Fig. 4), carrying ladles of matte into the converters, and ladles of slag and blister copper out of the converters. Although it is not shown in Fig. 4, the converter slag is usually sent for post-processing to recover a portion of the entrained copper (Davenport et al., 2002b), so that it may be recycled into the smelting and/or converting operations. Also, the SO_2-containing offgas is captured from the smelting and converting operations, to produce sulfuric acid (H_2SO_4) (Davenport et al., 2002b; Sohn, Kang and Chang, 2005).

For the smelting stage, nearly all copper smelters employ either a flash furnace or a bath furnace (Kapusta, 2004). A flash furnace exposes the incoming sulfide particles to a stream of

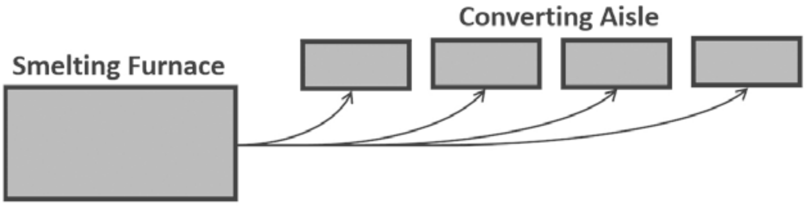

Figure 4 — Smelting furnace feeding a converting aisle within a conventional copper smelter.

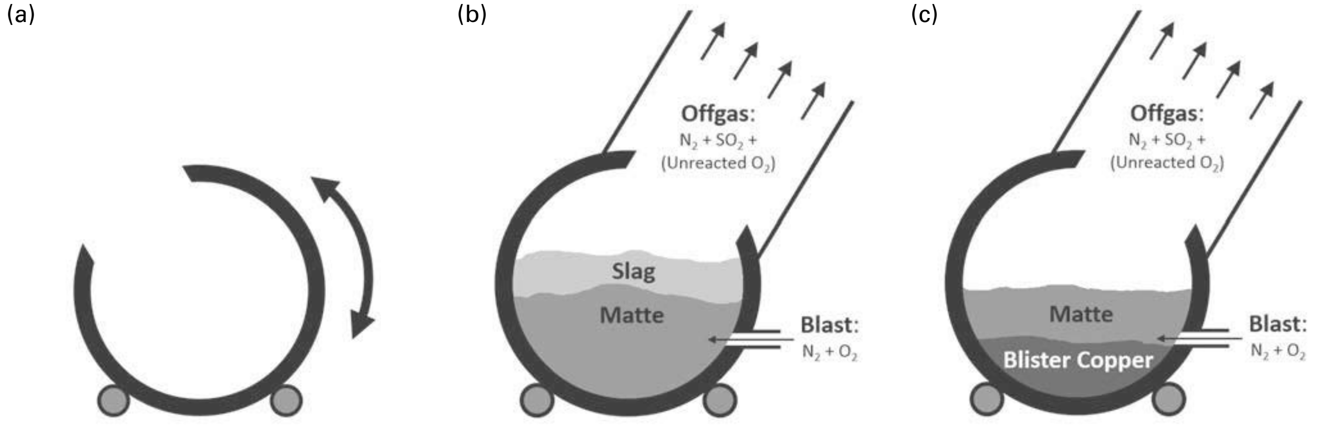

Figure 5 — Cross-sectional view of a Peirce-Smith converter (a) rotating into or out of charging/discharging position, (b) during slag-blow and (c) during copper-blow.

oxygen-enriched air. The resulting matte droplets and iron oxide particles fall to the bottom of the furnace, where the iron oxide combines with fluxing agents to form slag, as per the slag-blow (Pérez-Fontes et al., 2007; Swinbourne and Kho, 2012). Within a bath furnace, the incoming sulfide and flux particles are dispersed into the bath, which is subject to a blast of oxygen-enriched air. Depending on the vessel design, the blast is injected through the side (Mackey and Campos, 2001), the top (Floyd, 2005) or the bottom (Jie, 2013).

Flash furnaces obtain matte grades from 50 to 70 weight percent Cu, whereas bath smelters can obtain matte grades as high as 75 weight percent Cu (Mackey and Campos, 2001). A high-grade matte is mainly Cu_2S, with nearly all of the FeS having been eliminated during the smelting stage; this type of matte is called “white metal,” with grades above 70 weight percent Cu. The converting of white metal is hence dominated by the copper-blow.

Converting is the main bottleneck, as it sets the copper throughput for the entire smelter (Dettmer, 2007; Navarra and Kapusta, 2009). Indeed, conventional plants are configured such that the smelting furnace or furnaces can produce matte in excess of the nominal converting capacity. This allows the smelting furnace to accumulate and maintain a reservoir of matte that acts as a buffer (Navarra et al., 2016). If a batch of blister copper is completed unexpectedly quickly, the reservoir allows the next batch to be executed without delay. In general, production schedules are constructed so that the converting aisle is never starved of matte (Navarra, 2016). To draw an analogy with chemical kinetics (Coker, 2001a), converting is the “rate-determining step” in the system dynamics of copper smelters.

Conventional copper smelters usually use Peirce-Smith converters, although certain smelters feature Hoboken converters instead of Peirce-Smith (Kapusta, 2004). Both designs consist of a rotary cylinder, with a mouth that receives matte and secondary feeds, and from which the slag and blister copper are discharged (Fig. 5a). In the case of Peirce-Smith converters, a hood is lowered over the mouth, functioning as a gas outlet during the blowing (Figs. 5b and 5c). The Hoboken converters have an integrated siphoning system instead of a hood, which reduces offgas leakage and dilution but is somewhat cumbersome (Davenport et al., 2002b) and may be prone to mechanical problems.

A converting cycle begins when an empty converter receives an initial charge, including two or more ladles of matte, plus a variable amount of cold feed. The converter is then rotated into the blowing position, so that the slag-blow may be applied (Fig. 5b). To prevent the vessel from overflowing, it may be necessary to halt the blowing intermittently, and skim away the accumulated slag. This usually provides space for one or two additional ladles of fresh matte, and perhaps some cold feed, before resuming the slag-blow. After a final skimming, the copper-blow is performed (Fig. 5c). Eventually, all of the matte is converted into blister copper and is then discharged into ladles. This signifies the end of the cycle.

Table 1 — Ranges of operating values for a Peirce-Smith converter.

Parameter	Range	Unit
Matte grade	50 to 75	% Cu
Quantity of matte	100 to 500	t
Oxygen enrichment	21 to 30	Vol % O_2
Blast rate	250 to 1000	Nm^3/min

The duration of converter cycles can range from two to 12 hours, depending on the processing parameters described in Table 1, as well as the nature and quantity of cold feed. The intensity of converting is quantified by multiplying the oxygen enrichment and blast rate. From this, the cycle duration can be estimated roughly, by assuming that 85 to 95 percent of the incoming oxygen reacts with the melt (Navarra and Kapusta, 2009). Also, roughly 80 to 95 percent of the incoming iron is reacted to form fayalite, and the rest forms magnetite. Nonetheless, the characterization of the cold feeds is unreliable, which introduces statistical variations into converter cycles.

Peirce-Smith and Hoboken converting are capable of accepting a wide range of cold feeds, including various types of scraps, rejected anodes, dusts and reverts (Davenport et al., 2002b). In particular, reverts are a heterogeneous mass of partially converted matte and slag having uncertain composition, hence uncertain heat capacity (Navarra, Pubill and Kapusta, 2012). At the onset of a converting cycle, it is unclear how much reverts will be required to control the temperature. Moreover, it is unclear how much additional blowing time is necessary in order to convert it. Therefore, the use of reverts introduces statistical variation into the duration of the converter cycles.

Statistical variations can diminish the overall throughput of an industrial plant, particularly if these variations occur at bottlenecks. This concept has long been understood in the context of manufacturing, as described by the lean doctrine, as well as theory of constraits (Goldratt, 2009). In Navarra et al. (2016), DES was adapted to quantify the detrimental effects of variable Peirce-Smith — or Hoboken — cycles and how they may be partially mitigated by adjusting the matte grade.

For conventional copper smelters, there is usually a limit on the number of converter blows that can be executed simultaneously. This is due to the limited offgas handling capacity (Navarra, 2016). Small to medium-sized smelters, such as HVL in Chile and Rönnskär in Sweden, blow into only one converter at a time. The end of blowing for one converter is synchronized with the beginning of blowing for another converter (Fig. 6). Larger smelters, such as Chuquicamata and Altonorte, both in Chile, may blow into two converters simultaneously (Navarra and Mendoza, 2013; Pradenas, Zuñega and Parada, 2006). In the terminology of theory of constraints, the offgas handling system is said to be a “capacity constraint resource” (Dettmer, 2007).

There are several nonconventional alternatives to Peirce-Smith and Hoboken converting that produce blister copper continuously (Davenport et al., 2002c) rather than in batches. Kennecott-Outotec flash (KOF) converting is especially unconventional (Pérez-Tello, Sohn and Löttiger, 1999; Pérez-Tello et al., 2008) as the matte is frozen into solid granules, and possibly stockpiled, prior to being fed into the converter. The presence of a stable stockpile ensures that the KOF converter is not starved of feed. However, KOF converting is constrained to use high oxygen enrichment — about 80 volume percent O_2 — because excess nitrogen convection would hinder the remelting of the matte.

We suspect that matte granulation technology can be implemented in conventional copper smelters (Fig. 7), assuring a stable supply of cold feed with predictable composition and heat capacity (Navarra and Mucciardi, 2015). A main advantage of KOF converting could thus be replicated within conventional copper smelters. However, the conventional smelters would operate at much lower oxygen enrichment (Table 1), implying much less energy consumption than the KOF system. Indeed, a conventional smelter could control the heat balance of the converter by adjusting the balance of granulated versus molten matte that is fed into the converting aisle. This is analogous to the dry versus moist concentrate that is fed into the smelting furnace (Fig. 3).

Copper smelters are reluctant to experiment with the scheme of Fig. 7, even though matte granulation is a proven concept for KOF converting (Pérez-Tello, Sohn and Löttiger, 1999; Pérez-Tello et al., 2008). In general, changes in the operational practices of a smelter must be justified by quantifying the benefits and risks. Moreover, a local change to a unit operation cannot be accurately quantified unless it is simulated along with corresponding changes in matte grade (Navarra et al., 2016), scheduling practice (Navarra, 2016) and other plant-wide considerations. Computational tools are thus indispensible to break the status quo of conventional copper smelters.

Hierarchical DES framework to analyze copper smelter dynamics. The thermochemical aspects of copper smelters can be incorporated within DES, to provide an extensible framework to analyze the operational system dynamics. For complex problems, the simulation framework should be developed in phases (McMeekin, Twigge-Molecey and Blake, 2015) so as to direct an appropriate level of detail toward the critical aspects of the plant.

Depending on the goals of the particular study, the operations and structures illustrated in Figs. 1-7 can each be described in increasing detail and accuracy. This goal-oriented perspective must be maintained, especially when confronting process diagrams that are overburdened with technical details, such

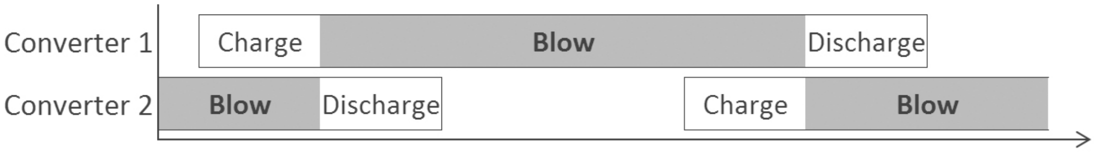

Figure 6 — Overlapping between converting cycles in converter 1 and converter 2. Blowing is performed in at most one converter at a time, due to limited offgas handling capacity.

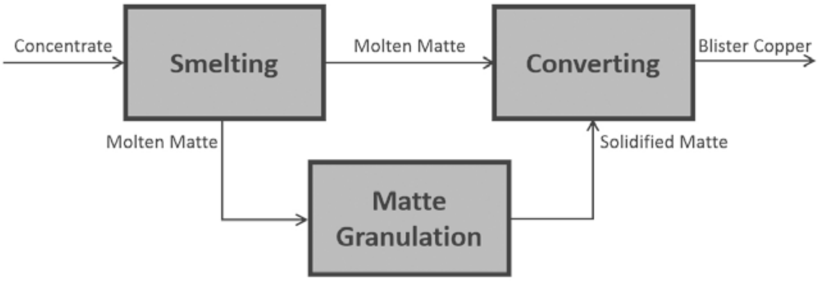

Figure 7 — Matte granulation in a conventional copper smelter.

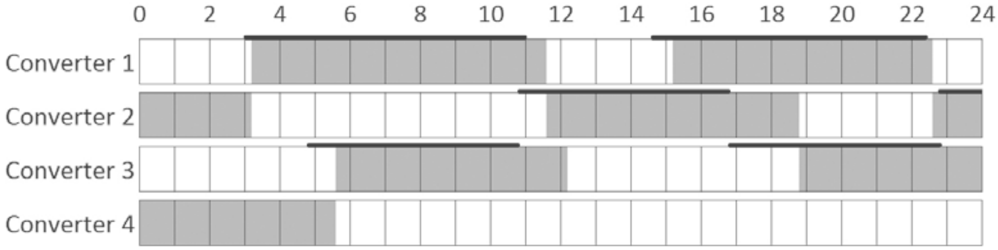

Figure 8 — Typical Gantt chart produced by simulation. Dark lines represent projected cycle times, whereas gray bars represent the actual cycle times. The leftmost gray bars are continued from the previous scheduling period.

as recirculating feeds, byproduct flows, stockpiles, control systems, electricity, ventilation. These details tend to hinder multidisciplinary problem-solving efforts, unless they are preceded by a sequence of simpler diagrams, or models. DES software such as Arena (Rockwell Automation, Milwaukee, WI) allow the different components of the smelter to be represented as submodels. In some cases, it may be helpful to develop sub-submodels.

The DES paradigm is based on a clock that advances in steps, from one discrete event to the next, without explicitly representing the dynamics that occur between the events. The state variables are updated only when a discrete event is executed. This may involve random number generation to determine the time between events, and to determine the updated values of the state variables. Because of its use of random number generation, DES is regarded as a class of Monte Carlo simulation (Altiok and Melamed, 2007).

Events that occur within a copper smelter include:

1. The smelting furnace attaining a matte level threshold.
2. The initiation and completion of converting cycles.

Matte level thresholds will be discussed below. Nonetheless, these first two categories are often sufficient in the early stages of DES development. The resulting framework allows the oxidation mass balance – that is, the slag-blow and copper-blow – to be integrated with conventional smelter dynamics (Fig. 4).

Additional events include, but are not limited to:

3. Individual skimming and recharging operations during the slag-blow of a converting cycle.
4. The transition from the slag-blow to the copper-blow of a converter cycle.
5. The arrival and departure of individual ladles to or from individual furnaces.
6. The initiation and completion of refining cycles.
7. The transition from the oxidation to the reduction phase of a refining cycle.
8. The offgas handling system reaching a threshold level of acid.
9. The arrival of concentrate from the mines.
10. The departure of copper anodes to the electrorefinery.

Whether or not these events should be explicitly represented depends on the particular study and the phase of development. For example, it is not advisable to represent individual ladles, except in later phases of development and only in specialized studies that analyze crane motions (Coursol and Mackey, 2009).

Continuous processes can be represented within a DES framework using finite difference schemes that have adaptive time stepping, such as the Runge-Kutta-Fehlberg method (Kelton, Sadowski and Swets, 2007). The incorporation of continuous processes within DES is sometimes called discrete rate simulation (Damarion and Nastasi, 2008). The adaptive time-stepping determines the moment at which a continuous variable crosses a threshold. Ultimately, the crossing of a threshold is regarded as a discrete event.

In conventional copper smelters, the matte level rises continually, except when matte ladles are sent to converting or when a smelting furnace reaches its maximum holding capacity and must therefore stop production. Therefore, thresholds should be defined for when the furnace reaches a sufficient level to charge or recharge a converter, and for when the holding capacity is reached. If a smelter is using a continuous converting system (Davenport et al., 2002c; Pérez-Tello, Sohn and Löttiger, 1999; Pérez-Tello et al., 2008), it may also be necessary to define thresholds related to continuous converting dynamics.

Statistical variations of converter cycle durations are an important aspect of smelter dynamics, which can have a significant impact on the throughput (Navarra et al., 2016). Depending on the particular study, there may be other important sources of variation. For instance, the following section incorporates the uncertainty of the meteorological conditions surrounding the smelter. In general, operational policies are designed to mitigate the cumulative effect of statistical variations. DES provides a computational framework in which to develop and compare these policies.

Figure 8 depicts the accumulating discrepancy between scheduled and actual converter cycle times, which accrues throughout a scheduling period. Incidentally, the final condition of the smelter at the end of a period corresponds to the initial condition at the beginning of the following period. This must be taken into account by the scheduling algorithm. In practice, the converting schedules are produced every 12 or 24 hours (Navarra and Mendoza, 2013; Pradenas, Zuñega and Parada, 2006). Longer scheduling periods would lead to a misallocation of resources – for example, oxygen supply or offgas handling – due to the accumulation of statistical variations. Scheduling algorithms have been incorporated within DES frameworks (Navarra, 2016) to simulate hundreds of days, thus to optimize key production parameters such as matte grade (Navarra et al., 2016). Arena has a Visual Basic for Applications (VBA) interface, in which scheduling algorithms can be programmed.

Alternate modes of operation can be associated with different scheduling algorithms, having different short-term objectives (Navarra, 2014). For instance, a smelter may have a main mode of operation that maximizes the copper throughput. Suppose that, on average, this mode results in a build-up of reverts that have to be reprocessed. When the reverts inventory reaches a threshold, the policy may be to switch to an operational mode that is less productive, but which results in a net consumption of reverts. Simulation techniques are used to parameterize such policies: in this case, to determine the critical reverts inventory that triggers the revert-consumption mode.

After a DES framework has been adapted to a particular installation, the framework may be used to analyze plant upgrades. However, a fair comparison requires that the new hypothetical configurations should be appropriately parameterized (Navarra and Mucciardi, 2015). For example, an increase in Peirce-Smith blast intensity might be best utilized by changing the matte grade.

Modern smelters can benefit from sensors that operate within the furnaces, and are linked to expert control systems. In particular, the Semtech OPC (Optical Production Control) System (Semtech Metallurgy AB, Lund, Sweden) signals the end of the copper-blow, providing tight controls on the residual sulfur that is retained in the blister copper (Parra et al., 2015; Prietl, Filzwieser and Wallner, 2005). DES is a means to quantify the benefits of Semtech OPC and other sensors. Moreover, DES can be used to justify the development of new sensors and expert systems. Indeed, a DES framework can be adapted to simulate the system dynamics that benefit from additional sensors, compared with current practices.

At a fundamental level, smelter system dynamics are centered on the oxidation reactions, which occur in the smelting and converting operations. This suggests a common basis for DES development. Beyond this common basis, however, individual smelters each experience particular operational problems. Especially for complex problems, the DES should be developed over several phases, beginning with the underlying thermochemistry, and incorporating increasing level details regarding the operational aspects that are most relevant.

Case study

Meteorological concerns surrounding Paipote. The Hernán Videla Lira (HVL) smelter is located in Chile's Atacama region, in the town of Paipote, which is approximately eight kilometers from the regional capital of Copiapó. The HVL smelter is a major asset of the *Empresa Nacional de Minería* – which is National Mining Company in Spanish – also known as Enami.

Enami is a state company, but its mission is to promote private-sector small and medium-sized mining companies by providing metallurgical and commercial services (Herrera, 2014). The HVL smelter is a uniquely important smelter from a socioeconomic standpoint. It receives highly variable sulfide ore from more than 80 mining complexes, most of which produce less than 5,000 t/y of concentrate. In turn, these complexes provide direct and indirect employment throughout the region of Atacama. Enami has been remarkably innovative so that this scale of mining may remain internationally competitive (*Minería Chilena,* 2014).

In spite of its socioeconomic importance, the HVL smelter is criticized for its SO_2 emissions. The smelter employs a Teniente bath furnace that feeds into two alternating Peirce-Smith converters (Fig. 8), thus producing nearly 100,000 t/y of copper (Kapusta, 2004). This corresponds to roughly 240,000 t/y of SO_2 gas, 90 percent of which is captured and transformed into sulfuric acid (Herrera, 2014). In response to increasingly strict environmental norms, HVL has planned equipment upgrades that will allow more than 95 percent of SO_2 capture and are to be fully implemented before the end of 2019 (*Minería Chilena*, 2014).

Meanwhile, under current operation, the blowing rates into the smelting and converting furnaces are adjusted as a function of the meteorological conditions. HVL employs a team of meteorologists who analyze the data from an array of sensors located at several stations in the vicinity of Paipote (*Diario Chañarcillo*, 2011). Based on this data, the meteorologists forecast the ability of the surrounding atmosphere to disperse the effluent gas. Their analysis incorporates factors such as temperature, pressure, humidity and wind velocity. Ultimately, they consider three levels of meteorological severity, which each correspond to a mode of operation: Normal, Bad and Extreme (*Comisión Nacional del Medio Ambiente*, 2003).

Without divulging sensitive information, it can be stated in general terms that:

- The Normal operational mode employs higher blowing rates than the Bad mode and, in turn, the Bad mode employs higher blowing rates than the Extreme mode.
- Within the meteorological forecasts, there is statistical uncertainty regarding the exact transition times between the meteorological severity levels.

If deteriorating meteorological conditions are forecast – either Normal-to-Bad or Bad-to-Extreme – there is a risk that the transition occurs sooner than expected. Consequently, the air quality is negatively affected if the Normal mode is still in effect after the Bad conditions have arrived, or if the Bad mode is still in effect after the Extreme conditions have arrived. This type of misalignment between operational mode and meteorological conditions will be called "environmental violation."

In practice, this risk of environmental violation is mitigated by incorporating a buffer time in the schedule such that the operational mode is changed early, before the meteorological deterioration is expected to occur. However, a preemptive change of mode corresponds to a loss of production. The following section describes a DES framework that has been developed to quantify the trade-off between production and environmental risk.

In addition to HVL, there are several other smelters that actively monitor meteorological conditions, including Codelco's Ventanas smelter in Chile (Lazo, Curé and Gaete, 2006), and Vale's Copper Cliff smelter in Canada (Vale Canada, 2015). However, it is questionable how well the meteorological data is incorporated into actual operational practices. In general, the operational response to changing meteorological conditions is poorly standardized. To a large extent, this is due to the interdisciplinary barrier that separates production engineers from meteorologists.

The methodical development of a DES framework supports multidisciplinary collaboration and is an important step toward the optimization of HVL's operational policies. Moreover, the framework can eventually be used to evaluate options for plant upgrades. The developments made at HVL will provide insight for other smelters.

Sample computations. This section demonstrates the DES framework that was developed in collaboration with the HVL smelter, incorporating actual meteorological forecasts made during 2015. In order to respect the confidentiality of HVL, most of the parameters used in this section were adapted from data published by Boliden AB's Rönnskär smelter (Ek and Olsson, 2005). Thus the computations describe a fictitious

Table 2 — Adaptation of published converting data from the Rönnskär smelter.

Parameter	Ek and Olsson (2005)	Adapted values	Unit
Matte grade	~61	61	% Cu
Content of matte ladle	50	50	t
Ladles per converter cycle	6 to 7	6	—
Oxygen enrichment	< 26	25	Vol % O_2
Blast rate	750	750	Nm^3/min
Copper scrap addition	70 to 120	85	t/cycle
Slag-blow duration[a]	2 to 3	2.81	h
Skiming/recharge time	< 0.83	0.75	h
Copper-blow duration[a]	4 to 5	4.00	h

[a] Adjusted based on heat and mass balances.

plant that resembles the Rönnskär smelter and is subject to the meteorological challenges of HVL.

Table 2 summarizes the converting parameters adapted from Rönnskär. These values were fixed directly, except for the slag-blow and copper-blow durations, which were determined iteratively, by adjusting the reverts data, as described below. The adapted data in Table 2 reveals that there are 183.0 t/cycle of primary copper production, not including recycled scraps and reverts. Summing the last three entries in Table 2, each cycle requires a total of 7.56 h, hence a production rate of 24.21 t/h. This can be extrapolated to give an annual production of roughly 212,000 t/y, which is similar to Rönnskär's reported value for 2003 of 214,200 t/y (Ek and Olsson, 2005).

Table 3 describes additional heat and mass balance values that were assumed in order to calculate the duration of the slag-blow and copper-blow that occur within the converters (Table 2). These values were entered into the converter modeling software of Navarra and Kapusta (2009), which incorporates heat of formation and specific heat data.

Without the incorporation of reverts, (1) the slag-blow was found to overheat the converter, and (2) the copper-blow duration was found to be below the published lower limit of four hours (Table 2). The reverts were therefore formulated to simultaneously satisfy the slag-blow heat balance and to extend the copper-blow to exactly four hours. For simplicity, the reverts were assumed to be a mixture of $2FeO \cdot SiO_2$ and Cu_2S. The first component satisfies the heat balance, while the second component extends the copper-blow. In actuality, reverts may have several more oxide and sulfide species (Navarra, Pubill and Kapusta, 2012).

Supposing that the 85 t of copper scrap denoted in Table 2 is sufficient to maintain a bath temperature of 1,250 °C during the copper-blow, the heat balance reveals an average heat release of 2.22 MW into the surrounding environment, mainly through radiation — this does not include the heat carried out by the offgas. The same heat release rate was assumed for the slag-blow, which finally allows a rough characterization of the reverts (Table 4).

For the purposes of the current study, Tables 3 and 4 support the slag-blow and copper-blow durations given in Table 2, hence a total cycle time of 7.56 h under Normal meteorological conditions. Following this analysis, the data of Table 5 were entered into the DES framework, which considers a 50 percent slow-down for Bad meteorological conditions, and 75 percent

Table 3 — Assumed values for converting heat and mass balances.

Parameter	Values	Unit
Oxygen efficiency	95	%
Fe_3O_4 in slag	5	%
Input matte temperature	1,200	°C
Blast temperature	50	°C
Slag-blow offgas temperature	1,230	°C
Bath temperature after slag-blow	1,250	°C
Copper-blow offgas temperature	1,250	°C
Bath temperature after copper-blow	1,250	°C

Table 4 — Quantities estimated from converter heat balance.

Parameter	Values	Unit
Average heat loss to surrounding environment[a]	2.22	MW
Reverts addition	114.78	t/cycle
Cu_2S in reverts	43	%
($2FeO \cdot SiO_2$) in reverts	57	%

[a] Calculated from copper-blow and assumed for slag-blow.

Table 5 — Production parameters in accordance to meteorological conditions.

Meteorological conditions	Matte production rate (t/h)	Converter cycle duration (h)
Normal	39.68	7.56
Bad	19.84	15.12
Extreme	9.92	30.24

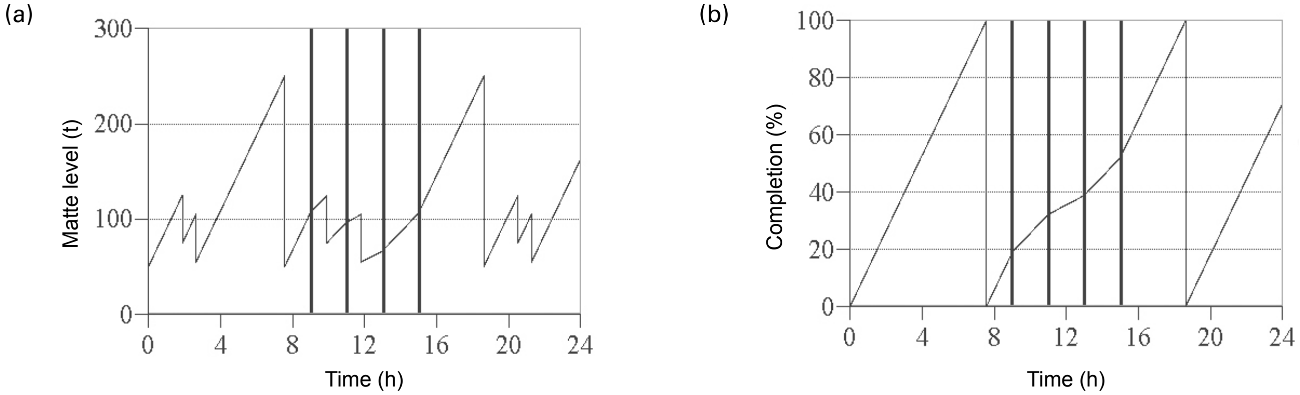

Figure 9 — (a) Simulated matte level within the smelting furnace and (b) simulated converter cycle completion, in response to changing mode of operations marked by thick vertical lines.

slow-down for Extreme conditions. It should be pointed out that Bad and Extreme conditions are only ever held for a portion of a converter cycle, so that converting cycles rarely exceed 12 h.

For simplicity, the matte production rate was balanced with the converting rate: for example, 300 t/cycle and 7.56 h/cycle gives 39.68 t/h. In practice, the matte production level may exceed the nominal converting rate, to maintain a buffer against the variation in converter cycle durations (Navarra et al., 2016). However, the current set computations consider constant cycle durations.

The DES framework considers matte level thresholds, initiation and completion of converting cycles, as well as skimming

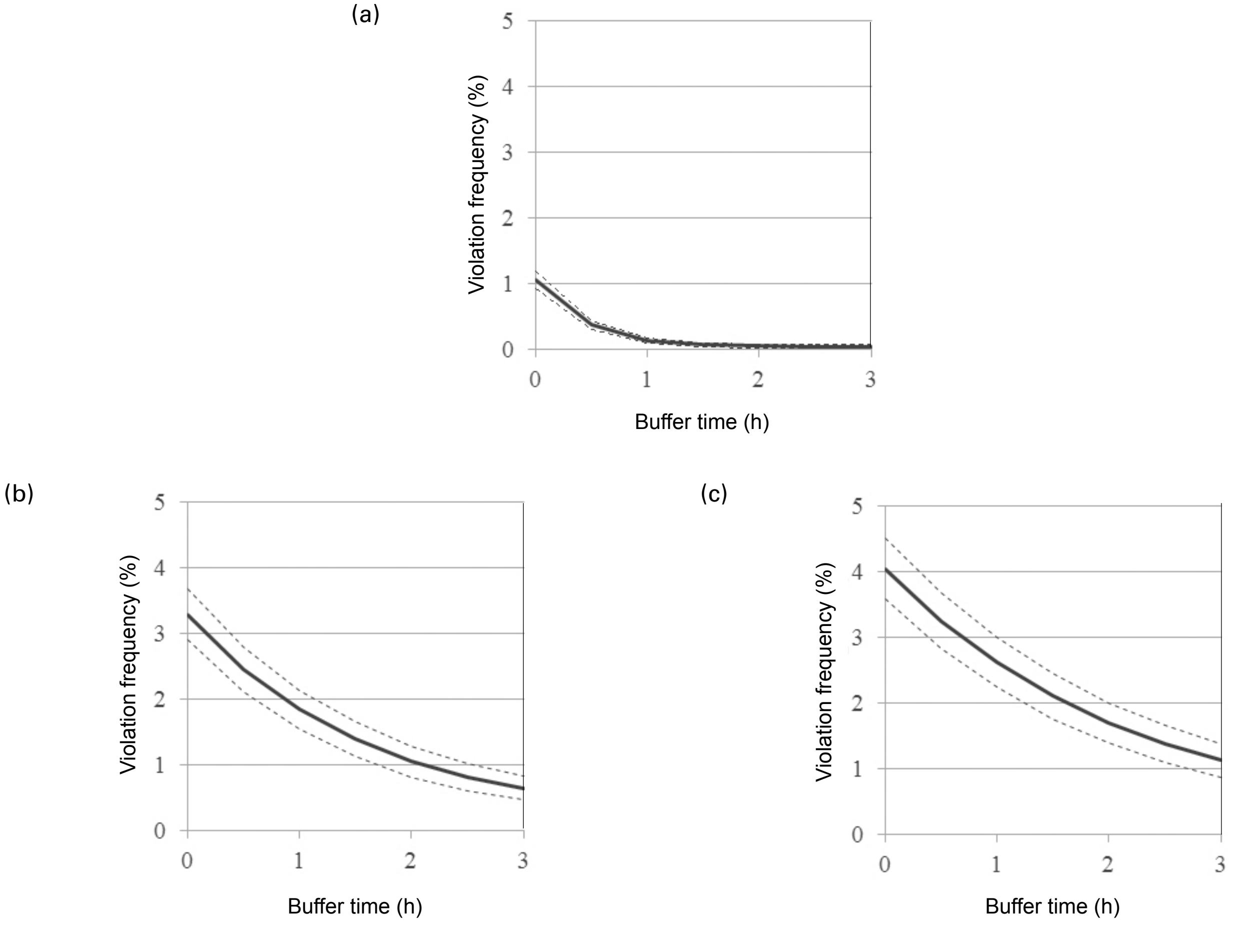

Figure 10 — Application of buffer time to reduce frequency of environmental violation, with standard deviation of transition times equal to (a) a half hour, (b) one hour and (c) two hours. The dashed lines delineate the 95 percent confidence interval of the mean.

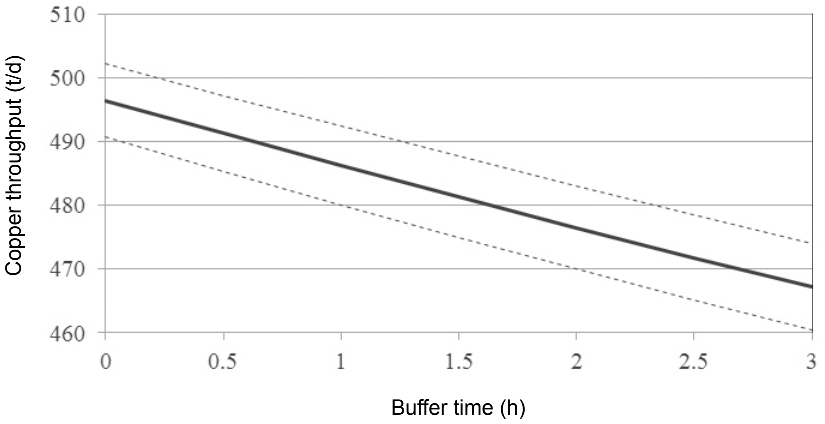

Figure 11 — The application of buffer time causes a decrease in copper throughput. The dashed lines delineate the 95 percent confidence interval of the mean.

and recharging operations. This corresponds to the first three items listed earlier as events that occur within a copper smelter. In accordance with the industrial practices at Rönnskär, the initial converting charge consists of four ladles, followed by a first recharge that occurs 25 percent into the cycle, and a second recharge that occurs 35 percent into the cycle. Each of these recharges consists of one ladle of matte.

Figure 9 shows output from the DES framework based on a 24-h scenario in which the mode of operation undergoes four transitions: Normal-to-Bad at nine hours, Bad-to-Extreme at 11 h, Extreme-to-Bad at 13 h, and Bad-to-Normal at 15 h. Figure 9a shows the matte level in the furnace, as it is decremented by four ladles at the beginning of a new converter cycle and by one ladle during the recharging operations. In Fig. 9b, the first cycle is completed entirely under the Normal mode, requiring exactly 7.56 h. The second cycle is slowed down, as the Bad and Extreme modes imply slower progress, requiring roughly 11 h to complete the cycle.

Figures 10 and 11 were based on 100 meteorological scenarios taken from the HVL plant data in 2015. Each of these scenarios corresponded to a 72-h forecast that gave expected transition times. For the purposes of the simulation, the transition times were assumed to follow a Gaussian distribution with standard deviation σ, representing a risk of environmental violation. Results were obtained for σ values of a half hour, one hour and two hours. Copper throughput is not affected by σ, so only a single graph is shown in Fig. 11.

The simulation considers 24-h scheduling periods, hence three periods per meteorological scenario. The deviations accumulate throughout a 24-h period and are corrected only at the beginning of the next scheduling period. There is thus a slightly higher risk of environmental violation at the end of a scheduling period than at the beginning.

The curves of Figs. 10 and 11 were generated considering buffer times of 0.5, 1, 1.5, 2, 2.5 and 3 h. These buffer times were only applied for deteriorating conditions — Normal-to-Bad and Bad-to-Extreme — and not for improving conditions — Extreme-to-Bad and Bad-to-Normal. For each of the buffer time values, the 100 scenarios were tested under five different sets of initial conditions, hence 500 replicas per point.

Figures 10 and 11 demonstrate the value of accurate meteorological forecasts. For instance, if $\sigma = 0.5$ h, then the violation frequency can be held below 1 percent with virtually no buffer time (Fig. 10a). If $\sigma = 2$ h, then more than 3 h of buffer time is required (Fig. 10c). According to Fig. 11, this corresponds to a production decrease of roughly 30 t of copper per day, or 6 percent.

The DES framework incorporates meteorological forecasts and operational policies, in addition to commonly practiced mass and heat balances that are fundamental to copper smelters. Future development will be to develop more sophisticated policies that make better use of the incoming meteorological data.

Conclusions and future work

The collaboration with the HVL smelter supports our general viewpoint that DES provides a computational framework to extend the thermochemical analysis of copper smelters and quantify multidisciplinary aspects of operational system dynamics. The mass and heat balancing parameters of Tables 2-5 were used to estimate converter cycle time (Table 5) so that the DES framework could assess the tradeoff between copper production and environmental risk (Figs. 10 and 11). This type of quantitative multidisciplinary analysis had not been previously available. Moreover, the same general approach is directly applicable to all copper smelters, particularly those that follow conventional dynamics (Fig. 4). Additionally, the concepts of system dynamics and DES can be adapted to other metallurgical systems.

The computational development presented in this paper is concurrent to ongoing collaboration with several smelters. We are committed to working with metal producers, and related suppliers, consulting firms and information systems specialists. There is particular interest to bring multidisciplinary perspectives into metallurgical plants, to obtain new solutions to longstanding operational problems.

Acknowledgments

Funding for the current work has been provided by the Chilean government through its FONDECYT – Iniciación program for young researchers (Project N° 11140078). Special thanks are due to the staff of the Hernán Videla Lira smelter, for their feedback.

References

Altiok, T., and Melamed, B., 2007, "Output analysis," *Simulation Modeling and Analysis with Arena*, Elsevier, Oxford, UK, Chap. 4, pp. 55-64, https://doi.org/10.1016/b978-012370523-5/50010-9.

Brininstool, M., 2015, "Copper," *Mineral Commodity Summaries*, U.S. Geological

Survey, Reston, VA, pp. 48-49, https://doi.org/10.3133/70140094.

Campbell, A., Reed, M., and Warner, A., 2013, "Debottlenecking and optimisation of copper smelters leveraging simulation," *Nickolas Themelis Symposium of Pyrometallurgy and Process Engineering* (Copper 2013), R. Bassa, R. Parra, A. Luraschi and S. Demetrio, eds., The Chilean Institute of Mining Engineers, Santiago, Chile, pp. 1071-1080.

Cardona, N., Mackey, P., Coursol, P., Parada, R., and Parra, R., 2012, "Optimizing Peirce-Smith converting using thermodynamic modeling and plant sampling," *JOM*, Vol. 64, No.5, pp. 546-550, https://doi.org/10.1007/s11837-012-0329-x.

Coker, A.K., 2001a, "Reaction rate expression," *Modeling of Chemical Kinetics and Reactor Design*, Gulf Professional Publishing, Houston, TX, Chap. 3, pp. 109-217, https://doi.org/10.1016/b978-088415481-5/50005-x.

Coker, A.K., 2001b, "Industrial and laboratory reactors," *Modeling of Chemical Kinetics and Reactor Design*, Gulf Professional Publishing, Houston, TX, Chap. 4, pp. 218-259, https://doi.org/10.1016/b978-088415481-5/50006-1.

Comisión Nacional del Medio Ambiente, 2003, "Resultados del plan de descontaminación de la Fundición Hernán Videla Lira," [Results of the pollution mitigation plan of the Hernán Videla Lira Smelter], Santiago, Chile, pp. 1-17. [In Spanish]

Coursol, P., and Mackey, P., 2009, "Optimization of the Xstrata Copper-Horne smelter operation using discrete event simulation," *CIM Bulletin*, Vol. 102, No. 1114, pp. 5-10.

Damarion, C., and Nastasi, A., 2008, "Discrete rate simulation using linear programming," *2008 Winter Simulation Conference*, S. Mason, R. Hill, L. Mönch and O. Rose, eds., pp. 740-749.

Davenport, W., King, M., Schlesinger, M., and Biswas, A., 2002a, "Extracting Copper from Copper-Iron-Sulphide Ores," *Extractive Metallurgy of Copper*, Elsevier, Oxford, UK, pp. 1-10.

Davenport, W., King, M., Schlesinger, M., and Biswas, A., 2002b, "Batch converting of copper matte," *Extractive Metallurgy of Copper*, Elsevier, Oxford, UK, Chap. 9, pp. 131-154, https://doi.org/10.1016/b978-008044029-3/50012-5.

Davenport, W., King, M., Schlesinger, M., and Biswas, A., 2002c, "Continuous converting," *Extractive Metallurgy of Copper*, Elsevier, Oxford, UK, Chap. 10, pp. 155-172, https://doi.org/10.1016/b978-008044029-3/50013-7.

Davenport, W., King, M., Schlesinger, M., and Biswas, A., 2002d, "Fire refining and casting of anodes: Sulfur and oxygen removal," *Extractive Metallurgy of Copper*, Elsevier, Oxford, UK, Chap. 15, pp. 247-263, https://doi.org/10.1016/b978-008044029-3/50018-6.

Degterov, S., and Pelton, A., 1999, "A thermodynamic database for copper smelting and converting," *Metallurgical and Materials Transactions B*, Vol. 30, pp. 661-669, https://doi.org/10.1007/s11663-999-0027-4.

Dettmer, H., 2007, "Introduction to the theory of constraints," *The Logical Thinking Process: A Systems Approach to Complex Problem Solving*, ASQ Quality Press, Milwakee, WI, Chap. 1, pp. 3-30.

Devia, M., Wilkomirsky, I., and Parra, R., 2012, "Roasting kinetics of high-arsenic copper concentrates: a review," *Minerals & Metallurgical Processing*, Vol. 29, No. 2, pp. 121-128.

Diario Chañarcillo, 2011, "Enami fija su postura ante episodios de contaminación de Fundición Hernán Videla Lira," [Enami stands its ground following pollution incidents at the Hernán Videla Lira Smelter]. Copiapó, Chile. [In Spanish]

Ek, M., and Olsson, P., 2005, "Recent developments on the Peirce-Smith converting process at the Rönnskär smelter," *Converter and Fire Refining Practices* (TMS Conference), A. Ross, T. Warner and K. Scholey, eds., The Minerals, Metals and Materials Society, Warrendale, PA, pp. 19-26.

Fan, Y., Parra, R., Parada, F., and Wilkomirsky, I., 2006, "Interaction of cupric ferrite, copper matte and slag at 1573 K," *Minerals & Metallurgical Processing*, Vol. 23, No. 3, pp. 126-132.

Floyd, J., 2005, "Converting an idea into a worldwide business commercializing smelting technology," *Metallurgical and Materials Transactions B*, Vol. 36, pp. 557-575, https://doi.org/10.1007/s11663-005-0047-7.

Goldratt, E., 2009, "Standing on the shoulders of giants – production concepts versus production applications: the Hitachi Tool Engineering example," *Gestao e Producao*, Vol. 16, No. 3, pp. 333-343.

Groover, M., 2000, "Process planning and concurrent engineering," *Automation, Production Systems and Computer-Integrated Manufacturing*, Prentice Hall, Upper Saddle River, NJ, Chap. 25, pp. 775-795.

Herrera, C., 2014, "Fusión de concentrados en Fundición Hernán Videla Lira," [Smelting of concentrates at the Hernán Videla Lira Smelter]. Enami, Santiago, Chile, pp. 1-22. [In Spanish]

Jie, Y., 2013, "Latest development of oxygen bottom-blowing copper smelting technology," *Nickolas Themelis Symposium of Pyrometallurgy and Process Engineering* (Copper 2013), R. Bassa, R. Parra, A. Luraschi and S. Demetrio, eds., The Chilean Institute of Mining Engineers, Santiago, Chile, pp. 873-887.

Kapusta, J., 2004, "JOM world nonferrous smelter survey part I: Copper," *JOM*, Vol. 57, No. 2, pp. 19-26, https://doi.org/10.1007/s11837-004-0086-6.

Kelton, W., Sadowski, R., and Swets, N., 2007, "Continuous and combined discrete/continuous models," *Simulation with Arena*, McGraw-Hill, Cambridge, MA, Chap. 11, pp. 465-503.

Kyllo, A., Richards, G., 1998, "Kinetic modeling of minor element behavior in copper converting," *Metallurgical and Materials Transactions B*, Vol. 29, pp. 261-286, https://doi.org/10.1007/s11663-998-0029-7.

Lazo, P., Curé, M., and Gaete, H., 2006, "Modeling of the sulfur dioxide dispersion in the Puchuncavi city using the program ISC3," *Ingeniare*, Vol. 14, No. 3, pp. 229-237.

Mackey, P., and Campos, R., 2001, "Modern continuous smelting and converting by bath smelting technology," *Canadian Metallurgical Quarterly*, Vol. 40, No. 3, pp. 355-376, https://doi.org/10.1179/cmq.2001.40.3.355.

McMeekin, R., Twigge-Molecey, C., and J. Blake, J., 2015, "Project development," *Metallurgical Plant Design*, Canadian Institute of Mining Metallurgy and Petroleum, Montreal, Canada, Chap. 5, pp. 87-105.

Minería Chilena, 2014, "Fundición Paipote en la ruta de la modernización," [Paipote Smelter on the road to modernization]. Santiago, Chile. [In Spanish]

Mourtzis, D., Doukas, M., and Bernidaki, D., 2014, "Simulation in manufacturing: Review and challenges," *Precedia CIRP*, Vol. 24, pp. 213-229, https://doi.org/10.1016/j.procir.2014.10.032.

Navarra, A., 2016, "Automatic scheduling and scientific management of copper smelters," *Transactions of the Institutions of Mining and Metallurgy: Section C*, Vol. 125, No. 1, pp. 39-46, https://doi.org/10.1179/1743285515y.0000000018.

Navarra, A., 2014, "Discrete event simulation and scheduling algorithms for the development of copper and nickel converting operational modes," *Bill Davenport Honorary Symposium* (Conference of Metallurgists), E. Partelpoeg, M. Moats, M. King, D. Jones, E. Ozberk and T. Okabe, eds., Canadian Institute of Mining, Metallurgy and Petroleum, Montreal, Canada, Paper 8311.

Navarra, A., and Kapusta, J., 2009, "Decision-making software for the incremental improvement of Peirce-Smith converters," *International Peirce-Smith Converting Centennial Symposium* (TMS Conference), J. Kapusta and T. Warner, eds., The Minerals, Metals and Materials Society, Warrendale, PA, pp. 231-250.

Navarra, A., Kuan, S., Parra, R., Davis, B., and Mucciardi, F., 2016, "Bottleneck Analysis of Conventional Copper Smelters," *International Conference on Industrial Engineering and Operations Management*, A. Ali and A.T. Bon, eds., Industrial Engineering and Operations Management Society, Detroit, MI, pp. 2395-2406.

Navarra, A., and Mendoza, O., 2013, "Automatic scheduling of Altonorte operations using greedy algorithms," *Nickolas Themelis Symposium of Pyromentallurgy and Process Engineering* (Copper 2013) , R. Bassa, R. Parra, A. Luraschi and S. Demetrio, eds., The Chilean Institute of Mining Engineers, Santiago, Chile, pp. 223-235.

Navarra, A., and Mucciardi, F., 2015, "Discrete event simulation to quantify upgrades of Peirce-Smith converting aisles," *Applications of Computers and Operations Research in the Mineral Industry*, S. Bandopadhyay, S. Chatterjee, T. Ghosh and K.V. Raj, eds, Society for Mining, Metallurgy & Exploration, Englewood, CO, pp. 54-64.

Navarra, A., Pubill, A., and Kapusta, J., 2012, "Convex projection to estimate heat content of cold charges in Peirce-Smith converting," *Computational Thermodynamics and Kinetics Symposium* (TMS Conference), Z. Liu, M. Asta, J. Warren, Y. Wang, R. Arroyave and Y. Wang, eds., The Minerals, Metals and Materials Society, Warrendale, PA, pp. 151-158.

Parra, R., Sbarbaro, D., Verdeja, L., Mochón, J., and Bustinza, I., 2015, "Spectral characterization and image analysis in ferrous and non-ferrous process metallurgy for the design of new sensors for process control," *Torstein Utigard Memorial Symposium* (Conference of Metallurgists), M. Muinonen, T. Marin and N. Stubina, eds., Canadian Institute of Mining, Metallurgy and Petroleum, Montreal, Canada, pp. 1-12.

Pérez-Fontes, S., Pérez-Tello, M., and Prieto-López, L.O., 2007, "Thermoanalytical study on the oxidation of sulfide minerals at high temperatures," *Minerals & Metallurgical Processing*, Vol. 24, No. 2, pp. 275-283.

Pérez-Tello, M., Madrid-Ortega, I.M., and Sohn, H.Y., 2008, "Model for the fragmentation of copper matte particles during flash converting," *Minerals & Metallurgical Processing*, Vol. 25, No. 1, pp. 53-60.

Pérez-Tello, M., Sohn, H.Y., and Löttiger, J., 1999, "Determination of the oxidation characteristics of solid copper," *Minerals & Metallurgical Processing*, Vol. 16, No. 2, pp. 1-7.

Pradenas, L., Zuñega, J., and Parada, V., 2006, "Codelco, Chile programs its copper-smelting operations," *Interfaces*, Vol. 26, No. 4, pp. 296-301, https://doi.org/10.1287/inte.1060.0207.

Prietl, T., Filzwieser, A., and Wallner, S., 2005, "Productivity increase in a Peirce-Smith converter using COP KIN and OPC system," *Converter and Fire Refining Practices* (TMS Conference), A. Ross, T. Warner and K. Scholey, eds., The Minerals, Metals and Materials Society, Warrendale, PA, pp. 177-190.

Rotuska, K., and Chmielewski, T., 2008, "Growing role of solvent extraction in copper ores processing," *Physicochemical Problems of Mineral Processing*, Vol. 42, pp. 29-36.

Sohn, H., Kang, S., and Chang, J., 2005, "Sulfide smelting fundamentals, technologies and innovations," *Minerals & Metallurgical Processing*, Vol. 22, No. 3, pp. 65-76.

Swinbourne, D., and Kho, T., 2012, "Computational thermodynamics modeling of minor element distributions during copper flash converting," *Metallurgical and Materials Transactions B*, Vol. 43, pp. 823-829, https://doi.org/10.1007/s11663-012-9652-4.

Talja, J., Chen, S., Mansikkaviita, H., and Berg, C.G., 2013, "Optimal drying solution for copper concentrate," *Nickolas Themelis Symposium of Pyrometallurgy and Process Engineering* (Copper 2013), R. Bassa, R. Parra, A. Luraschi and S. Demetrio, eds., The Chilean Institute of Mining Engineers, Santiago, Chile, pp. 49-60.

Vale Canada, 2015, "Environmental Management System and Community Engagement Report," pp. 1-15.

Wheeler, M., and McGinty, J., 2015, "Plant layout and logistics," *Metallurgical Plant Design*, Canadian Institute of Mining Metallurgy and Petroleum, Montreal, Canada, Chap. 10, pp. 205-240.