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Optimal Selection of Matte Grade in Copper Smelting Process ⋆

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Abstract: This work presents the sensitivity analysis of a hierarchical scheduling framework for the copper smelting process with respect to the change in matte grade. The aim is to find the matte grade that can maximize the throughput of the copper smelting process. This study considers multiple-PSC units and a multiple-batch hierarchical scheduling framework that finds an optimal schedule for the process using promising heuristics. The process is briefly discussed, and the simulation results are discussed in detail to provide a comprehensive view of the effects of the matte grade on the operation of the copper smelting process.

Keywords: Process optimization, Maintenance scheduling and production planning, Applications in advanced materials manufacturing

1. INTRODUCTION

In process industry, copper smelters are used to extract copper from copper ores. Optimal operation and scheduling of the copper smelting process have become more and more important and attractive in the 21st century when markets call for competitive and sustainable development in the copper industry. During the operation of the copper smelting process, part of the copper in the concentrate is lost to the waste which affects the throughput of the process (Ahmed et al. (2021), Davenport and Partelpoeg (2015)). Furthermore, high-quality copper ores are running out, and the use of low-quality concentrates is becoming a standard practice (Ahmed et al. (2021)). Hence, there is a growing interest in the copper industry to reduce those copper losses to address the growing imbalance between the copper supply and demand ((ICSG)). One way to address this challenge is to find the optimal matte grade, which can reduce copper losses during the process operation, thereby increasing the throughput.

Copper smelting is a large-scale industrial process consisting of a flash smelting furnace (FSF), Peirce-Smith converters (PSC), an anode furnace (AF), and other smelting units. Two units that contribute significantly to copper loss are the FSF and PSC units (Ahmed et al. (2022)). The FSF produces matte of the desired grade. Process personnel typically determine this matte grade beforehand.

The matte grade is a deciding factor in the copper smelting process as it affects the copper losses, matte production, input concentrates usage, and the PSC batch time (Davenport and Partelpoeg (2015)). Increasing the matte grade decreases the FSF matte production as more impurities are removed from the input concentrates, which makes the FSF the bottleneck for the entire process. Contrary to that, decreasing the matte grade increases the FSF matte production. If the PSC units are unable to process the matte at the same rate it is produced by the FSF, they will act as a bottleneck for the entire process, causing a slowdown in the entire process. Furthermore, if a lower matte grade value is selected for the process operation, the FSF input concentrates feed rate could be compromised to respect the FSF storage capacity constraints. Generally,

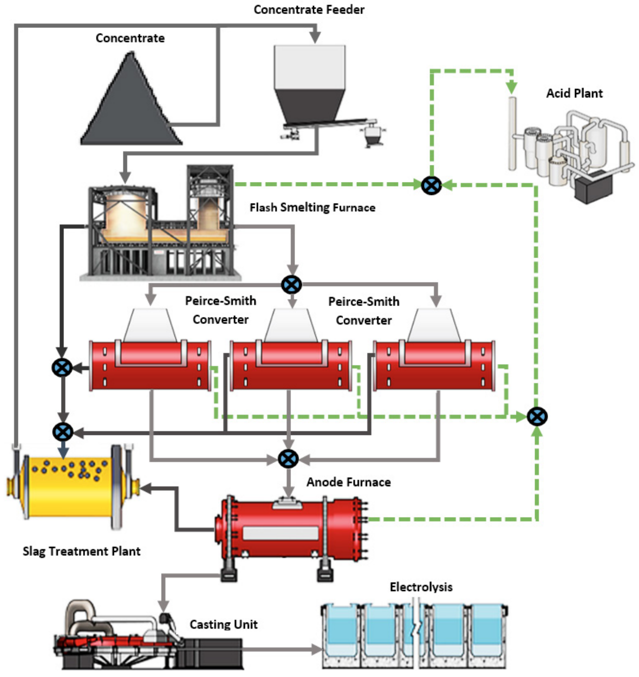

Fig. 1. Copper smelting process (adopted from (Ahmed et al. (2021)))

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decreasing the FSF feed rate is not favored as it directly affects the throughput of the smelting process. In addition to that, copper losses start to increase in the FSF as the matte grade increases, while they decrease in the PSC with the increase in the matte grade value (Ahmed et al. (2021)). Thus, process personnel is keen to find the optimal matte grade that can provide a cost-effective operation without compromising on the throughput of the process.

To design a scheduling framework for a large-scale process, two potential approaches are centralized and hierarchical. In the centralized approach, all the information of the process is gathered centrally with no distinction among the process units (Marcos et al. (2014)). Rojas et al. (2006) proposed a centralized scheduling framework for the copper smelting process that maximizes copper production while considering various environmental and operational constraints. Similarly, Harjunkoski et al. (2006) used continuous-time mixed integer linear programming (MILP) techniques to develop a centralized scheduling framework that aims to maximize the throughput of the smelting process. Another continuous-time centralized scheduling framework was proposed by Suominen et al. (2016), which also focuses on maximizing smelting production while providing an optimal schedule. In our prior work (Ahmed et al. (2022)), we have developed a centralized scheduling approach that resolves process inter-dependencies and provides a plant-wide optimal solution. Our findings indicated that this approach is useful for a smelting process with a small number of units only. The centralized approach is generally undesirable for a large-scale process, such as a copper smelting process, considering the computational demands, scalability, single-point failure, and data-protection issues (Marcos et al. (2014), Moroşan et al. (2010)).

An alternative to the centralized approach is the hierarchical approach which treats each unit as an independent scheduling problem and a coordinator is used to enable communication between these scheduling problems. It offers the advantage that the size of the scheduling problem does not increase with the addition of new units, allowing for plant-wide optimization with minimum computational costs. Therefore, the hierarchical approach has attracted significant interest in developing scheduling solutions for large-scale processes. For instance, Ruben et al. (2013) developed a hierarchical framework that uses price-based heuristics to achieve a plant-wide solution for a process that consists of four sub-processes. In our previous work (Ahmed et al. (2022)), we designed a hierarchical scheduling framework for the copper smelting process, which uses hard heuristics to resolve process inter-dependencies and provide a feasible schedule. In another study (Ahmed and Vilkko (2023)), we developed a hierarchical scheduling framework that finds a feasible schedule for the copper smelting process by resolving process inter-dependencies using price-based heuristics. This framework uses PI controllers to calculate the optimal prices to achieve an optimal solution. The studies mentioned above overlook the crucial aspect of selecting suitable matte grades, which can significantly enhance the process throughput. Consequently, the effectiveness of the proposed solutions may be constrained in various real-world copper smelter applications.

Motivated by increasing the throughput of the smelting process, this study provides a sensitivity analysis of a hierarchical scheduling framework to the change in the matte grade. The objective is to find a matte grade that maximizes the FSF feed rate and decreases the copper losses during the process operation. The scheduling framework examined in this study is developed using discrete-time techniques, which employ effective heuristics to address the inter-dependencies among the process units.

2. HIERARCHICAL FRAMEWORK FORMULATION

The objective of the copper smelting process is to maximize the throughput of the AF by minimizing the copper losses during the process operation and to maximize the FSF feed rate, as given in equation (1). Here, h is the scheduling instant, H is the maximum value of the scheduling horizon, $feed_{FSF}$ is the FSF feed rate, Cu_{FSF} represents the copper loss during the FSF operation, and Cu_{PSC} is the copper loss during the PSC operation.

$$\max_{\substack{feed_{FSF},\\ Cu_{FSF}, Cu_{PSC}}} \sum_{h=1}^{H} feed_{FSF}^{h} - \sum_{h=1}^{H} (Cu_{FSF}^{h} + Cu_{PSC}^{h}) \quad (1)$$

Inter-dependencies between the FSF and PSC units exist due to the violations of FSF storage capacity limits, and PSC logistical and flow constraints. Inter-dependencies arise from the FSF when the matte in the FSF exceeds its maximum storage capacity or drops below its minimum storage threshold. Logistical inter-dependencies between the PSC units exist when a low-priority PSC unit requests for matte loading before preceding high-priority PSC units. Similarly, flow inter-dependencies arise when two or more PSC units are in the slag blow or copper blow stage simultaneously.

This hierarchical framework is subject to multiple assumptions. The composition of input concentrates has a significant effect on the copper smelting process. Although the proposed framework can generate a viable solution for any type of input concentrate, a commonly used type of input concentrate is chosen to offer a more practical solution. Moreover, this study does not focus on a specific FSF; therefore, the initial inventory of FSF and the feed rate of input concentrates are chosen arbitrarily. The FSF processes the same types of input concentrates and produces matte with a grade that is defined by the process personnel beforehand.

The PSC units may be available concurrently or at different times. In the latter case, the earliest available PSC unit is assigned with the highest priority, and the lowest priority is assigned to the latest available unit. If multiple units are available simultaneously, priority is assigned randomly. All PSC units are the same in dimensions and follow a consistent sequence of operations to produce batches of blister copper. Moreover, the FSF nor the PSC units requires any maintenance during the process operation.

The hierarchical framework consists of three entities: a FSF model; a PSC model; and a coordinator. These entities are discussed briefly here, but details are provided in (Ahmed et al. (2022)). Input concentrates are fed to the

FSF to produce matte. This matte production increases with the increase in the feed rate $feed^h_{FSF}$ as concentrates are available at a faster rate for the matte production, while it decreases with the increase in the matte grade mg as the FSF requires more time to oxidize the required amount of unwanted elements, as given in equation (2). Equation (3) provides the amount of matte produced during the FSF operation. Here, $matte_{trans}$ is the amount of matte shifted from the FSF to a PSC unit, and $PSC^{n,h}_{load}$ contains the matte loading time to the PSC unit n at time instant h.

During the FSF operation, the matte grade mg is selected that remains unchanged, while the feed rate $feed^h_{FSF}$ is open to adjustment. The objective of the FSF is to maximize the input concentrates feed rate and minimize the copper losses, as given in equation (4). The matte is transferred periodically to the PSC units for further processing where it passes through multiple slag blow stages and one long copper blow stage before it is available to the AF.

$$\begin{aligned} &prod^h_{FSF} \propto feed^h_{FSF} \\ &prod^h_{FSF} \propto \frac{1}{mg} \\ &feed_{min} \leq feed^h_{FSF} \leq feed_{max} \end{aligned} \tag{2}$$

$$\begin{aligned} mass^h_{FSF} &= mass^{h=0}_{FSF} + mass^{h-1}_{FSF} + prod^h_{FSF} \\ &- matte_{trans} \times \sum_{n=1}^{N} PSC^{n,h}_{load} \end{aligned} \tag{3}$$

$$\max_{feed_{FSF}} \quad f_{FSF} = \sum_{h=1}^{H} (feed^h_{FSF} - Cu^h_{FSF}) \tag{4}$$

To ensure that only one operation occurs inside the PSC at a single time and that all operations follow the proposed scheduling recipe, equations (8) and (9) are used. Here, t is the scheduling time of an individual PSC batch, z_i is the i^{th} repeating operation in the PSC $(z \in Z, i \in I)$, $b^t_{z_i}$ represents the occurrence of an operation inside PSC at time t, while the $s^t_{z_i}$ ensures that all the operations are scheduled in the same manner as described by the process personnel. The scheduling recipe is typically predefined and stored in the set Z, which specifies the order of operations. The scheduling horizon for PSC units is typically much shorter than the overall scheduling horizon $(T << H)$.

To address inter-dependencies at a batch level, the PSC model receives conflicting loading times $LogisNo^h$, blowing times $FlowNo^h$, and FSF capacity violating instances $FSFNo^h$ from the coordinator. Equations (5)-(7) are then utilized by the model to identify the corresponding conflicting time instances. Following that, it uses equation (10) to prevent the PSC unit from executing loading operations or blow operations at conflicting times.

$$PSC^t_{load} = \begin{cases} 1 \;\; LogisNo^h \;\; \forall t = h - Start^{n,b}_{batch}) \\ 0 \;\; \text{otherwise} \end{cases} \tag{5}$$

$$PSC^t_{blow} = \begin{cases} 1 \;\; FlowNo^h \;\; \forall t = h - Start^{n,b}_{batch}) \\ 0 \;\; \text{otherwise} \end{cases} \tag{6}$$

$$FSF^t_{no} = \begin{cases} 1 \;\; FSFNo^h \;\; \forall t = h - Start^{n,b}_{batch}) \\ 0 \;\; \text{otherwise} \end{cases} \tag{7}$$

The PSC model calculates the amount of unwanted elements, and copper losses during the operation process. The objective function of a PSC unit is shown in equation (11), which minimizes the amount of copper losses (Cu_{PSC}), unwanted elements content in matte imp_{PSC}, and unnecessary idle times $idle_{PSC}$ for batch b on PSC unit n. At the end of each iteration, each PSC unit returns its loading timings, blow timings, copper losses, batch end time, and other necessary information to the coordinator.

$$\sum_{\substack{z_i \in \\ operation}} b^t_{z_i} \leq 1 \tag{8}$$

$$\sum_{\substack{z_i \in \\ operation}} \sum_{t=1}^{t} s^t_{z_i} \geq \left(position_{z_i} \times b^t_{z_i+1} \right) \tag{9}$$

$$\sum_{t=1}^{T} b^t_{z_i} \begin{cases} = 0 \quad PSC^t_{load} \neq 0 \text{ or } FSF^t_{no} \neq 0 \\ \qquad\qquad \forall z_i = loading_i \\ = 0 \quad PSC^t_{blow} \neq 0 \\ \qquad\qquad \forall z_i = slag_{blow_i}, copper_{blow} \\ = fix_{z_i} \;\; PSC^t_{load} = 0 \text{ and } PSC^t_{blow} = 0 \\ \qquad\qquad \forall z_i = loading_i,\ slag_{skim_i} \\ \geq min_{z_i} \;\; PSC^t_{load} = 0 \text{ and } PSC^t_{blow} = 0 \\ \qquad\qquad \forall z_i = slag_{blow_i},\ copper_{blow} \\ \leq max_{z_i} \;\; PSC^t_{load} = 0 \text{ and } PSC^t_{blow} = 0 \\ \qquad\qquad \forall z_i = slag_{blow_i},\ copper_{blow} \end{cases} \tag{10}$$

$$\begin{aligned} \min_{\substack{Cu_{PSC}, \\ imp_{PSC}, idle_{PSC}}} \quad f^{n,b}_{PSC} = \sum_{t=1}^{T} \Big(& Cu^{n,b,t}_{PSC} + \\ & imp^{n,b,t}_{PSC} + idle^{n,b,t}_{PSC} \Big) \end{aligned} \tag{11}$$

In this hierarchical framework, the coordinator relies on heuristics to address inter-dependencies between the FSF and PSC units. Since no interlinking constraints exist between these units, a heuristics-based approach is considered optimal for effective coordination. The coordinator is capable of addressing inter-dependencies among the process units and providing a near-optimal solution with minimum computational demands.

The heuristic comprises two parts: the first part addresses inter-dependencies among the FSF and PSC units, while the second part aims to achieve a near-optimal solution with minimal computational costs. Each iteration of the hierarchical framework involves solving for the maximum number of $N \times B$ independent PSC scheduling problems.

For simplicity, this PSC scheduling problem is referred to as *batch*.

At the beginning of the hierarchical framework, the coordinator assigns priorities to the PSC units. To address inter-dependencies, the coordinator provides each batch with three distinct pieces of information during each iteration: $LogisNo^h$, $FlowNo^h$, and FSF^h_{No}. Every batch uses this information, solves the scheduling problem, and returns its solution to the coordinator.

The coordinator arranges batch solutions in ascending order of the batch start times to determine the loading times and blow times over the complete scheduling horizon, as given in equations (12)-(13). $Load^{n,b,t}_{batch}$ contains the loading information of the batch b on PSC unit n, $Blow^{n,b,t}_{batch}$ has the blow information of the batch b on PSC unit n, and $Start^{n,b}_{batch}$ is the start time of the batch. The coordinator sends the $PSC^{n,h}_{load}$ to the FSF model. The FSF model solves its scheduling problem and returns its mass trajectory $mass^h_{FSF}$ to the coordinator. From the $mass^h_{FSF}$, the coordinator determines the conflicting FSF violating time instances using equation (14). Here, max_{FSF} and min_{FSF} are the predefined FSF maximum and minimum matte storage limits. Next, the coordinator identifies the logistic and flow constraints violating times using equations (15)-(16). Finally, the coordinator uses the batch end time $End^{n,b-1}_{batch}$ to update the batch start time, as given in equation (17).

If inter-dependencies exist in the schedule, the coordinator communicates the calculated information with the batches and initiates a new iteration. However, if the schedule is free of all scheduling inter-dependencies, it calculates the total copper losses during the PSC units operation using equation (18), and the simulation stops. Here, N is the total number of PSC units, and B is the total number of batches. Fig. 2 illustrates the operation of the coordinator and how it resolves inter-dependencies. Details about variables and symbols used can be found in (Ahmed et al. (2022)).

$$PSC^{n,h}_{load} = \begin{cases} 1 & h = (Load^{n,b,t}_{batch} + Start^{n,b}_{batch}) \\ & \forall Load^{n,b,t}_{batch} \neq 0 \\ 0 & \text{otherwise} \end{cases} \tag{12}$$

$$PSC^{n,h}_{blow} = \begin{cases} 1 & h = (Blow^{n,b,t}_{batch} + Start^{n,b}_{batch}) \\ & \forall Load^{n,b,t}_{batch} \neq 0 \\ 0 & \text{otherwise} \end{cases} \tag{13}$$

$$FSFNo^h = \begin{cases} 1 & max_{FSF} < mass^h_{FSF} < min_{FSF} \\ 0 & \text{otherwise} \end{cases} \tag{14}$$

$$LogisNo^h = \begin{cases} 1 & \sum_{n=1}^{N} PSC^{n,h}_{load} > 1 \\ 0 & \text{otherwise} \end{cases} \tag{15}$$

$$FlowNo^h = \begin{cases} 1 & \sum_{n=1}^{N} PSC^{n,h}_{blow} > 1 \\ 0 & \text{otherwise} \end{cases} \tag{16}$$

$$Start^{n,b}_{batch} = End^{n,b-1}_{batch} + 1 \tag{17}$$

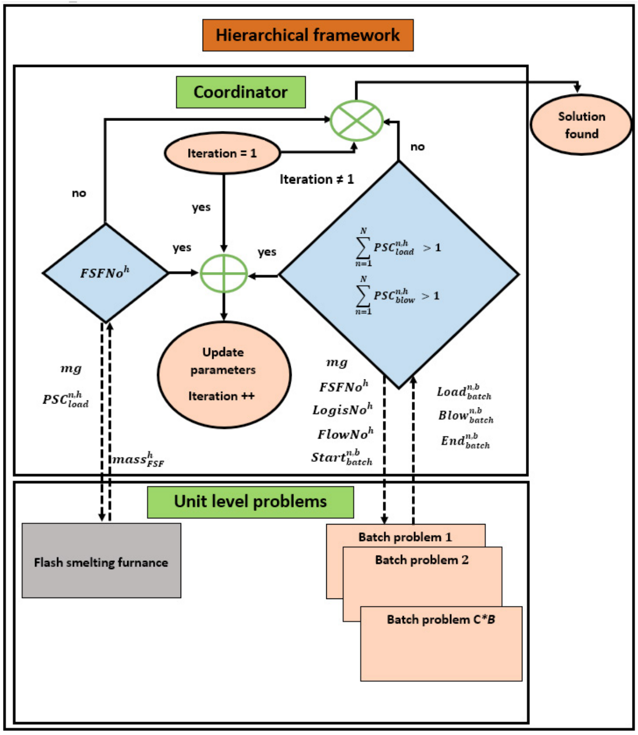

Fig. 2. Hierarchical scheduling framework (adapted from (Ahmed et al. (2022)))

$$Cu^h_{PSC} = \sum_{n=1}^{N}\sum_{b=1}^{B}\sum_{t=1}^{T} Cu^{n,b,t}_{PSC} \qquad \forall h = t + Start^{n,b}_{batch} \tag{18}$$

3. SIMULATION

In this work, we assume a copper smelting process that consists of one FSF and three PSC units where each PSC unit produces five batches; as a result, 15 batches are produced during each simulation. However, the given hierarchical scheduling framework can employ any number of PSC units or batches per unit. The aim is to analyze the effect of the matte grade on the FSF performance, copper losses during the process operation, and the CPU time required to find a feasible solution.

In this study, the rate of copper loss in FSF and PSC is taken from the literature, which is piece-wise linearized to keep the linearity in the framework (Bellemans et al. (2017), Tan (2007)). The matte grade changes with a step of 0.1 percent during each simulation. From each simulation, the copper losses, the FSF feed rate, and the CPU time as shown in Fig. 3-6. The copper losses during the PSC batch are the mean losses, whereas the total copper losses are the sum of copper losses in the FSF and PSC batch.

In this study, the matte grade values are categorized into three parts: lower values (61 percent or lower), medium values (between 61 percent - 72 percent), and higher values (72 percent or higher). For the lower matte values, the amount of copper losses in the FSF is negligible, while these losses are significant during the PSC operation as

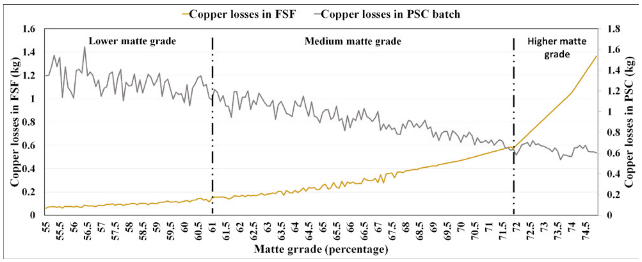

Fig. 3. Copper losses in FSF and PSC units

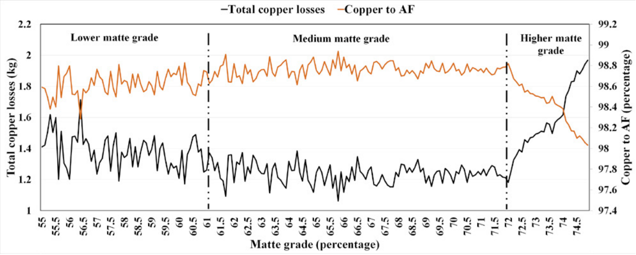

Fig. 4. Total copper losses and copper to AF

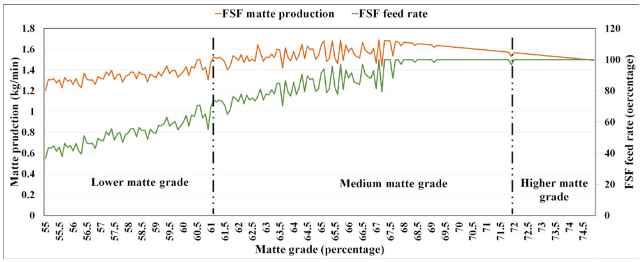

Fig. 5. FSF feed rate and matte production

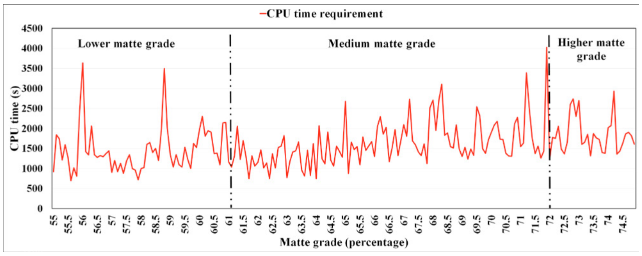

Fig. 6. CPU time

shown in Fig. 3. The amount of copper losses during the PSC operation depends on the timing of the slag blows (Ahmed et al. (2021)). Given that the duration of slag blows is higher for the lower matte values, copper losses are higher during the PSC operation for the lower matte grade values. Additionally, the FSF produces matte at a high rate, but the PSC units do not process the matte at the same speed. As a result, PSC units are the bottleneck, and the FSF's feed rate is compromised to meet its capacity constraints.

For the lower matte grade values, the total amount of copper losses does not increase significantly with the change in the matte grade; therefore, the AF receives the input material with a high content of copper, as shown in Fig. 3-6. As the objective of the smelting process is to increase the FSF feed rate point and reduce the total copper losses, operating the smelter at lower matte grade values produces sub-optimal solutions due to the sub-optimal operation of the FSF.

For the higher matte grade values, copper losses decrease during the PSC operation due to the shorter duration of the slag blows, but these losses increase exponentially during the FSF operation. Therefore, the FSF is the real contributor to the total copper losses. For higher matte grade values, the FSF operates optimally by utilizing its maximum feed rate. The reason is that the shorter PSC batch time increases the demands for the matte, which moves the FSF from a sub-optimal to an optimal operational point. Despite the optimal operation of the FSF, operating the smelting process at higher matte grade values provides a weak solution due to the higher amount of copper losses. Therefore, such solutions are also categorized as sub-optimal.

In contrast to the lower and higher matte grade values, operating the smelting process at the middle matte grade values provides relatively better solutions. As the matte grade value begins to increase (greater than 61 percent), the increase and decrease of the copper loss rate are almost linear during the operation of the FSF and PSC units. In addition, increasing the matte grade decreases the PSC batch time, which increases the matte demand. Consequently, the FSF feed rate increases and the quality of the solution begins to improve, moving from the sub-optimal to a more acceptable solution.

The matte grade values between 67.3 percent to 71.9 percent produce the optimal solutions. For those matte grade values, the rate of copper loss during the FSF and PSC unit operations is approximately linear; therefore, the total copper losses almost remain unchanged, as shown in Fig. 4. As the demand for the matte increases due to shorter PSC batch time, the FSF is putting into use the maximum amount of feed concentrates; hence, it is operating at an optimal operational point. As the copper losses are minimum and the FSF operates optimally, such solutions are categorized as optimal solutions.

This study evaluates the framework complexity in terms of CPU time required by the solver to obtain an optimal solution for a given matte grade. Fig. 6 shows the CPU times. The medium matte grade values require slightly higher CPU time than the other values. This is because both the FSF and PSC units partially contribute to the bottleneck for middle grade values. Therefore, the number of iterations that the coordinator takes to find an optimal solution is high, so the CPU time is high. Nevertheless, the CPU times for the middle grade matte values do not significantly differ from those of the other matte grade values. Therefore, in terms of complexity, operating the smelting process at the middle matte grade has nearly similar computational costs but produces better solutions.

CONCLUSION

In this study, we presented the effect of the matte grade on the total copper losses and throughput of the smelting process. Based on the arguments and simulation results, we presented the optimal matte grade values that can be used for better process operation. The understudy framework consists of a linear discrete-time FSF model, a discrete-time PSC model, and a coordinator that resolves the process inter-dependencies. The current framework produces a predetermined number of PSC batches within a flexible schedule horizon. As a future improvement, the scheduling horizon could be set as a fixed parameter, allowing for the computation of the maximum number of PSC batches that can be produced within the specified time frame.

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