European Journal of Operational Research 000 (2015) 1–13

Contents lists available at ScienceDirect

European Journal of Operational Research

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

Decision Support

Optimizing mining complexes with multiple processing and transportation alternatives: An uncertainty-based approach

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ARTICLE INFO

Article history:
Received 28 February 2014
Accepted 1 May 2015
Available online xxx

Keywords:
Metaheuristics
OR in natural resources
Mining complex
Stochastic orebody simulations
Operating alternatives

ABSTRACT

Mining complexes contain multiple sequential activities that are strongly interrelated. Extracting the material from different sources may be seen as the first main activity, and any change in the sequence of extraction of the mining blocks modify the activities downstream, including blending, processing and transporting the processed material to final stocks or ports. Similarly, modifying the conditions of operation at a given processing path or the transportation systems implemented may affect the suitability of using a mining sequence previously optimized. This paper presents a method to generate mining, processing and transportation schedules that account for the previously mentioned activities (or stages) associated with the mining complex simultaneously. The method uses an initial solution generated using conventional optimizers and improves it by mean of perturbations associated to three different levels of decision: block based perturbations, operating alternative based perturbations and transportation system based perturbation. The method accounts for geological uncertainty of several deposits by considering scenarios originated from combinations of their respective stochastic orebody simulations. The implementation of the method in a multipit copper operation shows its ability to reduce deviations from capacity and blending targets while improving the expected NPV (cumulative discounted cash flows), which highlight the importance of stochastic optimizers given their ability to generate more value with less risk.

1. Introduction

A mining complex can be interpreted as a supply chain system where material is transformed from one activity to another (Goodfellow, 2014). The primary activities (or stages) consist of: mining the materials from one or multiple sources (deposits); blending the material considering stockpiling; processing the material in different processing paths accounting for multiple operating alternatives; and transporting the products to port or final stocks using one or multiple transportation systems.

For a given processing path (e.g. mill-roaster in a refractory ore operation), it is possible to have multiple operating alternatives; for example, a mill may be operated using two different options: fine or coarse grinding (Fig. 1). If the mill is operated using fine grinding, there is often a very high energy consumption, which is associated with a higher processing cost and also requires larger residence times for the material processed, thus limiting the mill throughput. A coarse grinding option requires less energy and residence time in the mill, which decreases the operating cost and increases the mill throughput, however, it results in a lower recovery in the roaster downstream. Furthermore, different processing alternatives often impose different blending requirements. For example, the tolerable amount of free silica of the input material may be lower when operating the mill at fine grinding given that the presence of this element increases the hardness of the material. When a mill is bottlenecking the system, it is better to use a coarse grind with higher throughput in the early periods of the life-of-mine (LOM), and, to use a finer grind to maximize recovery towards the end of the LOM (Whittle, 2014). During the early periods, a mining complex incurs an opportunity cost for having material with large residence times in the mill, however, as the quantity of ore remaining in the mining complex diminishes, there is no opportunity cost.

Once the material is processed through the different processing paths and using some available operating alternatives, existing transportation systems, either continuous (belt conveyors, pipe transport) or batch (trucks, rail transportation), are used to transport the processed material to one or several ports or final stocks. Accounting

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http://dx.doi.org/10.1016/j.ejor.2015.05.002

Please cite this article as: L. Montiel, R. Dimitrakopoulos, Optimizing mining complexes with multiple processing and transportation alternatives: An uncertainty-based approach, European Journal of Operational Research (2015), http://dx.doi.org/10.1016/j.ejor.2015.05.002

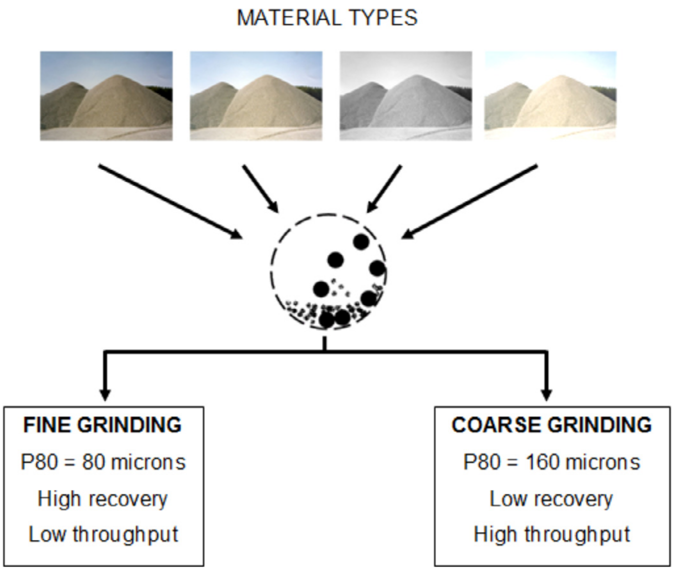

Fig. 1. Operating alternatives for a mill.

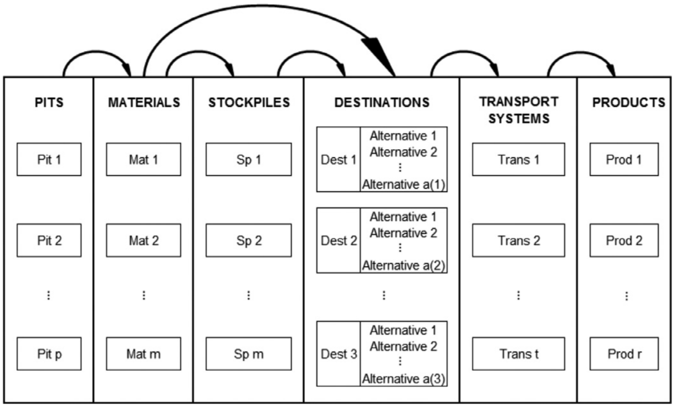

Fig. 2. Flexibility of the mining complex.

for transportation systems in the optimization of mining complexes is important, given that they may limit the overall system output. In a mining complex, it is common to have multimodal transportation that involves the use of separate contractors or operators for each type of transport (Zamorano, 2011). To account for the demand of transportation of material processed, it is necessary to establish the feasible relations between processing paths and transportation systems; specifically, a particular transportation system may be able to handle output material from some of the available processing paths: For example, in a pyro/hydrometallurgical complex, a hydraulic pipe may be able to transport the material output from the lixiviation plant whereas the material output from the pyrometallurgical plant is transported to the final stocks via trucks. Once the feasible transport relations are established, the demand for transportation is evaluated by considering the throughput relationships (output/input tonnages) for each processing path given the operating alternative implemented. For example, the output/input tonnage relation and the metallurgical recovery in a gold flotation plant change if the mass pull is 4 or 7 percent (Hadler, Smith, & Cilliers, 2010). When the transportation of processed material is the bottleneck in the overall system, the operating conditions at the different processing paths must be evaluated. To overcome this limitation, it may be useful to re-evaluate throughput specifications of the processed material. Whittle (2010) shows that by increasing the copper concentrate from 28 to 32 percent in some periods on a sulfide deposit, the metallurgical recovery decreases by 7 percent, but the NPV increases by 6 percent given the possibility of transporting more concentrated ore on the pipe, which is the bottleneck of the system.

Optimizing mining complexes by considering geological uncertainty and the different activities simultaneously is a large combinatorial optimization problem (Fig. 2). Several efficient methodologies have been developed in stochastic environments for the mine production scheduling problem (Bendorf & Dimitrakopoulos, 2013; Godoy, 2003; Godoy & Dimitrakopoulos, 2004; Goodfellow & Dimitrakopoulos, 2013; Lamghari & Dimitrakopoulos, 2012; Lamghari, Dimitrakopoulos, & Ferland, 2013; Montiel & Dimitrakopoulos, 2013). The integration of multiple activities during optimization in deterministic frameworks include the work of Hoerger, Seymour, and Hoffman (1999); Wharton (2007); Whittle (2007); Whittle (2010a); Whittle (2010). This paper presents a new model for optimizing multipit mining complexes that incorporates processing and transportation alternatives and accounts for geological uncertainty by means of stochastic orebody simulations (Fig. 3). Stochastic simulation of mineral attributes provides possible representations of the mineral deposits that are consistent with the data and with the geological model (Dowd, 1994). A mining complex may contain several deposits discretized into a large number of mining blocks leading to optimization models of prohibitive size. To solve the optimization model presented in this paper, a solution approach that uses simulated annealing algorithm is developed and implemented.

2. Method

2.1. Overview

In a mining complex, the material flows from the deposits as raw material to ports or final stocks as saleable products. To optimize the mining complex, the different stages that are involved must be considered simultaneously (Fig. 4). First, the multiple material types coming from the mine(s) are sent to the available processes or to stockpiles where they are blended to meet the quality requirements. At each process the material is transformed into intermediate or final products, which are then transported to ports or final stocks. The goal when optimizing a mining complex is to maximize discounted cash flows while minimizing deviation from mining and metallurgical processing targets, such as capacities associated to the different processing and transportation options and blending requirements regarding the different metallurgical properties. These metallurgical properties control the operation of the different processes and are calculated as mathematical expressions of the different grade elements, e.g., fuel value is a metallurgical property that controls the operation on a roaster.

2.2. Optimization model

Maximize

$$O = \sum_{t=1}^{T} \left(\frac{1}{S} \left(\sum_{s=1}^{S} discprofit(s,t) - penalty(s,t) \right) \right) \quad (1)$$

Subject to

$$mineproduction(s,t) = \sum_{i=1}^{I} \sum_{d=0}^{D} X_{itd} \cdot m_{is} \quad (2)$$

$$tonnesentmine(s,t,d) = \sum_{i=1}^{I} X_{itd} \cdot m_{is} \quad (3)$$

$$\begin{aligned} tonnestockpiles(s,t) = {} & tonnestockpiles(s,t-1) \\ & - \sum_{d=1}^{D} tonnerehandle(s,t,d) \\ & + tonnesentmine(s,t,0) \end{aligned} \quad (4)$$

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