Debottlenecking of Conventional Copper Smelters

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Abstract—Copper smelters have two central operations: smelting, following by converting. Firstly, the smelting operation is continuous, and is usually over-dimensioned compared to the downstream operations. Secondly, the converting operation is performed in discrete batches that may be executed in parallel, and must share a limited set of resources, including offgas handling capacity and oxygen capacity. Converting is often a major bottleneck in conventional copper smelters.

In recent decades there have been considerable technological enhancements that focus on different aspects of copper smelters, such as high pressure injection, matte granulation, sensors, and expert control systems. Nonetheless, copper smelters are reluctant to implement these technologies unless they are adequately justified, both qualitatively and quantitatively.

The current paper adapts the Theory of Constraints to describe the bottlenecking phenomena that occur within copper smelters, and how they may be resolved using incremental technological upgrades. The resulting benefits can be quantified using a Discrete Event Simulation framework. Sample calculations are demonstrated.

Keywords—Copper smelting; Peirce-Smith converting; Theory of Constraints; Discrete Event Simulation; Rockwell Arena©, OptQuest©

I. INTRODUCTION

Annual copper production is roughly 18.5 million tons [1], worth $80 billion US/year. Within this total, conventional copper smelters represent approximately 60% [2,3,4], as depicted Figure 1. These so-called conventional smelters are characterized by the operational connections between the smelting and converting furnaces (Figure 2). There are roughly 100 conventional copper smelters in the world. They typically have one, or at most two smelting furnaces, feeding into several converters; the converters are placed side-by-side forming a converting aisle. Conventional

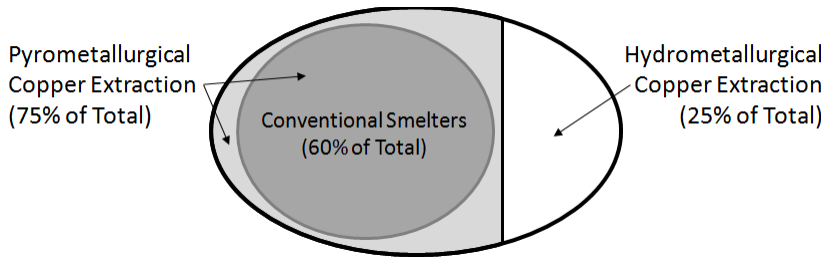


Fig. 1. Breakdown of world primary copper production.

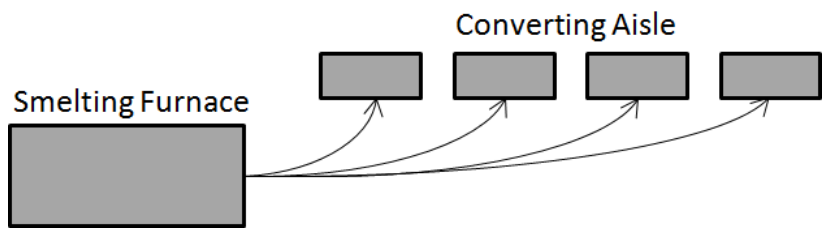


Fig. 2. Conventional copper production. The smelting furnace(s) continually produce(s) molten matte (50 – 75% Cu); cranes are used to carry ladles of matte into converters, which function in parallel to produce batches of blister copper (99.8% Cu).

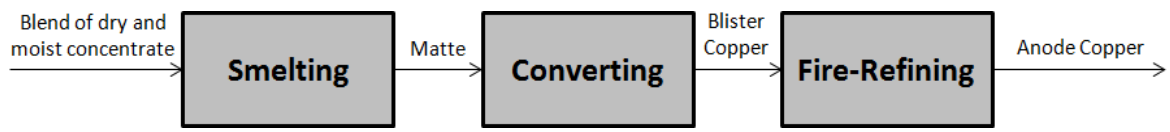


Fig. 3. Pyrometallurgical operations that are common to conventional and unconvensional copper smelters.

copper smelters tend to face similar operational problems; hence, the insight developed at a particular smelter may be generalized and adapted to other smelters.

The goal of a copper smelter is to profitably extract copper from mineral concentrates [5,6]. This goal-oriented perspective must be maintained, particularly when confronting process flow diagrams that are overburdened with technical details: secondary feeds, byproduct flows, stockpiles, control systems, electricity, ventilation, etc. These details tend to hinder multidisciplinary problem-solving efforts, unless they are preceded by a sequence of simpler diagrams, or models. Incidentally, operations management techniques from the 1980's and 1990's (c.f. [7,8]) have not been widely adopted by copper smelters, which may be due to interdisciplinary boundaries that separate industrial and metallurgical engineers.

Beginning with the goal (profitable copper extraction), additional technicalities may be examined in incremental levels of detail. Firstly, there is a distinction between pyrometallurgical and hydrometallurgical extraction; smelters apply the former. Pyro- and hydro-metallurgical extraction both require chemical reactions that penetrate into the bulk of the incoming minerals. The minerals must therefore be kinetically activated; otherwise, the reactions are confined to the surfaces, as the interior is increasingly obstructed. Smelters are categorically pyrometallurgical, because the incoming minerals are activated via heat and melting. In contrast, hydrometallurgical plants activate the incoming minerals by dissolving them in acid or other solvents [4]. In either case, the activated stream is fluid and mixable, allowing favorable kinetics.

In particular, copper smelters are fed with sulfide minerals that are a molecular combination of sulfur, iron and copper; the sulfur is removed as SO_2 offgas, while the iron is skimmed away as liquid slag [9], eventually resulting in molten copper. This pyrometallurgical approach is responsible for roughly 75% of primary copper production [2,3] (Figure 1), most of which follows the process of Figure 2. Hydrometallurgical processing is applied to oxides and complex ores [4], which represents roughly 25% of primary copper production.

Figure 3 depicts the pyrometallurgical operations within a copper smelter. The mineral concentrates are transported from the mine as a moist powder; this moisture prevents the powdered mineral from drifting away during transport, and reduces the risk of explosive reactions. To dry the minerals, they are held at elevated temperatures, typically between 400°C and 700°C [10,11]. In some cases, the elevated temperatures are combined with inflowing air, leading to certain superficial reactions, known as roasting [11]; this helps eliminate unwanted impurities, such as arsenic and antimony (a roasted mineral concentrate is often called a "calcine"). Depending on the type of smelting furnace, the heat balance within the smelting furnace may be controlled by including a certain amount of moist

concentrate, along with the dried concentrate. The resulting molten matte has a temperature of roughly 1200°C. This matte is then converted into so-called blister copper [5,9], which is over 98% pure, containing trace amounts of oxygen and sulfur. The blister copper is not yet allowed to freeze; otherwise, the deceasing solubility would cause SO_2 expulsion, forming a blistered and unacceptable product. Therefore, the molten blister copper is treated in a fire-refining furnace, giving a copper grade of roughly 99.5%, before being cast into solid anode slabs. The anodes may be then stacked and stored, and are usually transferred to an electrorefinery, to produce cathodes with over 99.95% purity [5].

The operations in Figure 3 can each be described in increasing detail, as necessary, depending on ***the*** problem at hand, i.e. *the* main constraint that limits a smelter's ability to profitably extract copper. Commercial software is commonly used to describe and predict the physical phenomena within pyrometallurgical furnaces, including thermochemical aspects [12], and fluid mechanics [13]. Moreover, the corrosive molten environment requires specialized measurement devices that are an ongoing area of the development [14,15]. Nonetheless, these aspects may be overshadowed by the operational dynamics that link smelting and converting (Figure 2), and that define conventional copper smelters.

Smelting and converting are truly the central operations in a copper smelter, as they transform the mineral input into a metallic, albeit unrefined, output. The centrality of smelting furnaces is apparent from the wording, since the plant is actually called a "smelter". Interestingly, the English word "melt" has synonymous origins with the Germanic "smelt" [16]. In modern language, however, smelting implies melting (i.e. a change-of-state from solid to liquid), plus an additional degree of processing, which may involve chemical reactions and/or separation of byproduct phases. Historically speaking, converting emerged as a separate operation from smelting in the mid nineteenth century for steelmaking, and was adapted to coppermaking in the early twentieth century [17,18], coinciding with the advent of Peirce-Smith converting, described in the following section.

For both steelmaking and coppermaking, it was found that only a portion of the reactions should be performed in the presence of the incoming solid mineral, i.e. in a smelting furnace. It is indeed beneficial to transfer an intermediate molten product (read matte) into a subsequent converting operation, which is intensive, and which yields a brute metal product (read blister copper). The distinction between pyrometallurgical converting and refining is somewhat qualitative: converting is perceptively more intense than the subsequent refining processes, and usually implies a greater change in the material composition. In both steel- and copper-making, the converted metal undergoes liquid-state refinement (read fire-refining), prior to casting [5,19].

Figures 2 and 3 are a simple overview of conventional copper smelters, accompanied by a simple introduction to metallurgical terms: smelting versus converting, matte versus slag, anode versus cathode, etc. Yet in reality, a copper smelter is a complex organization that is continually subjected to economic, social and environmental challenges. Engineers and managers are confronted with operational problems that are multifaceted, in which the most effective solutions come from an exchange of ideas. The organization must therefore consider a common (simplified) understanding of the process, which is understood across departments, and is the origin of problem-solving. Additional levels of details are introduced incrementally, isolating the aspects of the smelter that are most relevant to the problem at hand, and to the profitable extraction of copper.

II. PEIRCE-SMITH CONVERTING AS A BOTTLENECK

The original patent for Peirce-Smith (PS) converting was granted to William Peirce and E.A.C. Smith in 1909, extending earlier developments in copper and steel production [17,18]. Over a hundred years later, PS converting technology is still extensively used, applied in virtually every conventional copper smelter [2,3]. Furthermore, this technology continues to be installed within smelters [20].

Several alternatives to PS converting have emerged [9,21,22,23]. They perform similar chemical reactions, but are distinguished by the vessel geometry, as well as the mechanisms for handling incoming feeds and outgoing products. For the purposes of this paper, these alternatives may be considered "conventional", if their main feed is molten matte, and they produce discrete batches of blister copper (Figure 2). For example, a Hoboken converter is a PS converter with an integrated siphoning system for improved offgas capture [9]; it is nonetheless conventional, in the sense of Figure 2. In contrast, there are several nonconventional approaches to produce blister copper continuously [21], rather than in batches. Kennecott-Outotec Flash converting is especially unconventional [22], since the matte is frozen into solid granules, and possibly stockpiled, prior to being fed into the converter.

Within a given smelter, PS converting may be identified as an operational bottleneck by inquiring about the daily scheduling practices [24]. In particular, the smelting furnace can usually produce and hold matte, which exceeds the immediate converting capacity, assuming that the smelting operators are allowed an appropriate lead-time; the smelting schedule is thus a function of the converting schedule. Furthermore, since converting and smelting are the

two most demanding operations within a smelter, they impose scheduling restrictions for all other critical operations. Ultimately, the converter schedule sets the tempo for the entire smelter and is, in this sense [8,24], a bottleneck.

PS converters are pervasive in the copper industry, partly because of their simplicity. They are barrels with a mouth that receives matte and secondary feeds, and from which the slag and blister copper are discharged; the mouth also functions as a gas outlet. Charging and discharging are performed when the mouth is rotated in a forward position (Figure 4a). The converting reactions are performed when the mouth is positioned upward, and covered with a hood that captures the offgas (Figures 4b and 4c). Oxygen-enriched air is blown into the melt, as N_2 and SO_2 are exhausted through the hood. The offgas is captured so that the SO_2 may be converted into sulfuric acid. Nitrogen has a particularly important role as a convective coolant, entering the system at roughly 50°C and leaving the system at roughly 1200°C.

A converting cycle begins when an empty converter receives an initial charge, including one or more ladles of matte, plus an amount of cold charge. The converter is then rotated into the blowing position, so that the converting reactions can be applied. There are in fact two stages in copper PS converting. The first stage is known as the Slag-Blow, producing an iron-rich slag that floats above the matte (Figure 4b). To prevent the vessel from overflowing, it may be necessary to halt the blowing intermittently, and skim away the accumulated slag. This provides space for one or two additional ladles of fresh matte, and perhaps some cold charge, before resuming the Slag-Blow. Eventually, the last of the slag is skimmed away, leaving a bath that has less than 1% iron [9]. Continued blowing to react the matte is referred to as the Copper-Blow, causing the emergence of blister copper, which sinks below the matte (Figure 4c). Eventually the last of the matte is converted into blister copper. The discharging of the copper signifies the end of the converter cycle. Both the Slag- and Copper-Blows are exothermic, and would tend to overheat the vessel, if not for nitrogen convection, and the cooling effect of solid cold charge.

Chemically speaking, the matte is initially a mixture of FeS and Cu_2S. Ideally, the Slag-Blow is described as

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

However, a portion of the iron forms into unwanted viscous magnetite (Fe_3O_4), rather than fayalite ($2FeO{\cdot}SiO_2$), although this can be controlled by adjusting the composition of the flux [9,12]; this flux is predominantly silica (SiO_2) granules, combined with other stable oxides, such as CaO, MgO and Al_2O_3. In addition to slag viscosity, the flux composition affects the transport of minor elements, including arsenic, bismuth, silver and gold [9,25]. Minor elements notwithstanding, it is preferable for the slag to have low viscosity, so that it may be effectively skimmed. Furthermore, magnetite is a less productive usage of blast oxygen than fayalite, consuming 267.6 Nm^3 of O_2 per tonne of Fe, instead of 200.7. After the iron has been removed as slag, continued blowing corresponds to the Copper-Blow,

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

thus producing blister copper.

The duration of a converter cycle can be 2 to 12 hours, depending on the processing parameters in Table 1, as well as the nature and quantity of secondary feeds. The intensity of the converting operation can be quantified by multiplying the blast rate and oxygen enrichment. From this, cycle duration can be estimated roughly, by assuming

TABLE I. RANGES OF OPERATING VALUES FOR A PS CONVERTER

Parameter	Range	Unit
Matte copper grade	50 – 75	Weight %
Quantity of matte	100 – 500	Tonnes
Blast rate	250 – 750	Nm^3/min
Oxygen enrichment	21 – 28	Volume %

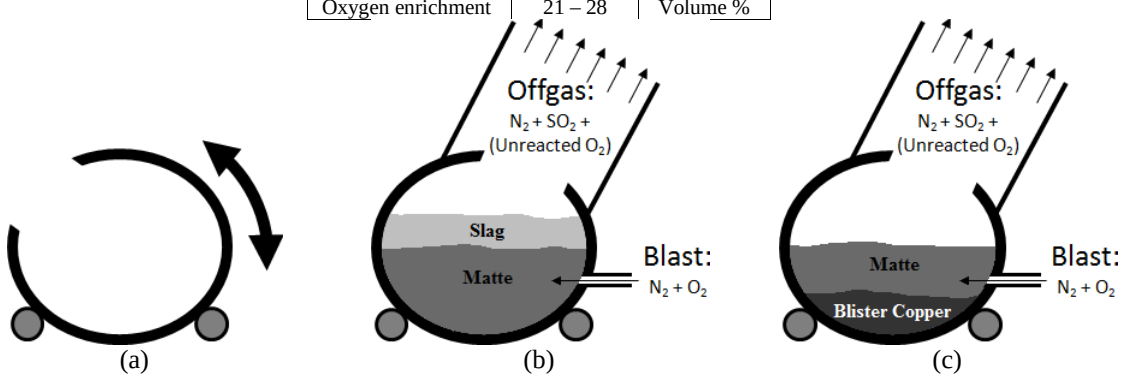


Fig. 4. Cross-sectional view of Peirce-Smith converter, in (a) rotating into or out of charging/discharging position, (b) during a Slag-Blow, and (c) during a Copper-Blow.

that 85–95% of the incoming oxygen reacts with the melt [26]; also, roughly 80–95% of the incoming iron is reacted to form fayalite, and the rest forms magnetite. Nonetheless, the characterization of cold feeds is usually unreliable, which induces statistical variations in converter cycles.

The matte grade is a key consideration in Table 1. Indeed, the Slag-Blow is effectively a continuation of the smelting reactions. For instance, a high-grade matte is mainly Cu_2S, with nearly all of the FeS having been eliminated during the smelting operation; this type of matte is called "white metal", with grades above 70% copper, as can be obtained by bath smelting technology [2]. In these cases, the converter cycles are relatively short (2 - 4 hours), and are dominated by the Copper-Blow.

There is generally some leeway to adjust the matte grade, thus re-distributing the workload between smelting and converting. However, the matte grade can only be changed slowly, over several hours, as the content of the smelting furnace is gradually passed downstream. In certain plants, the matte grade may be steadily tuned so that the smelting capacity is equal to the converting capacity; this maximizes the copper throughput, in a deterministic sense. In reality, however, these plants should set the matte grade below the deterministic optimum, leaving some extra capacity for the smelting furnace. This extra capacity allows the smelting furnace to maintain a buffer against the statistical variation that affect the converting operation. Therefore, when a converter cycle is completed faster than average, the subsequent cycle may draw upon the buffer; the buffer is then reestablished by activating the extra smelting capacity.

Statistical variations have a direct impact on what the matte grade should be, hence what the copper throughput should be. Incidentally, for a typical smelter, 5% of lost throughput corresponds to millions of dollars of lost revenue per month [27]. Even so, the negative impact of statistical PS cycle variation is not commonly understood. The matte grade should take into account the performance curves of the smelting furnaces, as well as the probability distributions for converter cycle times [28]. Moreover, local operational changes cannot be accurately quantified, unless they are simulated along with the corresponding changes in matte grade [28], scheduling practices [29], and other global considerations.

As a bottleneck, PS converting is notably different than what is classically observed in manufacturing systems [6,8]. Indeed, the flexible matte grade allows some of the Slag-Blow to be transferred to/from the smelting operation. This peculiar relationship between buffer and bottleneck is not possible in a classical assembly line, for instance. Indeed, the Lean doctrine employs buffers to ensure throughput, as per the Kanban system [7], but it is not directly applicable to PS converting because of the effect of variable matte grade. However, the Theory of Constraints (TOC) also considers buffers and bottlenecks [6,8], and is a generalization of the Lean doctrine that has been applied in the minerals industry [29,30]. TOC deliberately avoids making *a priori* assumptions about a particular organization or production environment, and is thus better suited to PS converting. In fact, much of TOC is to create consensus, emphasizing multidisciplinary teamwork, and the Socratic Method [6,31]; this focuses the discussion toward critical process parameters such as matte grade.

TOC states that every organization has a goal that governs its overall behavior. In a commercial organization, the goal is to generate economic profits [6], e.g. a copper smelter is to profitably extract copper. Beyond this, TOC assumes that complex organizations have very few constraints (typically one) that are limiting the organization's ability to attain this goal. The following steps are intended to focus the efforts for ongoing improvements (Figure 5):

1) Identify the system's constraint(s)
2) Decide how to exploit the system's constraint(s)
3) Subordinate everything else to the above decisions
4) Elevate the system's constraint(s)
5) If, in the previous steps, a constraint has been broken, then go back to step 1 (but do not allow inertia to cause a system's constraint)

In this sense, a constraint is "broken" if it is no longer directly limiting the economic throughput. Steps 1 – 3 do not

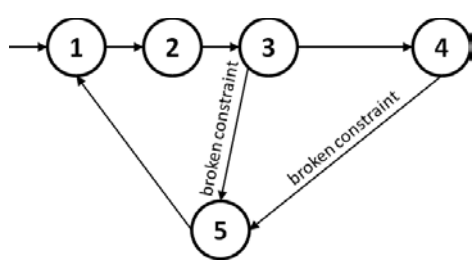


Fig. 5. Five focusing steps of the Theory of Constraints

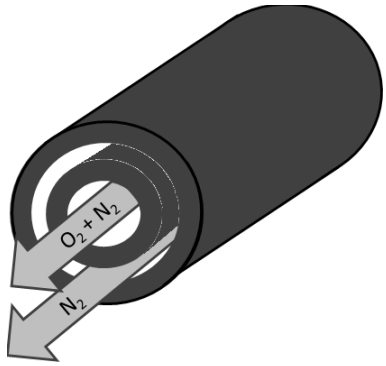


Fig. 6. High-pressure shrouded injectors.

require any significant capital investment, and often reveal 10 – 30% of hidden capacity [6]. In particular, Step 3 implies a global coordination, propagating the decisions of Step 2 to the relevant areas of the organization; these relevant areas can be identified with the help of Cause-and-Effect diagrams [32]. Only after the exploitation and subordination are complete, and only if this has not broken a constraint, should Step 4 be considered. In this sense, a constraint is "elevated" when it is broken via the deployment of organizational resources; this may require significant capital investment. However, organizations are reluctant to make such investments, unless they can be adequately justified, both qualitatively and quantitatively.

PS converting is criticized for its SO_2 fugitive emissions, whenever levels of SO_2 in the surrounding neighborhood exceed the allowable limit. Following strict environmental legislation, it has become common practice to limit the number of simultaneous converter cycles, so as not to overwhelm the offgas handling system [26]. Environmental legislation has impacted copper throughput, although this has been mitigated by a more rigorous coordination of the offgas handling system, with the smelting furnace and converting furnaces [33,34]. In the terminology of TOC, the offgas handling system is a "capacity-constrained resource".

For over 30 years [9,23,35,36], efforts have been made to increase the oxygen enrichment, thus to intensify the converting operation and increase the smelter throughput. As noted in Table 1, the traditional PS tuyeres are normally incapable of surpassing 28% [26]. At higher levels, the refractory lining suffers dramatic abrasion in the areas surrounding the tuyeres, rapidly rendering the vessel inoperable. At a sufficiently high pressure, however, the blast forms a sonic jet that penetrates deep into the melt, and is hence less abrasive than traditional operating conditions [26]; this allows the oxygen enrichment to be raised to over 35%. To further surpass this limit, the PS tuyeres can be retrofit with co-axial high-pressure injectors, which have been adapted from the steelmaking industry (Figure 6); the cooling nitrogen is concentrated in the outer periphery, thus freezing a protective shroud over the surrounding refractory. This co-axial approach can support oxygen enrichment levels as high as 50%. It is an integral part of the SKS technology, which is the most recently developed alternative to PS converting [23]. Incidentally, higher oxygen enrichment results in a stronger offgas (proportionately more SO_2, and less N_2), which is favorable for acid production [26].

An elementary mass balance would suggest that an increase in PS oxygen enrichment should correspond to an equivalent increase in PS production capacity, hence an increase in smelter throughput. Nonetheless, conventional copper smelters have been remarkably reluctant to adopt high-pressure shrouded injection (HPSI), which is only partly due to a failure to quantify the benefits [36]. Firstly, it should be noted that many smelters apply only moderate enrichments, ~25%, which indicates that enrichment may not be the most immediate constraint. Indeed, a more pressing concern appears to be the stable supply of high-quality cold feed. Ironically, an increase in oxygen enrichment may actually worsen the problem, since the decrease in nitrogen convection should be compensated with an increase in cold feed [26]. It is especially daunting that the cold feed has variable composition, hence variable heat capacity, thus increasing the variance in converter cycles.

In recent work [28], it has been proposed that waterless-matte granulation (WMG) could be installed to guaranty the availability of high quality cold feed (i.e. solid matte granules), which has predictable chemistry, and would therefore diminish the variations in PS cycle duration. Indeed, WMG can endow a conventional PS aisle with a key advantage of a Kennecott-Outotec Flash converter: a stable buffer of solid matte. Moreover, WMG may be a relatively minor capital investment that could fall within steps 1 – 3 of TOC, and is likely to be a preliminary step toward the gradual increase of oxygen enrichment, and possibly the installment of HPSI. The combined benefit of WMG and HPSI is an ongoing area of research.

A modern smelter can benefit from sensors that operate within the furnaces, and are linked to expert control systems. In particular, the Semtech OPC (Optical Production Control) signals the end of a PS converting cycle, providing tight controls on the residual sulfur that is retained in blister copper [14,15]. This sensor is particularly beneficial in reducing the variation (and costs) associated to the fire-refining process. Nonetheless, its adoption by industry has been relatively modest. Profitable copper extraction is generally limited by statistical process variation, yet there seems to be a shortage of conceptual and computational methodology that would justify the implementation the Semtech OPC, or that would motivate the development of new sensors. Following successful experiences in the manufacturing, the TOC may provide some guidance in such matters.

The authors of this paper believe that future copper smelters will have much tighter control on feed chemistry and converting cycles, benefitting from modern concepts in operations management, as well as innovative sensors and control systems. These advances cannot be directly transferred from the manufacturing paradigm, since copper smelters present their own set of particularities. Future development will therefore rely on multidisciplinary collaboration.

III. HIERARCHICAL FRAMEWORK TO SIMULATE CONVENTIONAL COPPER SMELTERS

When applying TOC to manufacturing systems, particular attention is given to the combined effect of interdependent discrete events, and statistical variation [6]. In the context of conventional copper smelters, the throughput is discretized by the converting operation, resulting in discrete batches of blister copper. Moreover, there are statistical variations due to the poor controls on secondary feeds, as well as fluctuations in oxygen efficiency and slag chemistry.

TOC explains the detrimental effects that occur when bottlenecks suffer from statistical variations. In general, a plant is running at full capacity only if a bottleneck is running at full capacity. Thus, if there is a negative event (or statistical deviation) that causes a temporary slow-down at the bottleneck, this implies a decrease in throughput for the entire plant. However, the converse is not true. Indeed, if there is an unexpectedly positive event (or statistical deviation), this does not necessarily result in increased productivity, considering that the bottleneck may already be operating at full capacity. Thus, the negative deviations are not canceled by positive deviations. For copper smelters, this implies that an efficient converter cycle does not necessarily compensate for an inefficient cycle.

To quantify the effect of statistically variable converter cycles, a simulation framework has been implemented using the commercial software Rockwell Arena© [24,28]. This software supports Discrete Event Simulation [37], thereby capturing the interdependence of events, combined with statistical variation. Additionally, the OptQuest® engine has been integrated into Arena®.(OptQuest® has also been incorporated into other simulation software packages such as @Risk® and Crystal Ball®). This engine applies metaheuristics and neural networks, as well as mathematical optimization techniques, to search for optimal parameterizations [38]. Specifically, OptQuest® can be used to determine appropriate matte grades that would maximize copper throughput.

The smelter simulation framework is hierarchical, meaning that different components of the smelter operation are represented as submodels. In accordance with multidisciplinary problem solving [32], each submodel can be developed and presented with a level of detail that is adequate to the problem at hand. In some cases, it may be helpful to develop *sub*submodels. For the purposes of this paper, the framework has been adapted to represent a simple conventional smelter, which maintains two operational converters.

In these types of smelters (e.g. the Ronnskar Smelter, [39]), there is usually a limited capacity for offgas, such that blowing may occur in only a single converter at a time. Therefore, the converting cycles are coordinated as per Figure 7; blowing begins in one converter, exactly as it is ends in the other, thus alternating between Converters 1 and 2. Larger smelters may have sufficient offgas capacity so that there may be two simultaneous converter blows. When the converters have different sizes and efficiencies, the coordination may be complex, and specialized scheduling algorithms can help maximize the daily throughput [24,33,34].

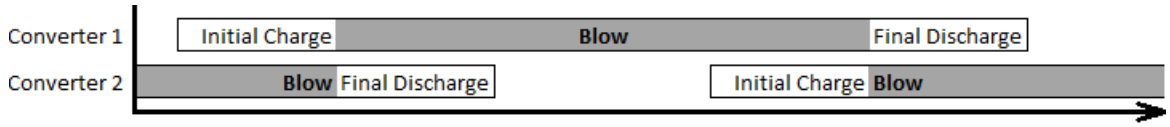


Fig. 7. Overlapping between converting cycles in Converter 1 and Converter 2. Blowing is being performed in one converter at a time, due to limited offgas handling capacity.

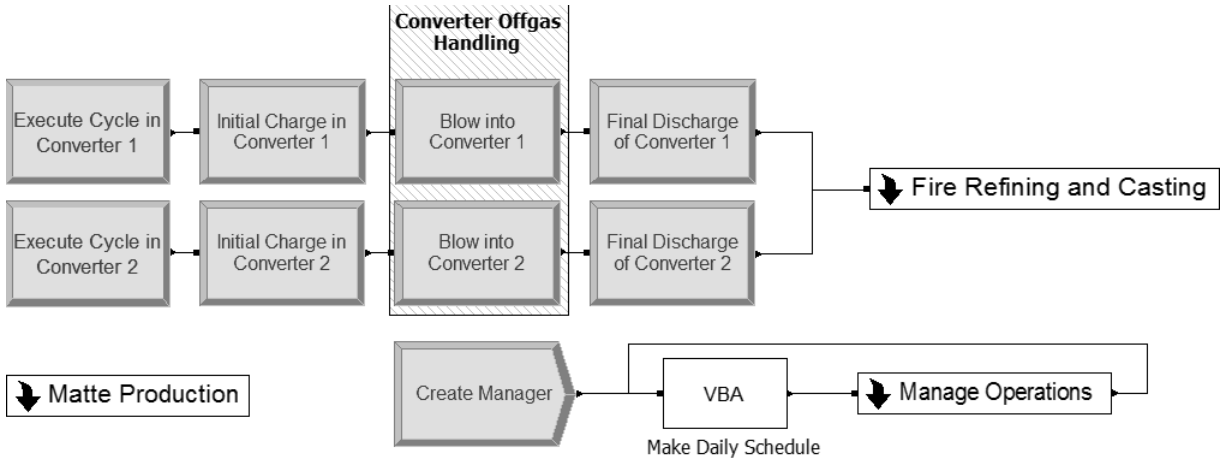


Fig. 8. Simulation model implemented in Arena©, to simulate copper smelter operation, with two converters.

The simple two-converter model is depicted in Figure 8. To signify the beginning of a cycle in converter 1, a red ball emerges from the *Execute Cycle in Converter 1* module. The converter is loaded with an initial charge, as the ball passes into the *Initial Charge in Converter 1* module, which requires a certain amount of time before the ball can pass into the following module, *Blow into Converter 1*. Moreover, the ball is not allowed to enter the *Blow into Converter 1* if another ball is occupying the *Blow into Converter 2* module, i.e. if there is an ongoing blowing operation in Converter 2; again, the limited offgas handling capacity prevents simultaneous blowing into two converters (Figure 7). The final discharge of the cycle is represented by *Final Discharge of Converter 1*. The completed cycles from both converters are sent into the *Fire Refining and Casting* submodel.

Figure 8 includes three submodels: *Fire Refining and Casting*, *Matte Production*, and *Manage Operations*. Each of these may be double-clicked so that they may be examined and developed in more detail, using the intermediate features of Arena© [40]. A converting cycle is not executed, until appropriate conditions are met within the *Matte Production* and *Manage Operations* submodels. In particular, *Matte Production* ensures that there is enough matte for the initial charge before executing a cycle, and *Manage Operations* ensures that the cycles alternate between Converters 1 and 2.

The *Manage Operations* submodel works in conjunction with the Visual Basic For Applications© (VBA) block, and is essentially the "brain" of the smelter. A single green ball is emitted from the *Create Manager* module at the beginning of the simulation, and enters the VBA block to obtain the daily production scheduling. This scheduling algorithm encapsulates the automated logic that is used to coordinate smelting and converting operations with critical resources and activities. There is a question as to which resources and activities to consider in the model; this depends on the problem at hand. In addition to smelting and converting, the current paper considers only the offgas handling, and the oxygen supply. In general, the framework can be used to compare different operational policies by changing the scheduling algorithm that is accessed by the VBA block, as well as the tactical responses to unexpected events that are implemented within the *Manage Operations* submodel.

Normally, the green ball emerges from the *Manage Operations* at the end of a simulated scheduling period, which represents 12 or 24 hours, depending on the smelter. The green ball is cycled back into the VBA block, in order to produce the next cycle. 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 [24,33,34]. However, there may certain events that trigger an unexpected scheduling. For example, there may be an unexpected breakdown in the acid plants, requiring a temporary change in the mode of operation, until the acid plant can be fixed; therefore, the green ball is released prematurely so that it can obtain a new schedule that corresponds to the new operational conditions.

Copper smelters exhibit an atypical relationship between the bottleneck (converting aisle) and the preceding buffer (smelting furnace), as described in the previous section. In classical manufacturing systems, a target buffer level is maintained to ensure that there is no interruption in the feeding of a bottleneck; an interruption of the bottleneck corresponds to lost throughput for the entire plant. In the case of copper smelters, the problem of determining an appropriate buffer level is coupled with the matte grade; it is faster to replenish low grade matte than high grade matte. The model of Figure 8 has been configured to quantify this effect, using the parameters described in Tables II and III, which are representative of actual operations [2,9,26]. For simplicity, the charging and discharging times have been set to zero.

TABLE II. MASS BALANCE PARAMETERS FOR SAMPLE COMPUTATIONS

Parameter	Value	Unit
Concentrate copper grade	35	Weight %
Concentrate iron grade	30	Weight %
Concentrate sulfur grade	35	Weight %
Oxygen capacity	400	Nm^3/min
Oxygen efficiency during smelting	90	%
Oxygen efficiency during converter Slag-Blow	90	%
Oxygen efficiency during converter Copper-Blow	90	%
Iron reacted during smelting that becomes fayalite	95	%
Iron reacted during converter Slag-Blow that becomes fayalite	80	%

TABLE III. LADLE-RELATED PARAMETERS FOR SAMPLE COMPUTATIONS

Parameter	Value	Unit
Ladle volume	15	m^3
Ladles for converter cycle initiation	4	-
Total ladles converted during converter cycle	5	-

Table II assumes that the concentrate is pure chalcopyrite, which is the most typical copper mineral [5]. The oxygen capacity of 400 Nm^3/min is to be shared between smelting and converting [27]. Throughout smelting, and both stages of converting, it is assumed that 90% of the incoming oxygen reacts with the melt. However, smelting is more effective then converting in the formation of fayalite, 95% versus 80%; the remaining iron forms magnetite.

The problem is to determine which matte grade maximizes copper throughput. Due to technological limitation, the matte grade is confined between 50% and 75% copper. Considering the fixed oxygen capacity, analytical techniques (i.e. linear programming [41]) prove that the deterministic optimum is at one of the two extremities, be it 50% or 75%. Given the parameters of Table II, the optimum is obtained with a matte grade of 75%. Essentially, the oxygen is more productive in the smelting furnace than in the converters, considering that it is more effective at fayalite formation. With a matte grade of 75%, the deterministic optimal throughput is roughly 267000 T/year of copper.

To incorporate the effect of statistically variable converter cycles, it is necessary to consider how much matte is processed within each cycle. Table III considers a fixed volume of matte per cycle, regardless of the matte grade. Four ladles are used for the initial charge, followed by a fifth ladle is inserted after the first skimming, giving a total of 75 m^3. To calculate the expected cycle time, this volume must be multiplied by the matte density, thus to convert it into a mass, and to apply a mass balance with the parameters of Table II. Nonetheless, the matte density is a function of the matte grade. Considering that matte is a mixture of Cu_2S and FeS, its density can be approximated as a weighted harmonic mean [28].

Having programmed the mass balance, and the density equation within the Arena model, OptQuest has been used to maximize copper throughput (Figure 9), by searching for appropriate matte grades (Figure 10). For simplicity, the converter cycle times were assumed to follow a Gaussian distribution, considering three different coefficients of variation (CV): 0.5, 1.0 and 1.5. Admittedly, realistic CV values are likely to be at or below 0.5. Nonetheless, the higher variations have been included for demonstrative purposes.

The horizontal axis of Figures 9 and 10 is the target buffer volume (TBV). This is taken to be the additional furnace capacity that is beyond the amount required for an initial converter charge. For example, if the TBV is 30 m^3, then the smelting furnace continually produces matte whenever the furnace level is below 90 m^3; this considers the 60 m^3 amount required for an initial converter charge (see Table III), plus the additional 30 m^3 buffer volume. Figure 9

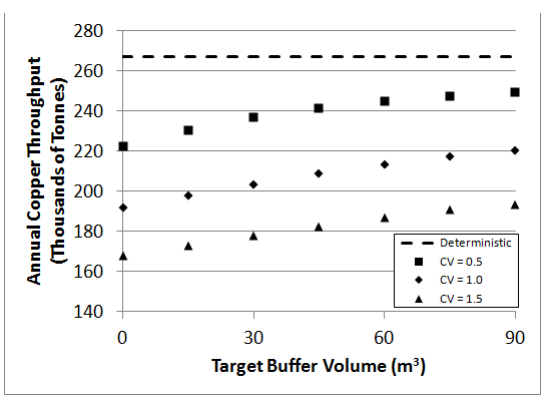
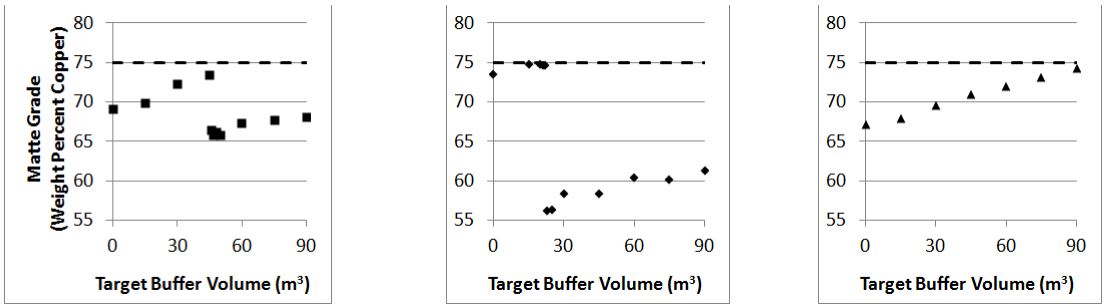


Fig. 9. Optimal annual throughput, as a function of target buffer volume, and coefficient of variation of converter cycle times.



(a) (b) (c)

Fig. 10. Optimal matte grade as a function of target buffer volumes, with coefficient of variation of converter cycle times equal to (a) 0.5, (b) 1.0 and (c) 1.5.

illustrates the negative effects of converter cycle variation; even the CV values of 0.5 are well below the deterministic optimum of 267000 T/year. Nonetheless, the buffer capacity mitigates the effect of statistical variation, as in classical manufacturing systems [6,7]. Unlike classical manufacturing systems, however, the optimal utilization of the buffer volume requires the careful adjustment of the matte grade. Indeed, the throughput values of Figure 9 are based on the matte grade values that have been proposed by OptQuest, and have been graphed in Figure 10.

Curiously, Figure 10a shows two competing trends. When the TBV is below 45 m^3, the tendency is maintain relatively high matte grades, favoring the productive fayalite formation that occurs in the smelting furnace. Nonetheless, the matte grade is kept below the deterministic optimum (75%), to ensure that the initial charges are produced sufficiently quickly to avoid delays in converting; this is especially the case when there is no buffer. However, a different trend dominates in the righthand side of Figura 10a, in which the priority is to utilize the buffer capacity in order to avoid delays in converting. This second trend represents a less efficient use of oxygen, which is compensated by having a more reliable supply of matte. The same two competing trends are also observed in Figure 10b, however the transition occurs when the TBV is roughly 23 m^3. Figure 10c is dominated by an extension of the second trend, in which the more buffer capacity is available, the less beneficial it is to deviate from the deterministically optimum matte grade.

Copper smelter engineers are not aware of how much throughput is being lost, simply due to poor bottleneck management. Figures 9 and 10 illustrate the importance of matte grade and TBV settings, in mitigating the effects of statistically variable converter cycles. These fundamental aspects must be considered within management policies (Steps 1 – 3 of TOC), prior to seeking capital investments (Step 4 of TOC), to implement plant upgrades. Without quantitative and qualitative justification, many conventional copper smelters will not obtain the appropriate upgrades, will not be competitive with newer plants that employ flash or SKS converting [22,23].

IV. FUTURE WORK

The concepts described in this paper will lead to important changes in the way copper smelters are being operated. The computational framework can incorporate data from any conventional copper smelter, and may be adapted to include whichever features are of particular interest, to analyze the constraints that are actively limiting the profitable extraction of copper. The authors hope to quantify the benefits of existing technologies such as HPSI, WMG and Semtec OPC, and to support ongoing innovations, such as new sensors and automated learning processes.

The research presented in this paper is concurrent to ongoing plant work in several copper smelters. The authors are committed to collaborating 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 problems. By participating in conferences such as International Conference on Industrial Engineering and Operations Management, partnerships will be established that will hopefully allow this research to progress.

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