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Effect of the objective function in the design of concentration plants

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ABSTRACT

Different objective functions have been used in the design of concentration plants. The frequently used functions correspond to the maximization of revenue or profit. However, there is no study examining the effect of the type of objective function on the design of these plants. This manuscript analyzes the effect of various objective functions, including the maximization of profits, the return on investment and the net present worth and the minimization of the payback period, among other functions. Additionally, the procedure for a flotation circuit design is presented that is based on a flexible superstructure, where the designer can choose the set of alternatives. Two cases were considered: the equipment design for a given circuit structure and the circuit structure design given the equipment. The generated models correspond to mixed integer nonlinear programming and nonlinear programming problems. The results indicate that the objective function has a significant effect on the obtained solution, as well as the concentration circuit structure.

1. Introduction

Flotation is a common technology used in industry for the separation of valuable components from the gangue minerals associated with the metal. The objectives of this process are to obtain maximum recovery of the valuable species and to maximize the concentrate grade. For various reasons, the separation stage is rarely complete, which is the reason why multiple interconnected flotation stages are used in practice. The optimization of a flotation circuit is typically justified because it processes thousands of tons of ore per year; thus, a marginal improvement can have a major economic impact (Méndez et al., 2009b).

The design of flotation circuits is based on the experience of the designer, which is supplemented by laboratory tests and simulations. There are several attempts in the literature to develop automated methods for designing such circuits. Most studies have used superstructures, which can express different alternative plant configurations. Then, a mathematical model is formulated based on the superstructure, and optimization techniques determine the optimal configuration and operating specifications of the plant.

These optimization techniques can be classified as mathematical programming and genetic algorithm approaches. Mathematical programming has been applied in several studies (Mehrotra and Kapur, 1974; Yingling, 1990; Schena et al., 1996, 1997; Cisternas et al., 2004, 2006). Because of the non-linearity characteristic of the problem, a simple kinetic model has been used and mixed integer programming methods have been applied to represent the alternatives using discrete values of stage recoveries and/or equipment sizes. Guria et al. (2005a, 2005b, 2006) were the first to apply genetic algorithm to flotation optimization design. Then, Ghobadi et al. (2011) employed genetic algorithm with additional process-based constraints. The advantage of these procedures is that they can obtain the global solution. However, in these studies the design problems were relatively small with 2 to 4 cells or bank circuits because of the computational cost of the genetic algorithm.

The literature on optimization-based process design can be classified into those who consider economic performance as an objective function and those who consider it a function of technical performance. Based upon a review of the literature, Novak and Kravanja (2006) showed that the objective function typically used for the design and synthesis of processes is economical. This objective function is sometimes used to minimize different types of costs to maximize profits or income. The selection of the objective function can have a large influence on the generation of the optimal solution, which was observed by Buskies (1997).

In mineral processing, technical objective functions were used in early research, for example, to maximize recovery, grade or combinations of these functions (Mehrotra and Kapur, 1974; Green, 1984; Reuter et al., 1988; Reuter and Van Deventer, 1990, 1992; Dey et al., 1989). Recovery and grade are opposite functions and therefore, the combinations of these functions can indirectly represent the profit of the process (Mehrotra and Kapur, 1974). Economic functions, especially for the maximization of profits or

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Nomenclature

C	cleaner stage
CC	Re-cleaner stage
$CC(i, k)$	mass flow rate of species k in concentrate streams of stage i
$CF(k)$	mass flow rate of species k in final concentrate
$CT(i, k)$	mass flow rate of species k in tail streams of stage i
c_t	total annual cost
$c_{op}(i)$	annual operational cost of stage i
c_{eq}	equivalent annual cost
D	annual depreciation
E_g	gas factor
F_C	annual cash flows,
$F(i, j, k)$	mass flow rate of species k in the stream from stage i to stage j.
F_i	total mass flow rate of the feed stream to stage i,
$F_c(i, j, k)$	mass flow rate of species k in the concentrate stream from stage i to stage j
$F_w(i, j, k)$	mass flow rate of species k in the tail stream from stage i to stage j
$FS(j,k)$	mass flow rate of species k in feed streams of stage i
$F_f(k)$	mass flow rate of species k fed to the circuit
FL	Lang factor
FL_w	Lang factor for working capital
g	grade
H	number of hours per year of plant operation
II	$\{i/i$ is flotation stage, circuit feed, final tail or final concentrate$\}$
I	$\{i/i$ is flotation stage, $i \in II\}$
I_F	fixed capital cost
I_w	working capital
K	$\{k/k$ *is a species*$\}$
L	$\{(i, j)/(i, j)$ *is a stream from stage i to stage j*, $i, j \in II\}$
LC	$\{(i, j)/(i, j)$ *is a concentrate stream* $(i, j) \in L\}$
LT	$\{(i, j)/(i, j)$ *is a tail stream* $(i, j) \in L\}$
MCM	cost of mine-crushing-grinding per ton of ore fed to the flotation plant
$N(i)$	number of flotation cells in stage i
P	concentrate
P_k	kilowatt-hours cost
P_B	profit before taxes
p	fraction of metal paid
$R_{max}(i, k)$	maximum recovery at infinite time of stage i for species k
Rfc	refinery charge
R_{OIB}	return on investment
r_{IRR}	internal rate of return
r_t	tax rate
R	rougher stage
S	scavenger stage
SC	scavenger-cleaner stage
$T(i, k)$	recovery of stage i for species k
Trc	treatment charge
t_{PB}	payback time
t_D	depreciation period
$V(i)$	cell volume in stage i
W	final tail
$WF(k)$	mass flow rate of species k in final tail
W_{NP}	net present worth
y	binary variable indicating the choice of the destination stream

Greek symbols

$\kappa_{max}(i, k)$	maximum rate constant of the rectangular distribution function in stage i for the species k
ρ_p	pulp density
$\tau(i)$	cell residence time in stage i
μ	grade deduction

Superscript

LO	lower bound
UP	upper bound
c	concentrate
w	tail

Subscript

c	concentrate
w	tail

revenues, have been used by several researchers (Schena et al., 1996, 1997; Abu-Ali and Abdel Sabour, 2003; Cisternas et al., 2004, 2006; Guria et al., 2005a). However, none of these works have studied the effect of the type of objective function on the configuration and design of the flotation plant. The aim of this paper is to analyze the effect of various economic objective functions on the optimal configuration of the plant and its design. Herein, two cases are considered: the selection of equipment and determination of operation conditions given the flotation circuit configuration and equipment sizes, and the flotation circuit configuration and equipment designs given the equipment selection and the operational conditions.

An additional contribution of this work is the development of a flexible superstructure that allows a set of alternatives to be defined for the variable that is being optimized.

2. Strategy

The strategy uses a superstructure of stages that represent alternative flotation circuit configurations. The superstructure is based on the generic representation of a stage, which is used to

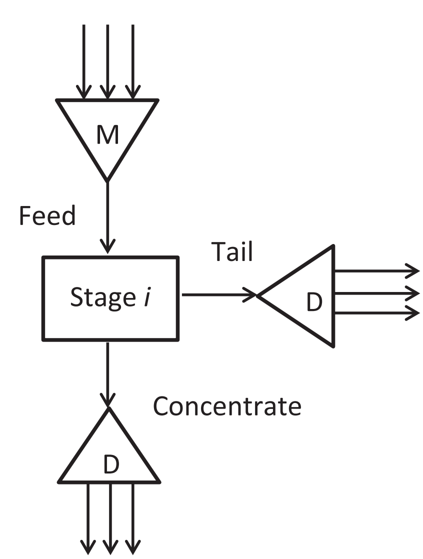

Fig. 1. Representation of the flotation stages.