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The effects of stage recovery uncertainty in the performance of concentration circuits

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ABSTRACT

This paper analyzes the effect of uncertainty in the recovery of each concentration stage on the global recovery and concentrate grade. The uncertainties are represented by normal, uniform and triangular probability distribution functions (PDFs). The case studies include the uncertainty in the recovery of each stage separately and simultaneously across all of the stages with different standard deviation levels. A total of 2880 cases were studied, which corresponded with twelve circuits, three distribution functions and 84 different combinations with standard deviations in the stage recoveries. For each case, 2000 simulations were performed, with an overall simulation total of 5.76 million. Among the conclusions obtained in this work are the following: 1) The shape of the distribution function in the output variables is dependent on the input distribution function, the concentration circuit and the uncertainty level; 2) when the recovery of a single stage is represented by a PDF, the other stage recoveries are assigned a deterministic value then the type of the PDF obtained for the global recovery is similar to the input distribution; 3) when considering uncertainty in several stages simultaneously, the resulting PDF type usually is not the same PDF type observed for the input variables; and 4) the circuit structure affects more than the stage recoveries in the analysis of the global recovery and concentrate grade.

1. Introduction

Montenegro et al. (2013) presented a method to analyze and design concentration circuits that involved uncertainty in the recoveries of each stage and the feed grade. In that study, normal probability distribution functions (PDFs) were used to represent the uncertainties in the input variables. However, there was no clarity about the characteristics of the uncertainties and how these characteristics affected the concentration circuits. This paper addresses this problem by analyzing the effect of different types of PDFs and standard deviation (SD) values for these distributions.

In the literature, there are few studies analyzing the effect of uncertainty applied to mineral processing. Xiao and Vien (2003) compared the variance or error propagation (EP) within the Monte Carlo method and found that the EP method presents limitations. The EP method is more accurate when the relationships between the input and output variables are linear, while the Monte Carlo simulation yields more accurate results when the systems are nonlinear. For this reason, the Monte Carlo simulation has been applied to various processes, with examples including fluidized bed systems (Kurup et al., 2008) and fluid flow through porous media (Jain et al., 2003).

Several tools and methods are available to analyze, design and optimize flotation circuits (Méndez et al., 2009), but these methods usually consider deterministic values in the input variables. However, there is uncertainty in several of these input variables. For example, the heterogeneous nature of mineral deposits (Gy, 2004a,b) generates uncertainties in the feed grade and recoveries of each flotation stage. A major review of these issues is beyond the scope of this paper, and the reader can read the introduction of Montenegro et al. (2013) for further discussion.

Various methodologies for the design of flotation circuits have been proposed in the literature, with most using optimization techniques. In these methodologies, the alternatives are presented through a superstructure, a mathematical model is developed, and an algorithm is used to find the best option based on an objective function. There are at least three reviews of studies concerning the optimal design of a flotation circuit including that of Mehrotra (1988), Yingling (1993a) and Méndez et al. (2009). Some examples that use this strategy are Yingling (1993b), Schena et al. (1996, 1997), Cisternas et al. (2004, 2006), Méndez et al. (2009), Guria et al. (2005a,b), Ghobadi et al. (2011), and Jamett et al. (2012). The differences between these studies depend on the superstructure used, the mathematical representation of the problem, and the optimization algorithm used. However, one problem with these methods is that the recovery of each stage must be modeled, and because the recovery of each stage is a function of many

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variables, there is uncertainty in the values obtained by modeling. Moreover, the number of alternatives is large and therefore simple stage model has been used to achieve adequate convergence in mathematical programming problems. If metaheuristic-based algorithms are used, it is possible to use more sophisticated stage models or cell models, but with problems of eight or more cells, it will be difficult to achieve convergence in a reasonable time. Therefore, it can be useful knowing the effect of uncertainty in the behavior of flotation circuit. This work analyzes the effect of uncertainty in the recovery of each concentration stage on the global recovery and concentrate grade.

2. Methodology

The methodology used was developed by Montenegro et al. (2013) and is briefly reviewed here. The circuits considered in this paper are represented by a superstructure to identify all of the variations considered (and those not included) in the analysis. In this work, as in Montenegro et al. (2013), twelve circuit alternatives are considered (Fig. 1). These alternatives are represented by a string where the letters indicate where the cleaner tail, scavenger concentrate and re-cleaner tail are sent. For example, the RRC circuit is built by sending the cleaner tail to the Rougher stage, the scavenger concentrate to the Rougher stage, and the re-cleaner tail to the Cleaner stage (see Fig. 2). For processes without a re-cleaner stage, two letters are included, and the SC process is constructed by sending the cleaner tail to the Scavenger stage and the scavenger concentrate to the Cleaner stage. The alternatives without a stage re-cleaner are RR, RC, SR and SC, and the alternatives with a re-cleaner stage are RRR, RCR, RRC, RCC, SRR, SCR, SRC and SCC.

After selecting the circuit to be tested, one or more of the variables that have uncertainties are selected for analysis. The uncertainty is represented by a PDF, including normal, uniform and triangular PDFs. In this work, the following cases were considered: the recovery of one stage (i.e., rougher, cleaner, scavenger, or re-cleaner) that exhibits uncertainty while the other stage recoveries have deterministic values and the case where the recoveries of all stages exhibit uncertainty. The uncertainty level for each variable is represented by its SD. The SD values considered for the stage recoveries were 0, 1, 3, 5 and 7. A total of 84 combinations of stage SD values were studied. An SD value of 0 indicates that the variable shows no uncertainty.

For each case, 2000 random values of the selected variables were generated using the PDF and SD. Simulations were performed for each of these values, the results were stored and the statistical indicators were calculated.

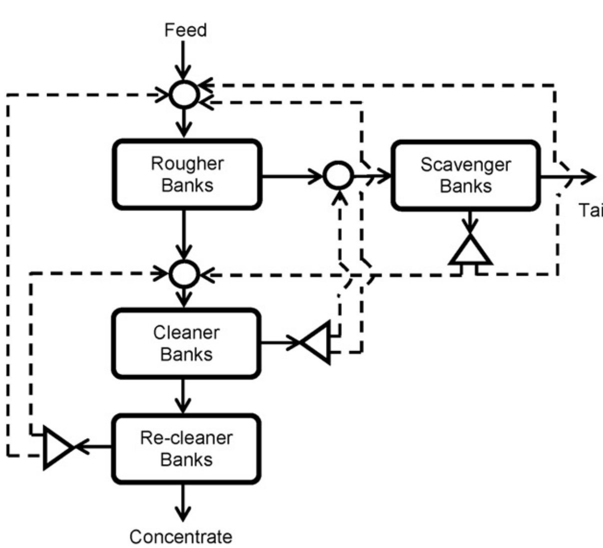

Fig. 1. Superstructure of the concentration circuits.

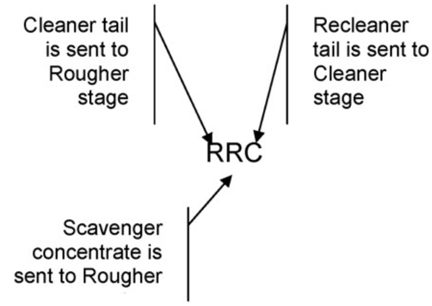

Fig. 2. Nomenclature used in the manuscript for flotation circuit.

Based on the simulation results metric indicators were determined and normalized for each circuit, PDF type and combination of SD values. Metric indicators were used to assess each objective and were classified based on their efficiency, quality and process stability. The indicators were as follows: 1) global recovery of valuable species, which is a measure of the efficiency of the process, 2) concentrate grade, which is a measure of the quality of the product, 3) global recovery SD, which indicates the degree of uncertainty of recovery, and 4) concentrate grade SD, which indicates the degree of uncertainty in the concentrate grade. Each of these indicators was assessed using the mean value, SD, kurtosis and skewness.

The procedure described above was repeated for each SD combination for the variables with uncertainties, each circuit to be analyzed and each PDF. Each PDF required 960 simulations; with a total of 2880 cases, there were 5.76 million simulations and 11,520 histograms of output variables. In this study, only the global recovery and concentrate grade were analyzed. Input values of the variables were generated using the PDF; for an example, Fig. 3 shows the histograms of the cleaner recovery with an SD of 3.

3. Results and discussions

The simulation results were tabulated for each of the 2880 cases studied, using a specific circuit for a specific combination of SDs and a specific PDF. Statistical descriptors for each case were determined, and a histogram was constructed. An analysis was performed based on the type of distribution, the level of SD and the effect of each circuit.

Graphs showing skewness versus kurtosis were constructed because the position on the graph indicate the type of PDF obtained. Positive kurtosis values indicate that the PDF has a mass distribution near the central value (leptokurtic), and negative kurtosis values indicate that the PDF presents a mass that is dispersed from the central value, thus showing a flat PDF (platykurtic). Positive values of the skewness factor indicate that there is a mass distribution (or data density) that is less than the central value, while negative values are observed for a mass distribution greater than the central value. In other words, skewness tells us the amount and direction of the skew, and kurtosis tells us how tall and sharp the central peak is relative to a normal PDF.

3.1. Effects of PDF type on global recovery

In Fig. 4, the circles, squares and triangles represent the values obtained when using normal, uniform and triangular PDFs, respectively, in the stage recoveries.

When the recovery of a stage is represented by a PDF, the other stages recoveries are assigned a deterministic value then the type of PDF of the global recovery obtained is similar to the input distribution. Thus, area A of Fig. 4 represents cases that possess near-normal PDF and corresponds to cases where recoveries of the rougher, cleaner, scavenger or re-cleaner stages were represented by a normal distribution while the other recoveries were considered constant. Zones B and C in Fig. 4 include cases where the recoveries of rougher, cleaner, scavenger