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Design of Flotation Circuits Including Uncertainty and Water Efficiency

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Abstract

The objective of the present study was to develop a procedure for flotation circuit design including uncertainty and water efficiency. The design process considers two stages: 1) optimal process design without consider water consumption, and 2) efficient use of water considering property integration.
For the flotation circuit design, we applied stochastic programming. In the optimization problem, it is desired to find the optimal configuration, equipment design and operational conditions of a circuit with multiple stages (rougher, scavenger, cleaner). The problem includes uncertainty in the feed composition and in the metal price. Each uncertain parameter is characterized probabilistically using scenarios with different occurrence probabilities. Then, considering the solutions to different scenarios, property integration is used to design the water integration system. Three properties are included: pH, oxygen concentration, and conductivity.
The application of procedure to an example, show that including uncertainty in the design process can be useful in finding better design and the property integration method can be extended to use in mineral processing. The novelty of this work is the integration of both methodologies and the application of these tools to mineral processing.

Keywords: process design, flotation, stochastic programming, property integration.

1. Introduction

Flotation is a physicochemical process which allows the mineral separation, such as copper sulfide minerals and molybdenum, from the remaining minerals which form most of the parent rock substrate, including contaminants such as arsenic minerals (Bruckard et al. 2010). The separation is carried out on milled aqueous mineral suspensions (pulp) subjected to forceful air bubbling, which produces the separation (flotation) of valuable metals from tailings based on hydrophobic and hydrophilic properties of the minerals. The flotation process is carried out in equipments, which are interconnected in predetermined arrangements that allow dividing the outputs of the systems into metal concentrate and tailings flows. Since the desired separation cannot be achieved in a single stage, various coupled stages are used. This is termed a "flotation circuit". The behavior of the entire process, therefore, depends on the configuration of the circuit, equipment design, and the chemical and physical nature of the pulp treated. It is for this reason that the preliminary design of the flotation circuit is very important, as it must take into account all the variables, parameters, and operational conditions.

Although flotation is a technology widely used in industry, the future of mineral processing will likely include more complex mineral processing, with higher levels of toxic elements, and higher charges at refineries and/or smelter for treatment of minor or toxic elements. For example, future treatment of copper ores will contain higher arsenic levels and higher penalties in the copper smelter (Ma and Bruckard, 2009). Further, the water is a fundamental resource in flotation. Most of the mining activity in Chile is carried out in the Atacama Desert and the mining companies use a great quantity of groundwater. A large fraction of the groundwater in the Atacama Desert is likely composed of "fossil" or "ancient" reserves that receive little or no recharge in today's hyperarid climate. Therefore, for the Chilean mining producers, it is of importance the elimination, reduction and re-use of this vital liquid.

The methods employed in flotation circuit design can be generally classified into heuristic (Chan and Prince. 1989), rigorous (Méndez et al. 2009), or hybrid (Gálvez, 1998). None of the preceding methods for designing flotation circuits has considered that the design may contain parameters which cannot be completely defined, or values which may be subject to degrees of uncertainty. Also, water efficiency has not been considered.

In the design of flotation circuits, large numbers of variables are handled, of which some may involve uncertainty, such as the feed grade, metal or product price, toxic elements composition, distribution of mineral, particle size, and others. Simonsen and Perry (1999) indicate that the type of uncertainty in mining operations includes market characteristics (especially price), mineral reserves and their composition, the functioning of the process (grades, efficiency), operational and capital costs, and the length of planning phases.

The objective of the present study is to develop a procedure for flotation circuit design including uncertainty and water efficiency. The design process considers two stages: 1) optimal process design without consider water consumption, and 2) efficient use of water considering property integration.

2. Model Development

In this section models for optimal process design without consider water consumption and water integration are briefly described.

2.1. Optimal process design

The flotation process depends on several design and operation variables. We consider a superstructure that includes three flotation stages: rougher, scavenger and cleaner stages as it is shown in figure 1. We allow for the consideration of multiple scenarios. The model consider constraints that enforces the kinetics of flotation and mass balance on each flotation stage, the behavior at the splitters and mixers, mass balance at the splitters and mixers, direction choice in the splitters, penalty the seller must pay for arsenic content in the concentrate, cell volumes, and costs associated with the flotation cells.

For the deterministic model we only have a single scenario, and the model then simply maximizes the total income subject to the dynamic and economical constraints. In the stochastic models we assume we have more than one scenario. Because of this we need to replace the objective by the maximization of the expected total income. For this we need the probability of a given scenario. In addition, we have that some of our decision variables can depend on the scenarios. This model corresponds to a stochastic MINLP.

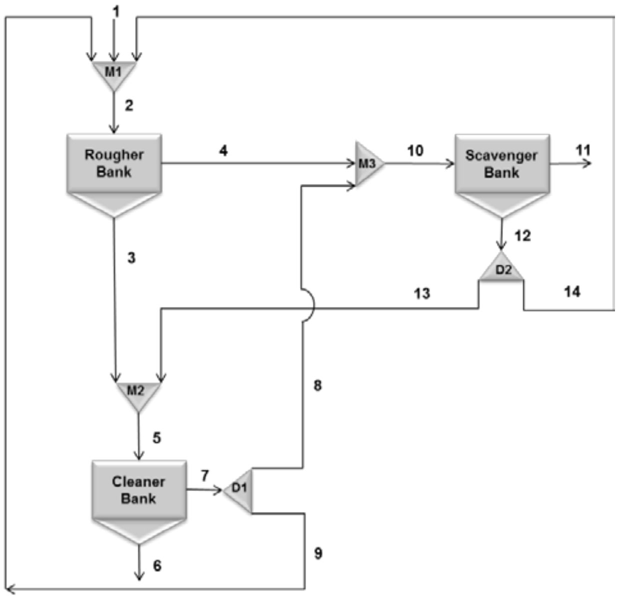

Figure 1. Superstructure of the flotation circuit.

2.2. Water integration

After the optimal flotation circuit configuration is determined, the water integration problem is addressed. This problem has not been analyzed before because the main concern in mineral processing has been the recovery and product grade. Water can be recycled from tail or concentrate dewatering operations. However, all water recovered in these operations cannot be recycled because it affects the flotation behavior.

Recently, El-Halwagi et al. (2004), has used the concept of clustering for process design based on property integration. Property integration is defined as a functionality-based, holistic approach to the allocation and manipulation of streams and processing units, which is based on tracking, adjusting, assigning, and matching functionalities throughout the process. Here the methodology developed by El-Halwagi et al. (2004) was used to design the water integration problem.

The overall problem definition given by El-Halwagi et al. (2004) can be adapted as follows: "Given a flotation circuit with certain sources (process streams and water streams) and flotation units along with their properties (pH, solid concentration, oxygen concentration) and constraints, it is desired to develop graphical techniques that identify optimum strategies for allocation and interception that integrate the properties of sources, sinks, and interceptors so as to optimize a desirable process objective (minimum usage of fresh water, maximum utilization of water recycled from tail and concentrate dewatering operations, minimum cost of slaked lime while satisfying the constraints on properties and flow rate for the sinks".

3. Application example

Consider the superstructure shows in figure 1. The feed has three mineralogical species: Chalcopyrite ($CuFeS_2$), Tennantite ($Cu_{12}As_4S_{13}$) and Gangue. Each has a specific floatability. Thus we can identify three chemical species of interest to our problem: copper, arsenic and gangue. The treatment plant capacity is 1920 Tpd. The objective is to maximize the total income. The decision variables to optimize are divided into design and operating variables. The first ones include equipment dimension as cell volume and total number of cells for each stage. The operating variables correspond to operating times for each cell of each stage, and direction of tails and concentrate streams. In the fully adaptable stochastic problem, the operating variables are able to adapt to each scenario for increase the total income. Otherwise, the design variables are the same for all scenarios.

The stochastic parameters are the copper grade in the feed and the copper price. Due to the variability of the ore processed and copper price, three levels are considered for both parameters. Then, the combination of these parameters is represented in 9 stochastic scenarios. For example, scenario 1 have a probability of 5%, and corresponds to a feed grade of 0.7% Chalcopyrite, 0.3% tennantite, and a copper price of 4.409 U.S. $ /Ton.

In the first case we use the deterministic model using as an input the average value of the stochastic parameters. This is the usual methodology employed in process design. The objective value of this problem was equal to 25,149,648 US$/year. However, the design and residence times for this solution where infeasible for several scenarios. We corrected this solution by fixing the obtained configuration and equipment dimensions and maximizing the income for each scenario by varying the residence time in each flotation stage. The expected income was 24,050,246. US$/year, with an average concentrate grade of 17.8% Cu and 0.70% As.

We then use the stochastic model, allowing all operational variables to be flexible with respect to the scenarios. Hence the residence times of each stage and the recirculation flow directions (cleaner tail and scavenger concentrate) vary for each scenario. The design variables, such as equipment sizing, are fixed for all scenarios. This results in a real expected income of 24,146,287 US$/year, with an average concentrate grade of 17.7% Cu and 0.69%As, and a completely flexible structure for each scenario.

Recirculation flow directions that vary with the scenarios might not always be implementable, so we also considered a stochastic model that only allows the residence time to vary. This results in a real expected income of 24,129,825 US$/year, with an average concentrate grade of 17.28% Cu and 0.7%As.

Both MINLP problems used in the previous sections are very hard to solve even with a state of the art solver such as BARON (Tawarmalani and Sahinidis, 2005).

Four cases of water integration were analyzed in the rougher stage. These include recirculation of water from tail thickeners and tail dumps, recirculation of tail from cleaner stage, and recirculation of concentrate from scavenger stage. Three properties were considered: pH, oxygen concentration (DO), and solid concentration (conductivity). Figure 2 shows the results for the case recycling cleaner tail, scavenger concentrate, circuit feed, and water recovered from tail thickener. The results show that is best to use water recycled from the tail thickener, and send the scavenger concentrate to the rougher stage.

4. Conclusion

A model for the design of flotation circuits under uncertainty has been presented. Uncertainty is represented by scenarios, including changes in the feed grade and metal price. The model allows changing the operating conditions (residence time and mass flows of each stream) and flow structure (tail and concentrate stream of cleaner and scavenger stage management) for each scenario, maintaining the fixed design (size and number of cells in banks flotation) for all scenarios. The model can be modified to include other uncertainties and other adaptive variables.

After the optimal flotation circuit configuration was determined, the water integration problem was addressed. The property integration approach developed by El-Halwagi et al. (2004) was used based on the properties pH, oxygen and solid concentration.
Future work includes the combination of the mathematical optimization approach with the property integration approach in one mathematical model.

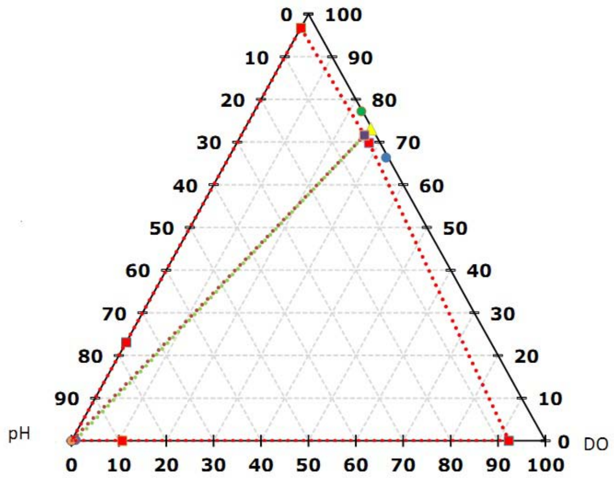

Figure 2. Optimal mixing point for mixing cleaner tail, scavenger concentrate, circuit feed, and water recovered from tail thickener.

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