SYNTHESIS OF FLOTATION BASED SEPARATION SYSTEMS

Luis A. Cisternas
Universidad de Antofagasta
Antofagasta, Chile

Edelmira D. Gálvez, Rodrigo E. Jorquera, and David A. Méndez
Universidad Católica del Norte
Antofagasta. Chile

Abstract

In this work a methodology is presented for defining the optimal configuration for flotation circuit and selection of appropriate equipment for the process. The problem is represented by three hierarchized superstructures. The first level represents separation tasks, which include: feed processing, concentrate processing, and tail processing. The second level represents the stream network needed to carry out each tasks. Where for each task a superstructure is developed which includes several operational stages. At the third level, several equipment alternatives are considered for each stage. The equipment discussed in the model includes flotation column and flotation cell banks, with and without grinding. The optimal selection of the circuit is made with an appropriate objective function, upon which the values of the operational and structural variables may be determined. The problem is formulated using disjunctive programming, which is converted to a MILP problem. The model includes mass balance, equipment models, operational conditions, and logic relationship. The paper presents an example to illustrate its application for effective design of a copper concentration plant.

Keywords

Process synthesis, flotation, disjunctive programming, separation, process design.

Introduction

Advances in process design and optimization have allowed several industries to improve their profitability and reduce investment. However, the extractive metallurgical industry has not reached this level of development in this area. In the metallurgical process design, bench scale laboratory and pilot plant programs are typically used to determine technically and economically optimum conditions. The object of the present study is to reduce cost in the design process using a hybrid between laboratory/pilot plant tests and modeling/optimization methods.

Flotation is the most broadly used process for the concentration of minerals, yet despite a vast amount of research and development over many years, today circuits are often designed based on experience and heuristics. This means that efficient flowsheet design depends largely on the experience of the process design team. Because of that, plant designs are usually over designed for safety reasons, and need to be replaced by appropriate design methods. These methods must maximize the profitability of the processing operations and speed up design procedures (Harris et al., 2002).

In this work a methodology is presented to facilitate the identification of the optimal flotation circuit configuration and equipment selection. The objective is not, of course, to replace the designer, but to add a new tool for the design process.

Model Basis

Flotation circuits for mineral processing are generally composed of a combination of several stages, including cell bank, flotation column and grinding. The flotation circuit configuration is one of the most important factors affecting the performance of a flotation circuit for a given feed material. Optimization of a flotation circuit includes three different aspects: One is to select which are the equipments required. Second is to determine the operation conditions, and third is to decide how to interconnect the equipments. Representation of the problem is a key aspect in determining these aspects.

We have presented the problem using three hierarchized superstructures. The first level represents separation tasks, which includes: feed processing, concentrate processing, and tail processing. The second level represents the stream network needed to carry out each tasks. This means that for each task a superstructure is developed including several operational stages. In the third level, for each stage several equipment alternatives are considered. The equipment in the model includes column and cell bank flotation, with and without regrind mills. This hierarchized representation allows an uncomplicated way to characterize a network with 36 items of equipments, with a large number of process alternatives. Also the superstructures representation avoids the presence of symmetrical structures, avoiding double counting and reducing the number of flowsheet configurations. The two first superstructures were proposed by Cisternas et al. (2004), whereas the last superstructure is presented here.

Figure 1 shows the superstructure utilized to represent separation tasks. The rougher system has the task of feed processing, cleaner system has the task of purification of rougher concentrate and/or scavenger concentrate to obtain the final concentrate, and scavenger system has the task of treating the tailings from rougher and/or cleaner to obtain the final tailing.

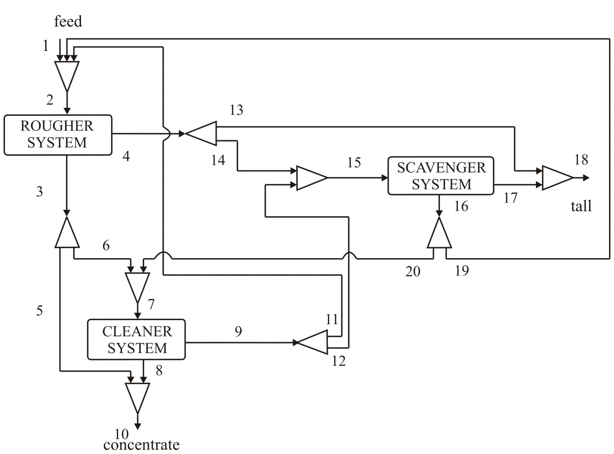

Figure 1. Task superstructure.

The stream network superstructure for each system is analogous to the task superstructure, but where each system is replace by a stage of flotation. This analogy allows for easy mathematical representation. These circuits are needed because flotation separations are not sharp.

Figure 2 shows the equipment network which is used for each stage in the stream network. Usually the equipment used in each stage includes conventional mechanical cells. Nevertheless, regrinding and column flotation must also be considered. Grinding is included because composite particles contains both valuable and gangue minerals, and because flotation is influenced by particle size and liberation. Therefore, in several flotation plants intermediate tailings and/or concentrates must be reground previous to further processing. Column flotation is also included because its can contribute both to cost saving and to increase revenues by improving the metallurgical performance of the circuits. Column flotation is usually used in cleaning sections in the copper industry (Schena and Casali, 1994), studies on its use in rougher sections has been developed for coal processing (Tao et al., 2000).

Optimization Model

For each superstructure a mathematical model is developed based on principles, operation conditions and rules. Disjunctive expressions are used to both represent equipment selection and to avoid bilinearities in the mass balance. An appropriate objective function is then formulated. The model has continuous (x) and binary variables (y), and corresponds to a mixed-integer linear programming (MILP) problem. The continuous variables x, which represent stream flow rates are assumed, for physical reasons, to be non-negative, and must in general obey mass balances, efficiency, and operational conditions. That is, these variables must satisfy equations like A x=0, where x is a vector of continuous variables and A is a matrix.

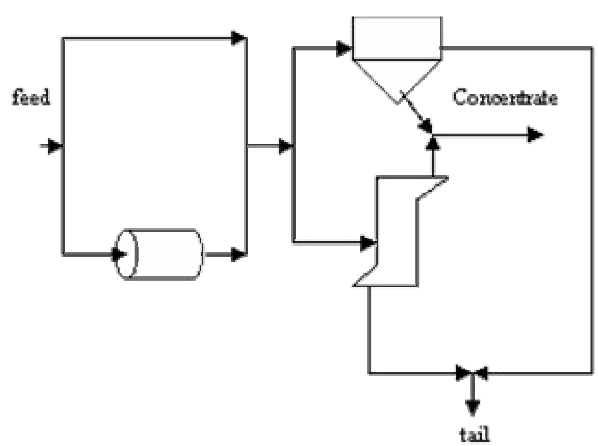

Figure 2. Equipment superstructure.

The mathematical models for the task and stream network superstructures are similar to the ones proposed by Cisternas et al. (2004), and include mass balance and operational conditions.

The equipment selection superstructure is modeled using disjunctive expressions. Grinding can be incorporated before flotation equipment. Grinding is simulated including a matrix which transforms flotation species. The quantitatively estimation of mineral liberation can be made from image analyses on polished ore sections. The effect that size has on flotation performance is incorporated in the flotation equipments. Flotation equipment is modeled using the ratio of flow concentrate to feed of each species. This ratio may be obtained from plant data, pilot plants, locked cycle flotation test (Nishimura and Shobu, 2000), or theoretical or empirical models (Gorain et al., 2000). The equipment selection superstructure model has the following form:

$$\begin{bmatrix} y_m \\ g(x)=0 \\ \begin{bmatrix} y_b \\ h(x)=0 \end{bmatrix} \vee \begin{bmatrix} y_c \\ h'(x)=0 \end{bmatrix} \end{bmatrix} \vee \begin{bmatrix} \neg y_m \\ g'(x)=0 \\ \begin{bmatrix} y_b \\ h''(x)=0 \end{bmatrix} \vee \begin{bmatrix} y_c \\ h'''(x)=0 \end{bmatrix} \end{bmatrix}$$

where y_m, y_b, y_c are boolean variables representing the existence of grinding, cells bank and column flotation respectively. The expressions g(x), g'(x), h(x), h'(x), h''(x), and h'''(x) are linear equations of continuous variables x, which apply in each case. The disjunctive expressions are converted into a mixed-integer lineal model.

The model includes logic conditions like "if the column in cleaner-rougher is selected and column in cleaner-cleaner is selected, then use grinding in cleaner-rougher". These logic conditions are modeled using binary variables as described in Raman and Grossmann (1991).

The optimal selection of the circuit is completed with an appropriate objective function, upon which the values of the operational and structural variables may be determined. Since in flotation circuits the income depends on the structure and operational conditions, a useful function is the difference between income and costs. The formula for the calculation of income incorporates the metallurgical efficiency of the plant, that is, the recovery and mineral content are opposite functions. It should be noted that as the mass flows of the species with a high grade increase in the concentrate, so does the profit. However, this increase in flows brings with it an increase in mass flows of low-grade value in the concentrate, which decrease the profits.

The mathematical programming model then is:

$$\begin{aligned} &\text{Max } U = c^T y + d^T x \\ &st \quad Ax = b \\ &\qquad Bx + My \le c \\ &\qquad x \in X \in \Re^n, y \in Y \in \{0,1\}^q \end{aligned}$$

Example

The paper presents an example to illustrate its application for effective design of a copper concentration plant. The model is applied to the design of a copper concentration plant, whose species are: k=1 (100% chalcopyrite), k=2 (75.1 % silica, 24.9% chalcopyrite) and k=3 (100% silica). The problem does not include scavenger stages in any of the systems, and the rougher and scavenger systems do not have cleaner stages. Also grinding and column flotation equipment are only considered in the cleaner system. Flow division was not considered for all the flow dividers. Figure 3 shows the circuit obtained. The optimal integer solution gives an annual profits of 16.85 million US$, while income from sales was 19.4 million US$. The problem, including a total of 592 equations and 408 variables (58 binary variables), was solved using the GAMS and OSL2 solver, in a Pentium IV processor in 1.027 seconds.

The sensitivity of the solution found to other levels of stream division was considered. Three levels of flow division were considered in this case (1/0, 0.5/0.5 or 0/1). The circuit obtained has the same structure as figure 3. This is in agreement with practice, because stream division is rarely used. Also the price of copper was switched from 1764 to 1300 $/tone and the optimal design was not the same. In the new optimal flowsheet the concentrate from the scavenger stage is recycled back to the rougher stage. This type of analysis is important because copper prices are very volatile and changes of this order are not uncommon.

Conclusions

The procedure developed can facilitate and speed up design of present-day procedures. An important feature of the model is its linearity, avoiding nonlinear characteristic of this problem. The mass balances in flotation bank and stream dividers were represented by disjunctive equations that permitted the presentation of bilinearities with mixed-integer linear equations. The results showed that for the example studied the division of flows had little effect on determination of the most efficient circuits. This result agrees with practice since it is unusual to divide a stream in mineral concentration circuits.

Modeling of the equipment selection was carried out using disjunctions with discrete values for the concentrate/feed stream ratio. Logic expressions were also incorporated in the model.

Studies of several other situations can test if the model will be useful in the analysis and design of circuits for mineral concentration. Future study will include application of the model to new situations.

Acknowledgments

The authors wish to thank CONICYT for financial support, through FONDECYT Project 1020892.

References

Biegler L.T., I. E. Grossmann, and A.W. Westerberg (1997). *Systematic methods of chemical process design*. Prentice Hall, New Jersey.

Cisternas L. A., E.D. Gálvez, M.F. Zavala, and J. Magna (2004). A MILP model for the design of mineral flotation circuits. *Int. J. Miner. Process*, in press.

Gorain B.K., J.P. Franzidis, K. Ward, N.W. Johnson and E.V. Manlapig (2000). Modeling of the Mount ISa rougher-scavenger copper flotation circuit using size-by-liberation data, *Minerals & Metallurgical Processing.* **17**, 173-180.

Harris M.C., K.C. Runge, W.J. Whiten, and R.D. Morrison (2002). JKSimFloat as a Practical Tool for Flotation Process Design and Optimization, In Mular A.L, D.N. Halbe and D.J. Barratt (Ed.) *Mineral Processing Plant Design, Practice and Control*, Vol.1, SME, pp 461-478.

Nishimura S. and K. Shobu (2000). Relation between locked cycle tests and continuous plant circuit in flotation, *Int. J. Miner. Process*, **59**, 9-15.

Raman R. and I. E. Grossmann (1991). Relation between MILP modeling and logical inference for chemical process synthesis. *Computers and chemical Engineering*, **15**, 73

Shena G. and A. Casali (1994). Column flotation circuits in Chilean copper concentrators. *Minerals Engineering*, **7**, 1473-1486.

Tao D., G.H. Luttrell and R.H. Yoon (2000). An experimental investigation on column flotation circuit configuration. *Int. J. Miner. Process*, **60**, 37-56.

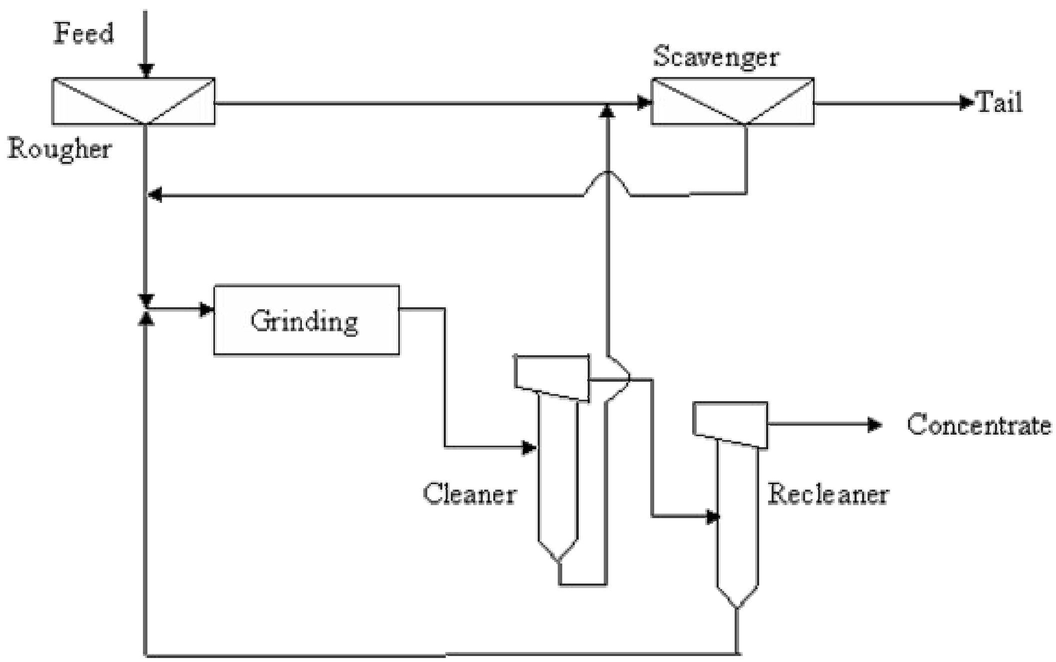

Figure 3. Optimized flowsheet for copper concentrate plant.