Analysis and improvement of flotation circuits for polymetallic ores

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Abstract

Current mining industry challenges require extracting all valuable elements and treating toxic materials from the ore. One way to achieve these objectives is through flotation plants that process polymetallic ores. The plants design of flotation polymetallic ores usually consists of a sequence of circuits to separate the valuable elements from the gangue without any integration between them beyond the sending of tails or concentrate streams from one plant to another. This work analyzes the integration of these circuits. First, plant design is carried out using optimization to select the best alternative from a set of circuit alternatives. Uniform distribution functions are used to represent recoveries with epistemic uncertainty, and the optimization problem is solved many times to identify a set of optimal solutions. Once this set of optimal designs has been identified, global sensitivity and uncertainty analyses are utilized to identify bottlenecks and improvements. The results showed that these integrated plants' design and analysis would introduce significant improvements in the operation of flotation plants for polymetallic ores. The advantages and challenges of integrated polymetallic ore plants are highlighted.

**Keywords**: Polymetallic ores, integrated circuits, global sensitivity analysis, improvement

* 1. Introduction

The mining industry presents critical challenges, given the increased demand for metals, the decrease in grades, the complexity of mining deposits, and the increase in environmental restrictions. This forces to consider extracting all valuable elements and treating toxic materials from the ore. One way to achieve these objectives is through flotation plants that process polymetallic ores. The design of polymetallic ores flotation plants usually consists of a sequence of circuits separating the valuable elements from the gangue without any integration between them beyond sending tails or concentrate streams from one plant to another. Flotation circuits are complex systems with many flotation stages and elements that participate in the system, speaking only of monometallic ore circuits. Using a task superstructure with an origin-destination matrix reduces the solution to the problem significantly (Cisternas et al., 2014). The flotation stage recoveries of stage $j$ of specie $i$, $T\_{i}^{j}$, which are needed to design these systems, are unknown because they depend on the circuit design. Then, to represent this epistemic uncertainty, a uniform distribution function, $T\_{i}^{j}\~U\left(a,b\right),$ can be considered. This range of recovery values ​​is sufficient for identifying a set of optimal flotation circuit structures (Cisternas et al., 2015). For the identification, Monte Carlo optimization is applied solving a mixed-integer linear programming (MILP) problem, guaranteeing a global optimum. This way, optimization methodologies can be used for circuits with many species and flotation stages (Calisaya et al., 2016). This design approach was applied by Botero et al. (2024) for the design of polymetallic ore circuits.

To identify bottlenecks in operation and propose additional improvement to polymetallic flotation circuits, global sensitivity analysis (GSA) can be performed, focusing on identifying input variables with the most significant effect on flotation circuit performance. The use of GSA applied to mineral processing has been studied (Lucay et al., 2015; Sepúlveda et al., 2013), and the Sobol-Jansen method has shown the best performance among several methods studied (Lucay et al., 2020). However, all these studies have only been conducted on monometallic ore circuits. This work analyzes the design of integrated flotation circuits for polymetallic ore. The polymetallic ore Kevitsa plant for copper (Cu) and nickel (Ni) is utilized as a case study.

* 1. Descriptive methodology

The species participating in the polymetallic circuit are chalcopyrite CuFeS2 (Cp), pentlandite Ni9Fe9S8 (Pn), pyrrhotite FeS (Po), and non-sulphur gangue (G). The species of interest for the Cu concentrate is Cp, and for the Ni concentrate is Pn. The feed to the flotation circuit is 8.07 t/h Cp, 5.44 t/h Pn, 14.73 t/h Po, and 903.84 t/h G, and the recovery data are presented in Table 1.

2.1. Optimal integrated design

According to the research conducted by Botero et al. (2024) the design strategy of monometallic ores can be applied to the design of polymetallic ores since few optimal structures were found for the circuits studied, given the uncertainty in the stage recoveries. The starting point should be using a superstructure - origin-destination matrix for each concentrate and tail stream based on the existing flowsheet. Then, new stream connections were included, including circuit integration between the Cu and Ni plants. The revenues were used as an objective function, and uniform distribution functions were generated based on plant data. The MILP problem was solved using CPLEX 12.9.0.0 on the GAMS platform.

* + 1. Global sensitivity analysis for improvement

GSA was applied to identify the stage recoveries that have a significant effect on the global Cu and Ni circuit recoveries and product grades. The products are the Cu and Ni concentrates. The studied mathematical models of the circuit are obtained by a mass balance representing the stage recoveries by uniform distributions. For the GSA, the Sobol-Jansen method was used, which implements the Monte Carlo estimation of the first-order and total Sobol indices simultaneously (Jansen, 1999; Saltelli et al., 2010). The sensitivity package under R project software was utilized using a random sample of 50,000 data points.

Table 1. Recovery data from the Kevitsa plant flotation circuit (Botero et al., 2024)

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Circuit** | **Stages** | **Symbol** | **Cp** | **Pn** | **Po** | **G** |
| **Cu** | Rougher | R1 | 0.543 | 0.112 | 0.085 | 0.013 |
| Cleaner | C11-C14 | 0.790 | 0.459 | 0.530 | 0.362 |
| Scavenger | S1 | 0.401 | 0.116 | 0.086 | 0.028 |
| **Ni** | Rougher | R2 | 0.253 | 0.350 | 0.272 | 0.044 |
| Cleaner | C21-C25 | 0.174 | 0.697 | 0.552 | 0.385 |
| Scavenger | S2 | 0.773 | 0.844 | 0.861 | 0.203 |

* 1. Results
		1. Optimal integrated Cu and Ni flotation design

Figure 1 represents the integral polymetallic flotation circuit obtained to produce Cu and Ni concentrates and a tail. The first flotation circuit, for the production of Cu concentrate, considers a rougher stage (R1), four cleaner stages (C11, C12, C13, and C14), and a scavenger stage (S1). The second flotation circuit, for the production of Ni concentrate, considers a rougher stage (R2), four cleaner stages (C22, C23, C24, and C25), a scavenger stage (S2), and a cleaner-scavenger stage (C21). Observe that the recirculation of a tail stream from the Ni C21 stage to the Cu R1 stage integrates both circuits. This integrated circuit increases the revenue from 261.9 MMUS$/year to 314.9 MMUS$/year, which is a 20% increase.

* + 1. Global Sensitivity Analysis (GSA)

The mathematical models utilized for the GSA were the global Cu and Ni recoveries, and Cu and Ni grades, in the polymetallic flotation circuit of Figure 1. These global recoveries were expressed as a function of the stage recoveries, $T\_{i}^{j}$. These stage recoveries were given by uniform distribution functions, $T\_{i}^{j}\~U\left(a,b\right)$, where the constant values​​$a$ and $b$ were obtained using the data in Table 1 ±0.05. The results are shown in Figures 2 and 3.



Figure 1. Integrated design of the Cu and Ni -Kevitsa flotation circuits. Modified from Botero et al. (2024).



Figure 2. Sobol total index (Si) for global Cu recovery [ a) Cp and c) Po, G stage recoveries], and global Ni recovery [ (b) Pn and d) Po, G stage recoveries].



Figure 3. Sobol total index (Si) for the main stage recoveries that influence a) copper grade in the Cu concentrate, and b) nickel grade in the Ni concentrate.

Figure 2a shows the total Sobol index of the$ T\_{Cp}^{j}$ variables that have the most significant effect on the global recovery of Cp are R1, S2, and C11 stages. This is an exciting result because stage S2 of the Ni circuit has an essential effect on the Cu recovery. Figure 2c indicates that stage R1 is the most relevant in the global recovery of Po and G species. Figure 2b demonstrates that S2 and R2 stages are the ones that have the most significant effect on the overall recovery of Pn. Figure 2d shows the most important impact of stage S2 on the global recovery of Po and stage R2 for the global recovery of G.

Figure 3a shows that the Po and G recoveries in stage R1 have the most significant effect on the Cu grade. Figure 3b shows that the variables with the most significant effect on the Ni concentrate grade are the G recoveries in stages R2 and S2 and Po recovery in stage S2.

* + 1. Improvement of the polymetallic flotation integrated circuit.

According to the GSA of the integral Cu and Ni flotation circuit, better control can be performed in the different flotation stages to increase the recovery of Cp and Pn in stage S2 and decrease the recoveries of Po and G in stages R1 and R2, to guarantee more remarkable global recovery and improvement in the grade of copper and nickel concentrate.

Table 2 shows the revenues, recoveries, and grades of the concentrates of the Cu and Ni in the polymetallic flotation circuit for the original design, the integral design, and the improvement by simulation of this integrated circuit of Cu and Ni, setting values, through flotation criteria, in the stages of most significant effects given in the GSA study, Table 1 (Gray highlighted data changed: $T\_{Cp}^{S2}=0.85$, $T\_{Pn}^{S2}=0.92$,$T\_{Po}^{R1}=0.06$*,*  $T\_{G}^{R1}=0.01$), $T\_{Po}^{R2}=0.2$, $T\_{G}^{R2}=0.02$).

Table 2. Summary of the performance of the original design, integrated design, and improvement after GSA.

|  |  |  |  |
| --- | --- | --- | --- |
| **Circuit** | **Revenues** | **Global recoveries** | **Concentrate grade** |
| **MM$US/year** | **Cp** | **Pn** | **Po** | **NSG** | **Cu**  | **Ni** | **Po** |
| **Original design** |
| **Cu** |  | 66.06 | 3.40 | 4.68 | 0.20 | 22.98 | 0.85 | 8.53 |
| **Ni** |  | 0.13 | 75.67 | 54.28 | 0.64 | 0.01 | 7.76 | 43.90 |
| **Total** | 261.9 |  |
| **Optimal integrated design** |
| **Cu** |  | 88.18 | 1.95 | 5.66 | 0.05 | 29.09 | 0.42 | 9.79 |
| **Ni** |  | 0.03 | 79.31 | 54.89 | 0.61 | 0.00 | 8.18 | 45.05 |
| **Total** | 314.9 |  |
| **Improved integrated design using GSA** |
| **Cu** |  | **91.97** | 2.06 | 0.39 | 0.04 | **30.50** | 0.45 | 6.90 |
| **Pb** |  | 0.03 | **88.03** | 54.30 | 0.50 | 0.00 | **9.60** | 45.47 |
| **Total** | 354.0 |   |   |   |   |   |   |   |

The significant improvements of the integral design concerning the original design shown in Table 3 indicate that studies should be carried out to incorporate integration in the design of polymetallic ore flotation circuits. The application of GSA allows increased revenues by 12% and 35% concerning the integrated design and original design, respectively.

* 1. Conclusions

Integrated designs would considerably improve the design of polymetallic ore circuits. Improvements in the optimal integral circuit operation and identifying bottlenecks can be made with a GSA. Thus, the focus should be on optimizing the operating conditions in those flotation stages that have a more significant effect on improving the recovery and grade of the metal concentrates.

In our case study, an integrated Cu and Ni polymetallic circuit obtained using optimization and the subsequent improvement proposal was analyzed, focusing on the scavenger stage, S2, that has a more significant effect on the global recovery of chalcopyrite and pentlandite, and in decreasing the floatability of pyrrhotite and gangue in R1 and R2 stages to increase the Cu and Ni grades, respectively.

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