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Innovative Applications of O.R.

Stochastic short-term mine production schedule accounting for fleet allocation, operational considerations and blending restrictions

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ABSTRACT

A new short-term mine production scheduling formulation is developed herein based on stochastic integer programming. Unlike past approaches, the formulation simultaneously optimizes fleet and mining considerations, production extraction sequence and production constraints, while accounting for uncertainty in both orebody metal quantity and quality along with fleet parameters and equipment availability, all leading to a well-informed sequence of mining that is expected to have realistic as well as high performance during a mine's operation. To assess the latter performance and implementation intricacies of the proposed formulation, the formulation is applied at a multi-element iron mine and the resulting monthly schedules are assessed and compared to the conventional mine scheduling approach showing: lower cost, minable patterns, efficient fleet allocation ensuring higher and less variable utilization of the fleet.

1. Introduction

Short-term mine production scheduling generates a sequence of extraction within an annual production plan. The production schedule is seen as the operational guide to meet the mine's long-term objectives developed under current operating conditions and constraints. It outlines extraction stages in terms of months, weeks or days. The optimization of short-term production scheduling is guided by the life-of-mine or long-term mine scheduling (Hustrulid & Kuchta, 1995) and it is typically optimized in two separate steps. The first step optimizes the physical sequence of extraction of materials. The second step optimizes the assignment of the mining equipment fleet based on equipment capacity, availability and hauling time. There are three limitations to the above mentioned separate optimization steps, which lead to non-optimal short-term production schedules, even if results are experimentally adopted to generate a combined final schedule.

First, the scheduling elements, material sequence of extraction and equipment utilization, are artificially separated when optimized so that they do not benefit from their simultaneous optimization. Second, neither of the optimization steps involved considers uncertainty in input parameters, nor do they account for the local variability of the characteristics of the materials being scheduled for extraction. Lastly, the optimization of the extraction sequence of material ignores operational considerations and fleet management, and thus can be unrealistic and become hostage to equipment availability. These limitations can have adverse effects on the performance of the production scheduling and this may lead to: (a) increased operating costs stemming from erroneous materials blending and decisions on material processing destinations; (b) uncertainty in equipment performance and sub-optimal equipment use; (c) inability to deliver expected material targets; and (d) infeasible mining patterns. This paper addresses these limitations

Several papers related to short-term production scheduling and fleet allocation are available in the technical literature; a first group outlines general concepts of short-term production scheduling optimization, while a second group of papers considers real-time fleet allocation. Early efforts in optimizing short-term mine production schedules focus on developing concepts and related formulations for deciding sequences of depletion based on mathematical programming (Fytas and Calder, 1986; Gershon, 1982; Kahle & Scheafter, 1979; Schleifer, 1996; Wilke & Reimer, 1977; Wilke & Woehrle, 1979). Accordingly, the outline of production progressions (extraction sequence) on a daily, weekly or monthly basis follows production targets set by the long-term mine production schedule. The optimization process considers the allocation of resources that match the available fleet capacity, the mine's layout

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and operational issues, such as mining direction. While accounting for the above, the objective function of related formulations is typically set to minimize production deviations from the yearly production plan targets; if these targets are met, then the expected long-term targets and overall mine valuation will likely be met. Key physical constraints are considered and include the mobility of mining equipment and mineable extraction patterns, as well as quality constraints leading to blending of materials to extract so as to match quality feed targets for various ore processing streams. More recent work stays within the same context; for example, Vargas, Morales, Rubio, and Mora (2008) present a mathematical programming formulation accounting for quality and geometric constraints, mill and mine capacity. Similarly, Eivazy and Askari-Nasab (2012) account for multi-destinations, blending stockpiles and decisions on ramps while their objective function minimizes mining cost, processing cost, waste rehabilitation cost, re-handling cost and hauling cost. The latter two approaches have drawbacks, such as the use of aggregation of mining blocks prior to optimizing, leading to suboptimal solutions, as aggregation of materials ignores the practical selectivity of preferred ore types and cannot deal with the actual hauling process during the optimization process.

As noted earlier, all the above work does not integrate a key aspect of short-term planning, namely, the management and dispatching of mining equipment/fleet. The real-time fleet allocation for short-term production planning is presented in Alarie and Gamache (2002), and Souza, Coelho, Ribas, Santos, and Merschmann (2010). A fleet dispatching system considers different allocation strategies given that transportation may represent more than 50% of operating costs (Alarie & Gamache, 2002). The solution strategies used in truck dispatching systems aim to improve productivity and reduce operating costs, however, the extraction patterns to be mined are assumed to be available. A shortcoming of these algorithms is that the whole tonnage of every pit are seen as a single macro block where the short-scale variability of the grade is lost and the one hour production and dynamic allocation of the fleet is only related to the dispatch system. L'Heureux, Gamache, & Soumis (2013) present a deterministic mixed integer programming model for short-term planning in open-pit mines. The sequence of mining of this model considers operational activities, such as drilling, blasting, transportation, ore processing capacity, the availability and the locations of shovels and drills. Drawback of this formulation is that the mined blocks by day are aggregated regular blocks. The definition of sectors to mine is usually linked to irregular patterns because of the local scale grade variability of the orebody and quality requirements.

More recent work considers minimizing operating costs of trucks since they represent the largest portion of the fleet in open pit mines (Topal & Ramazan, 2010), and is formulated as an integer program. Maintenance costs not only are a significant proportion but also change non-linearly depending on the road conditions, truck age and truck types. The stochastic extension (Topal & Ramazan, 2012) of this model considers the uncertainty in truck maintenance costs for the available fleet when matching annual production targets. The approach provides a maintenance cost distribution of the optimized equipment schedule minimizing the cost. However, similarly to other aspects of short-term planning discussed above, this last work is done assuming a sequence of extraction.

The work herein presents a new, integrated approach to short-term mine production scheduling based on stochastic integer programming (SIP), aiming to contribute towards generating well-informed production sequences and improved performance during a mine‘s operation. The proposed SIP formulation simultaneously optimizes both fleet and production schedule, accounts for operational considerations, such as mining width and mining directions, and considers the possible fluctuation and uncertainty of the metal grade and ore quality, fleet parameters and availability. The approach formulated is based on previous developments in long-term mine planning (Boland, Dumitrescu, & Froyland, 2008; Ramazan & Dimitrakopoulos, 2013; Lamghari & Dimitrakopoulos, 2012). Note that grade and ore quality uncertainty and variability is modelled herein through the generation of stochastically simulated scenarios of the mineral deposit being mined (Goovaerts, 1997), based on minimum and maximum autocorrelation factors for multivariate ore bodies (Desbarats & Dimitrakopoulos, 2000).

In the following sections, the proposed stochastic mathematical programming formulation for short-term mine production scheduling is described first. Then, an application at an iron ore mine presents the pertinent aspects and related intricacies of the proposed method while assessing its performance. Finally, conclusions and recommendations are provided.

2. Formulation

Short-term mine production scheduling is formulated as a stochastic integer programming model with recourse (Birge & Louveaux, 1997) and aims to minimize the total mining cost along with deviations from production targets, considers operational aspects such as mining direction and minimum width, and maximizes fleet utilization. In the formulation presented herein, the first-stage decisions are made before the uncertainty is revealed, then the second-stage decisions or recourse actions are made after uncertainty is considered. The notation used to formulate short-term scheduling follows. Note that indexes relate to the set of trucks, shovels, sectors, blocks, periods and realizations of uncertain parameters.

j: a sector or bench, where $j = 1, \ldots, J$
i: an shovel, where $i = 1, \ldots, I$
k: a block at sector j, where $k = 1, \ldots, K(j)$
l: a truck model, where $l = 1, \ldots, L$
p: a period of a production schedule, where $p = 1, \ldots, P$
ε: an element grade of k block that have economical value, where $\varepsilon = 1, \ldots, E$
δ: a deleterious element grade of k block, where $\delta = 1, \ldots, D$
s: simulated grade realization or scenario, where $s = 1, \ldots, S$
α: realization of shovel mechanical availability given historical data, where $\alpha = 1, \ldots, A$
r: truck cycle time and mechanical availability realization, where $r = 1, \ldots, R$

The parameters used at the fleet allocation, cost and penalties at objective function, production target and multi-element quality and tonnage are explained as follows:

h_{fleet}: fleet operation hours by period p
ι: maximum number of shovels allowed by sector
Q_i^{sh}: hourly production of shovel i.
$\omega_i(\mu_i, \sigma_i)$: mean and standard deviation of historical mechanical availability by shovel i
$a_{ij'}^{p-1}$: binary parameter, if shovel i is or not allocated to sector j' at previous period p-1
$c_{j'j}^{ExcM}$: cost of moving shovel from p-1 allocation sector j' to new allocation sector j
$c^{prodExc-}$: penalty cost for tonnage not produced regarding to the expected productivity
Q_l^{trk}: capacity of truck l