Minerals Engineering 117 (2018) 24–33

Contents lists available at ScienceDirect

Minerals Engineering

journal homepage: www.elsevier.com/locate/mineng

A quasi-review of conceptual flotation design methods based on computational optimization

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ARTICLE INFO

Keywords:
Flotation
Design
Optimization
Superstructures
Uncertainty

ABSTRACT

This paper presents a review and analysis of the research applying optimization to flotation design problems. Specifically, superstructures utilized, mathematical models, and optimization algorithms. The effect of epistemic and stochastic uncertainties are discussed. The new knowledge generated using this type of techniques are highlighted. As these techniques are not used in practice, the gaps for implementation are identified. The review leads to conclusions regarding the benefits of optimization based methods in practice and barriers to their use. Likely future developments are discussed.

1. Introduction

Flotation is one of the most used technologies in the mining industry for the treatment of numerous minerals. Despite the popularity of this technology, its use for more than 140 years (MEI, 2017), and the numerous published studies (see Fig. 1), there is still no model available that can represent the relationship between all the variables involved in its behavior. The lack of models capable of explaining and predicting flotation behavior is a challenge for engineering since engineering needs models to operate and design flotation equipment. In other words, if we don't have models we cannot quantify the behavior of changes in its variables. For this and other reasons, the design of flotation circuits is still made based on the experience of the designer supported by a series of experiments and computational tools, but where experience is still the major component of the design process.

With this, we do not mean that there is no knowledge about flotation, which is many and increasing every day in the scientific community, but this knowledge is mostly not represented by mathematical models. It is also true that there are numerous models available in the literature and that many are applied in practice to study, operate and design these processes (Zhang and Subasinghe, 2016; Jovanović et al., 2015). However, these models are applicable under limited conditions and usually require experimentation to adjust their parameters. Then, it is needed to know the operational conditions to adjust the models. However, those operational conditions are not fully known before to initiate the design. Furthermore, given the empirical nature of the models, the scaling of laboratory results at the industrial level is not fully represented by these models. Thus the design, analysis, and optimization of flotation processes have become a challenge not yet overcome. However, since the mid-1970s, numerous papers have been published on the design of flotation circuits based on optimization. A review and analysis of the progress made and the challenges ahead is the objective of this manuscript. Three previous reviews have been published (Mehrotra, 1988; Yingling, 1993a; Méndez et al., 2009a), this new one adds more analysis, discussion, and mainly focuses on three aspects, superstructure, optimization algorithms and mathematical models. Another important aspect is the analysis of the effect of the uncertainties, both epistemic and stochastic, on the design of these processes. Therefore, this quasi-review emphasizes on overview aspects and does not comprehensively review aspects such as flotation models.

2. The problem

The design of flotation circuits can be defined as given the characteristics of a mineral and the objectives of the design, determine the equipment, its connectivity, and the operating states. In other words, the design includes to select and size flotation, grinding, and dewatering equipment; Select the streams that interconnect these equipments (circuit or process structure); Determine the operating conditions of those equipments and the streams connecting these equipments.

Designing using optimization requires three elements (see Fig. 2). First, it is necessary to define superstructures representing a set of alternatives from which a set of optimal alternatives will be selected. Second, a mathematical model must be defined that models the alternatives of superstructures, imposes goals and constraints that must be met, and defines the objectives to be optimized. Finally, an algorithm is

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https://doi.org/10.1016/j.mineng.2017.12.002
Received 26 July 2017; Received in revised form 12 November 2017; Accepted 3 December 2017

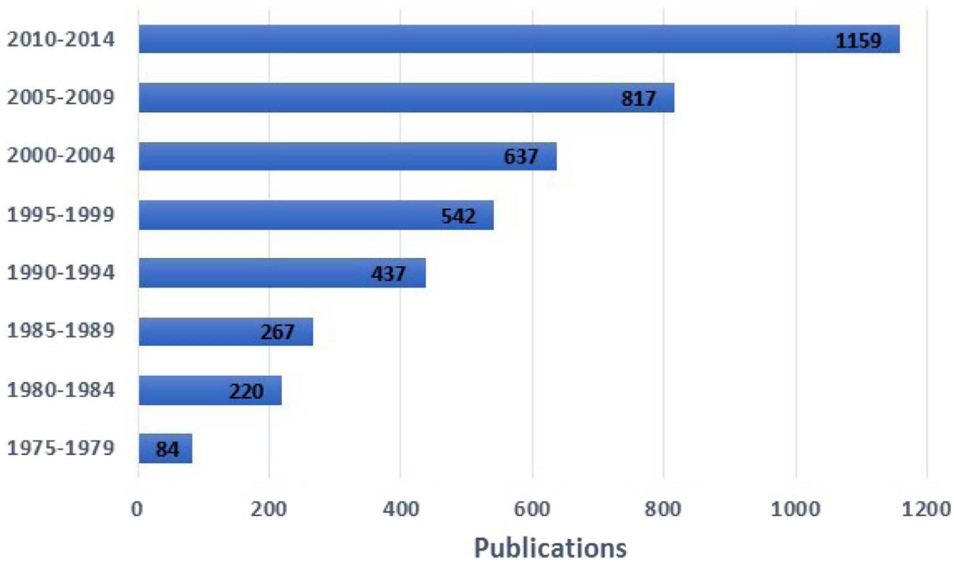

Fig. 1. Publications related with flotation in the research areas of Mining Mineral Processing and Metallurgy & Metallurgical Engineering in Web of Science.

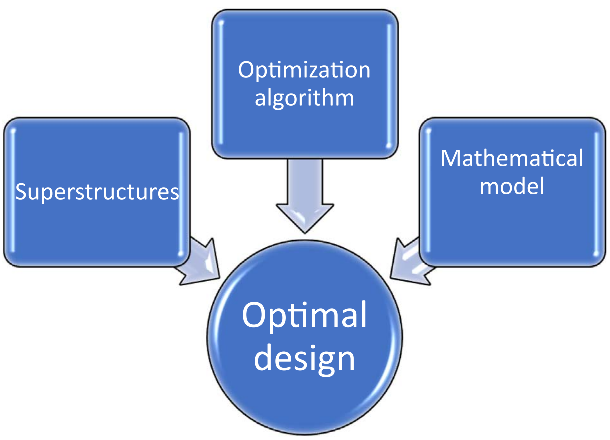

Fig. 2. Main elements of optimal design.

needed that is capable of solving the mathematical problem raised in the previous stage.

The generation of superstructures capable of representing all alternatives is an important challenge given that we do not know how many stages and which type is most appropriate for a given problem (e.g., if four stages are selected, do we need a second cleaner, a scavenger or perhaps a cleaner-scavenger?), that different technologies can be used to fulfill a specific task (e.g. bank of cells versus bank of columns), that superstructures that represent nonsensical alternatives or that equivalent alternatives can be generated combining of different forms the elements of superstructures. Given the combinatorial nature of the problem, it is also important to keep the size of superstructures as small as possible. The introduction of regrinding must also be included in superstructures because it is known to have an impact on costs, profits, recoveries, and grade of concentrates. It is not known whether the introduction of the dewatering stages (thickeners, hydrocyclones, and filtration), which is part of the flotation circuit, have an impact on the design of the flotation circuit.

The mathematical model that represents the alternatives of the superstructure must be on the one hand sufficiently rigorous to represent the phenomena and relations of the necessary variables for good design, and on the other hand, it should be simple enough that allows the optimization algorithm to be capable of obtaining the global optimum. If experimentation is required, this should be the cheapest and shortest to perform. Given the combinatorial nature of the problem, the size of the problem to be solved plays a critical role. Nonlinear expressions of equipment, cost functions, and material balances give complexity to the problem. The selection of equipment, stages, and direction of streams add more complexity because some variables acquire values in their limits (e.g. the fraction of stream sent from one equipment to another is usually 0 or 1) or because some equations need to be activated or deactivate according to the selected option (e.g. the technology used in a cleaner can be a bank of cells or columns, then the equations that represent each technology must be activated or deactivate depending on whether that technology is selected or not).

The algorithms needed to solve this type of problem must be able to solve nonlinear problems or mixed-integer nonlinear problems, where the nonlinear problem is nonconvex, for which algorithms are needed that can guarantee global optimum. It is known that any problem with integer variables is always nonconvex. However, the search for the optimal solution of integer problems is simpler than the search for the optimal global solution of nonconvex problems with its continuous variables. Although many problems have been solved with algorithms available in the literature, the algorithm capable of solving real-size problems is not available in the literature, at least there is no evidence that real-size problems have been designed to obtain the global optimum.

Other problems are present in the application of optimization in the design of flotation circuits. The presence of epistemic and stochastic uncertainty adds more challenges to the design of flotation circuits. Uncertainty is not considered in the conceptual design, although sales contracts specify narrow margins on the product specifications and the constraints imposed by the contract determine design decisions (Amini and Noble, 2017). Stochastic uncertainty is associated, among other variables, with the natural variation in the distribution of the composition and particle size of the feed, and the variation of the price of the metal to be concentrated. How to introduce these variations or how to define deterministic values are problems that must be addressed. The epistemic uncertainty is associated with the empirical nature of the parameters of the flotation models, which have a deterministic value for given conditions but are unknown at the design stage because the operational conditions and design are unknown. Note that ore variability is currently considered by stochastic strategic mine planning algorithms (Navarra et al., 2017), but not considered in the optimal conceptual design of concentration plants.

On the other hand, the incorporation of modifications in the way of design does not occur naturally in the organizations, this is carried out in the long term, after overcoming several stages and make various efforts. In other words, it is a cultural change within the organization that makes these designs (Gómez, 2010). Hence the importance of