CODELCO, Chile Programs Its Copper-Smelting Operations

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CODELCO's Chuquicamata Copper Smelter, located in Chile, must meet an environmental standard established in 2002 that limits the sulfur emissions from the copper-production process. This regulation placed new restrictions on the production process, and consequently the heuristic criteria based on years of operator experience no longer resulted in high production levels. We developed a model to maximize production while respecting metallurgic, operational, environmental, and other restrictions. We created two methods of planning daily activities for the plant. We developed a client-server tool that displays optimization results graphically and numerically based on data on operational conditions recorded in real time and data input manually. The smelter has used the system since March 2003. We found an increase in the quantity of copper concentrate processed of 25.4 percent.

Key words: production, scheduling: approximations, heuristics; industries: mining, metals.

CODELCO (Corporación Nacional del Cobre) in Chile produces copper, the principal export of this country, with sales in 2004 of $8,204 million. Copper concentrate smelting is one of the principal stages in the production of copper. Until March 2003, CODELCO's Chuquicamata concentrate smelter planned its operations according to heuristic criteria based on the general shift manager's experience. For many years, this method allowed the smelter to reach its strategic and tactical production goals. New environmental legislation requires the company to reexamine these procedures. It cannot use historical criteria to meet its productivity goals. It must consider many combinations and elements to achieve maximum productivity, use a model to represent the problem, and develop a method of obtaining a good solution.

The problem is characterized by many possible combinatorial solutions, nonlinear factors intrinsic to the metallurgical processes, and accumulated experience on the part of decision makers.

The Problem

The Chuquicamata mine's smelting process involves two stages: a smelting stage and a conversion stage. The smelting stage converts copper concentrate, with 29 to 33 percent purity, into a high temperature liquid mixture with a higher copper purity depending on the equipment used: a flash furnace (FF) or one of the teniente converters (TC-1 and TC-2). The FF converts copper concentrate into a liquid mixture, called *matte*, that is 62 to 68 percent copper; while the TCs convert the copper concentrate into white metal, which is 70 to 75 percent copper (Figure 1).

The resulting copper mixture, either matte or white metal, contains copper, iron, and sulfur, and requires further purification, which takes place in Pierce Smith
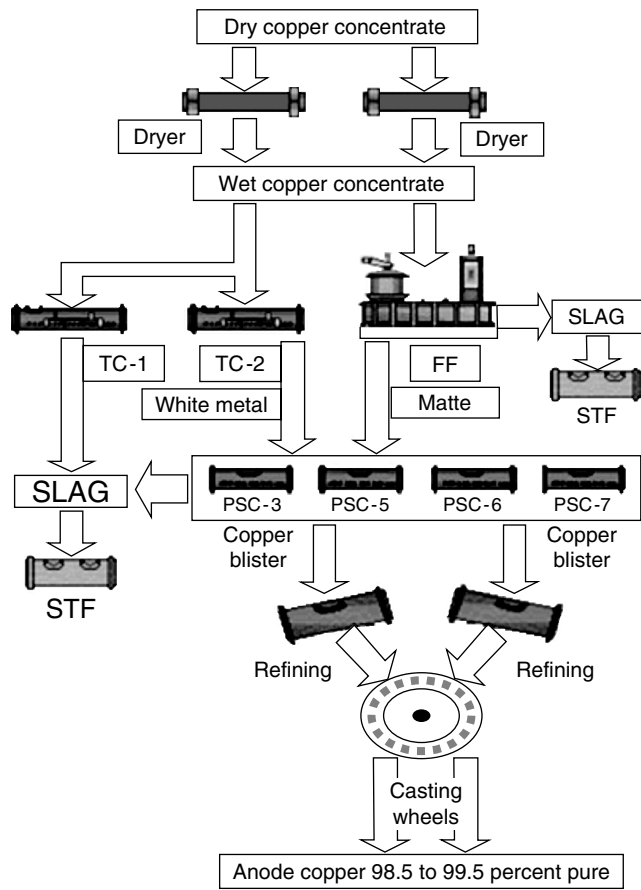
Figure 1: CODELCO'S Chuquicamata plant smelts copper concentrate in a flash furnace (FF) and two teniente converters (TC-1 and TC-2), producing a mixture that contains copper, iron, and sulfur (matte or white metal). It transports this mixture in big ladles to the Pierce Smith converters (PSC-1, PSC-5, PSC-6, and PSC-7) and then to refining and casting wheels. The final product is copper anodes.

converters (PSC-1, PSC-5, PSC-6, and PSC-7) during the conversion stage. Huge ladles transport the high-temperature, liquid mixture from the FF or TCs to the PSCs.

In each operating PSC, several cycles of five phases can be carried out daily: ladle loading, slag blowing, copper blowing, ladle emptying, and air-nozzle cleaning. Initially, the PSC is loaded with white metal and matte.

In the second phase, impurities are eliminated through the oxidation of ferric sulfide (FeS) at high temperatures with oxygen-enriched air. The resulting mixture contains smelted slag ($2FeO \cdot SiO_2$) float-

ing in the liquid because of its lower density. At the end of this phase, all the slag is removed and transferred to the slag-treatment furnace (STF) by means of ladles.

In the third phase, the operators eliminate sulfur from the copper mixture by adding oxygen-enriched air to produce a reaction between the oxygen (O_2) and the sulfur (S) to create sulfur dioxide gaseous, $SO_{2(g)}$. The $SO_{2(g)}$ flows through the pipeline towards the acid-treatment plant to produce sulfuric acid. The copper resulting from the copper-blowing process is known as copper blister and is 98.5 to 99.5 percent pure.

In the fourth phase, the copper blister is transported to the refining furnaces, which eliminate the remaining impurities. Then in the fifth phase, the operators inject air into the air nozzles of the converters to clean then. The resulting copper goes to the molding wheels to produce copper anodes.

The operators use ladles to load combinations of matte and white metal into the PSCs; these combinations may be pure matte, mixtures of matte and white metal, or pure white metal. The designation "Cycle 0-9" represents a cycle made up of zero ladles of matte and nine ladles of white metal. Eight to 11 ladles can be loaded into a single cycle. Therefore, the different possible combinations are Cycle 9-0, Cycle 8-1, Cycle 7-2, . . . , Cycle 0-9; however, a metallurgical analysis of the problem indicates that the cycles that produce the best plant performance are Cycle 4-5, Cycle 5-4, and Cycle 6-3. The set of cycles assigned depends on the availability of matte and white metal (Figure 2). A typical cycle takes approximately seven hours.
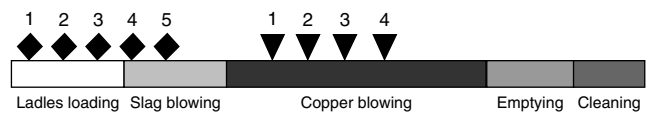

Figure 2: In this Gantt chart representing a 5-4 cycle, the plant loads five ladles of matte (diamonds) and four of white metal (triangles) into a Pierce Smith converter (PSC). It must program five phases in a period of time: loading the ladles, slag blowing, copper blowing, emptying the PSC, and cleaning the PSC.

The plant programs work for three shifts, 5:00 A.M. to 1:00 P.M., 1:00 P.M. to 9:00 P.M., and 9:00 P.M. to 5:00 A.M.. During each shift, 60 people work, a general shift manager, the corresponding shift managers, and the converter and smelter operators.

The problem consists of maximizing production and maintaining environmental standards on sulfur emission while respecting the operational conditions inherent to the process. The general shift manager uses a Gantt chart to determine when to transport smelted material. CODELCO's problem corresponds to a family of scheduling problems; however, the characteristics of the metallurgic process make it unlike those considered in the literature (Baker 1974, Pinedo 1995).

Based on years of plant experience, the best planning period is one day because the values for the input variables are uncertain for any longer period. The important variables include the quality of the copper concentrate available for the smelter; the quality of the air used in the chemical reactions, which depends on the oxygen plant; and the availability of the acid treatment plant.

The production environment is an 8,000 square meter building containing facilities for handling smelted metal mixtures at temperatures around 1,200 °C. Highly-skilled workers use two bridge cranes to transport the smelted metal mixtures. An operation consists of filling the ladle at an initial reactor, moving the ladle to another reactor, and emptying it into that final reactor.

Model and Algorithm

The objective of our optimization model is to maximize daily production, which is directly related to the number of cycles processed and more specifically to the number of ladles assigned to carry smelted copper between the smelting process and the conversion process. Consequently, the production time is related to the blowing-cycle times.

The model has the following constraints:

—To meet environmental standards, at most two PSCs can perform blowing operations simultaneously.

—To ensure that cycles are metallurgically feasible, matte ladles must be loaded before white metal ladles to respect the constraints on initial and final loading times for the slag-blowing and copper-blowing phases.

—To meet loading constraints, operators can load matte only up to 30 minutes before the end of slag blowing and can load white metal only up to 120 minutes before the end of copper blowing.

—Because of the unloading configuration, operators cannot use two ladles simultaneously to unload the FF or the TC, and they must time succeeding ladles to be within 20 minutes of each other for the FF, and 30 minutes for the TC.

—The contents of ladles per day must correspond to the tons of concentrate smelted by the FF and the TC. The FF has a nominal daily smelting capacity of 2,800 tons, and the TC of 2,200 tons.

—Each day, the initial situation left from the previous day must be respected in the actual daily programming.

To schedule the different operations in the concentrate smelter, we must take into account the different points of view of the PSC operators (smelter process), the FF operators, and the TC operators (conversion process). Both think that tasks should be assigned first to their department. We had to develop two algorithms to ensure that the computer system reflected both visions. The first algorithm, the conversion algorithm, determines the optimal manner of operating the PSCs and subsequently determines the optimal functioning of the FF and the TCs. The second algorithm determines the best sequence possible for loading ladles in the smelter process, and then defines a schedule to optimally transport them toward the conversion process.

The Conversion Algorithm

Step 1. Generate all combinations of cycles to assign to the PSCs during the day. Evaluate each combination of cycles according to the tons of copper the cycles in that combination will provide, verifying the constraint on the maximum number of ladles. For each combination, do Steps 2 and 3.

Step 2. Assign the cycles in a combination to the PSCs according to the WSPT rule (weighted-shortest-processing time first), satisfying the rest of the model constraints. Generate a set of feasible time intervals for loading ladles.

Step 3. Generate a tentative schedule for unloading the FF and the TCs, considering loading and unloading constraints. Calculate the tons of copper processed in the day associated with the combination of cycles under consideration. If that solution produces better results than the reference solution, store it as the new reference solution.

The Smelting Algorithm

Step 1. Generate all feasible ladle-loading combinations at any given time in the FF and the TCs (scenarios). Assign combinations homogeneously in a Gantt chart during the day. A combination is valid when it respects the loading and unloading constraints.

Step 2. Generate all feasible cycle assignments for the PSCs for one day of operation. Then, make each assignment without superimposing cycles and respecting operational, metallurgical, loading, and initial-condition constraints.

Step 3. For each scenario and each combination of feasible cycles, generate the corresponding Gantt chart. Based on maximizing production, determine the best solution and store it.

System Description

We used a client-server architecture and based the software development on Schwalbe's (2000) prototype. We developed both the client module and the server in VisualBasic. The server module contains two search algorithms written in the C language that permit us to generate the optimal solution; the client module produces the Gantt chart for the day and a record of ladle movement for any instant of the day.

For the server module, we developed connection routines that input plant operational conditions in real time based on an existing monitoring system. Alternatively, we could input the data manually. The system produces the results in graphical and numerical format. Based on the input data and using one or both of the solution algorithms, the systems produce a Gantt Chart that specifies the best schedule for the day and for each reactor (Figure 3). We installed the server module in the general shift manager's office and the client module in several computers throughout plant.

Results and Benefits

We tested the system over 40 days (March and April 2003), during which the actual quantity of processed copper concentrate came closer each day to the computer-generated result (Figure 4). During days 1 to 20, production levels were sometime even higher than the computer estimates because actual operating conditions varied from those estimated. For example, the copper concentrate fed into the plant might have a higher concentration of copper than expected, increasing the quantity processed. As the general shift manager acquired experience defining data, he adapted operations to achieve the recommended production values. Consequently, actual results and the computer projection converged towards the end of the 40-day test period, and this tendency has continued after the test period (Table 1). Average daily production for a 20-day period in May 2003 was 4,255 tons of processed copper concentrate, while the computer-estimated quantity was 4,736 tons, an 11 percent difference between actual production and the computer-estimated value. One year after system implementation, we obtained a new sample of system use versus actual production and obtaining a difference of 1.5 percent, showing that operators have improved their ability to follow the computer-proposed solution.

We also obtained data on the quantity of copper concentrate processed during a 14-day period one year prior to system implementation. Since that time, the government has imposed additional environmental constraints on production, so that current production methods are not comparable. The average amount of copper concentrate processed was 3,393 tons per day during that period. Some parts of the 25.4 percent improvement can be attributed to our system.

The principal benefits our computer system provides are the following:

—It supports shift managers in planning the copper smelter's production and operations.

—It permits people to create daily registers of ladle movement and diagrams of the operational systems at consoles throughout the plant.

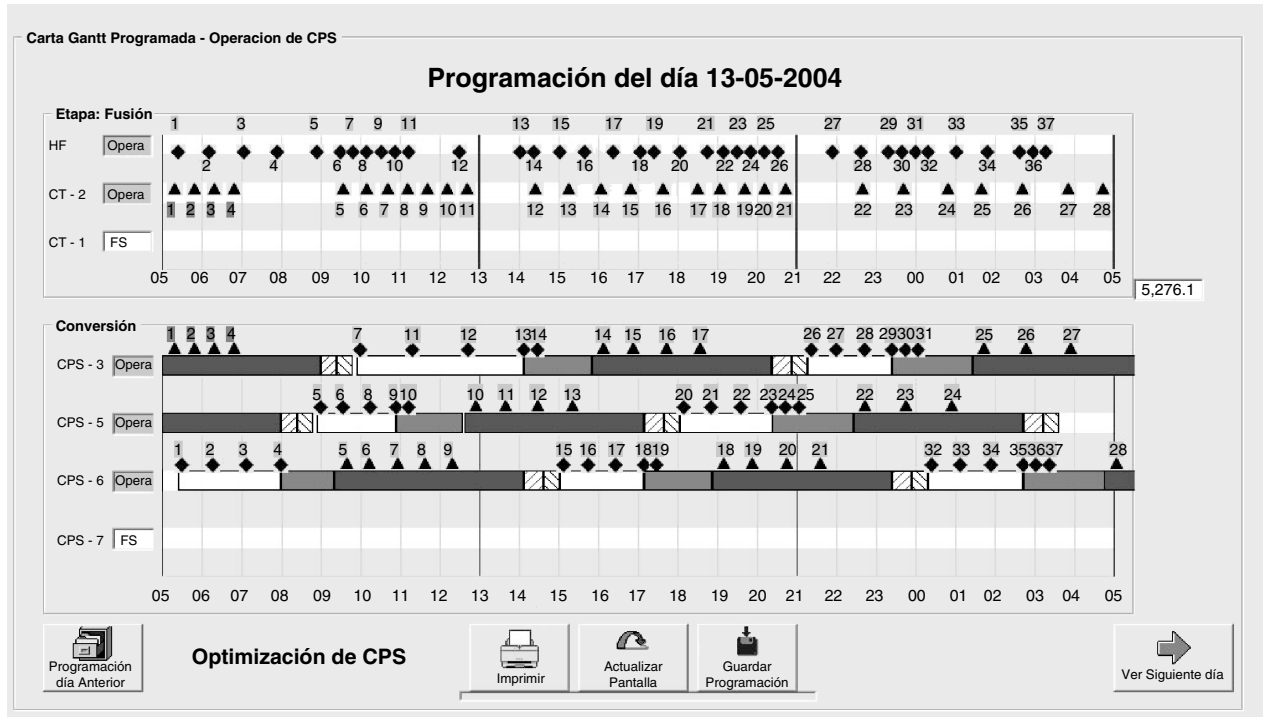—It supports planning work shifts based on data about the current situation.

Figure 3: In this Gantt chart covering 24 hours from 5:00 AM May 13, 2004 to 5:00 AM May 14, 2004, the first three horizontal stripes correspond to the unloading operations of the smelting reactors: FF, TC-2, and TC-1 (in Spanish, HF, CT-2, and CT-1). The diamonds and triangles (ladles of matte and ladles of white metal) indicate the times of unloading operations. The vertical lines indicate the beginnings and ends of the three shifts. At the right side of the chart, 5,276.1 tons is the algorithmically generated quantity of processed copper concentrate for this schedule; the bottom four horizontal stripes show the cycles for the conversion reactors PSC-3, PSC-5, PSC-6, and PSC-7 (in Spanish CPS-3, CPS-5, CPS-6, and CPS-7). TC-1 (CT-1) and PSC-7 (CPS-7) are not in operation. The program indicates that 37 ladles were generated in the flash furnace and 28 ladles of white metal in TC-2. All ladles were distributed to the PSC-3 to feed one 5-4 and one 6-3 cycle. At the beginning of this schedule, four white metal ladles are finishing a cycle corresponding to the day before. Also, two similar cycles are assigned to PSC-5. Finally, two cycles (4-5 and 5-4) and the beginning of a 6-3 cycle are assigned to PSC-6.
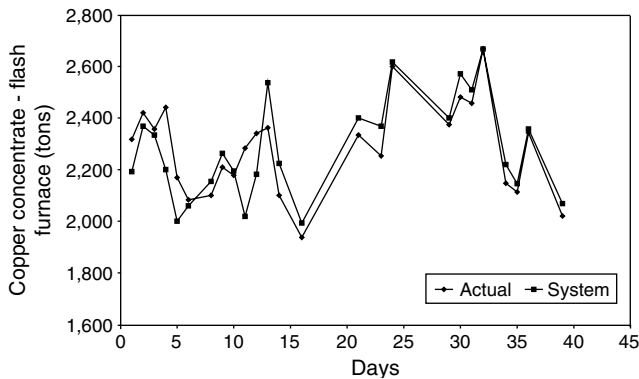

Figure 4: During the first 40 days of system operation, plant operators tried to follow program recommendations, improving over time.

—It produces a record of daily operations automatically.

—It anticipates situations that may impair operations in subsequent later shifts or days.

—It verifies that the production levels achieved correspond to those planned.

—It reprograms operations when reactors break down.

—It respects the existing environmental standards.

—It establishes standard goals for reactors and personnel.

—It simulates diverse operation and production scenarios rapidly.

—It allows smelter directors access to real-time information regarding smelter operations.

Day	Real processing (tons)	Conversion algorithm (tons)	Smelting algorithm (tons)	Best algorithmic result (tons)
1	4,172	4,288	3,739	4,288
2	3,971	4,226	4,289	4,289
3	3,565	3,901	3,325	3,901
4	4,196	4,991	4,544	4,991
5	4,440	4,184	4,384	4,384
6	4,501	4,766	4,609	4,766
7	4,486	5,106	4,728	5,106
8	4,653	4,743	4,598	4,743
9	4,301	4,505	4,520	4,520
10	4,176	4,822	4,447	4,822
11	4,031	5,394	4,749	5,394
12	3,919	4,671	4,479	4,671
13	4,802	4,294	4,641	4,641
14	4,419	4,838	4,704	4,838
15	4,582	4,554	4,343	4,554
16	4,182	5,151	4,574	5,151
17	5,190	5,002	4,075	5,002
18	3,398	5,025	4,775	5,025
19	4,006	4,695	5,159	5,159
20	4,102	4,481	4,640	4,481
Average	4,255			4,736

Table 1: In this table showing the copper-concentrate processing and smelting production obtained with proposed algorithms over a 20-day period, the second column shows the quantity of copper concentrate processed. Each day the program was executed with both algorithms (the third and fourth columns), the best algorithmic result was chosen (last column).

Conclusions

Once the general shift manager starts the system each morning at 5:00 A.M., he meets with his work team to plan the day's operations, to analyze the previous day's activities, to review the operating conditions, to input data about those conditions, and to create the optimal Gantt chart for the day. If operating conditions change during the day, he can cause the system to revise the plans for production for the remainder of the day. At the Chuquicamata copper smelter, managers maintain this routine in the belief that anticipating the day's events is more efficient than basing decisions exclusively on experience. Those responsible for strategic planning use the tool we developed to simulate functioning scenarios under extreme conditions.

We succeeded in developing optimization models and computer technology in this case because we formed a multidisciplinary work team that included metallurgic, computer, and industrial engineers and worked on the problem in the actual work environment over one year. During a three-month start-up period, we performed final modifications.

References
Baker, K. R. 1974. *Introduction to Sequencing and Scheduling*. John Wiley and Sons, New York.

Pinedo, M. 1995. *Scheduling: Theory, Algorithms and Systems*. Prentice Hall, Englewood Cliffs, NJ.

Schwalbe, K. 2000. *Information Technology Project Management*. Thomson Learning, Cambridge, MA.

Carlos Caballero D., Manager Smelter División CODELCO Norte, CODELCO Chile, writes: "The motive of this letter is to support the article 'CODELCO, Chile Programs Its Copper Smelting Operations,' an article that adequately reflects the benefits and difficulties that must be overcome to successfully implement an idea.

"The generated computer tool has produced important benefits for the copper smelter. Prior to system implementation, operations were programmed as the events occurred. Worker experience constituted the principal knowledge source for defining each new ladle movement. Consequently, routine tasks as well as unforeseen circumstances required a decision in real time. With the new system, the workers now have a guide for decision making. The system is executed daily to produce a Gantt Chart with that day's programming. In this way, the shift managers for each one of the involved machinery learn earlier when a higher production level is required, and if they faithfully follow that day's programming, they can reach the maximum possible production for that day's operating conditions. Since the system has been implemented, an ordering in activity performance can be observed.

"We are presently improving the initial system in order to incorporate operation planning for other stages of the smelting process."