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A stochastic optimization method with in-pit waste and tailings disposal for open pit life-of-mine production planning

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ABSTRACT

Environmental responsibility and the sustainable development of mineral resources are a topic of critical importance to the mining industry and at the same time relate to operational and rehabilitation costs to be considered in technical studies. Open pit mining operations impact their local environment in terms of their modification of the landscape and local ecosystems. Many of these impacts are the result of the transportation of large volumes of materials mined and shifted from and to different locations. External stockpiles and waste dumps occupy considerable space as well as involve substantial transportation costs to move materials from open pits to stockpiles and then move them back to the pit for rehabilitation after the end of exploitation. Depending on the shape of the deposit and the intended design of the pit, a desirable option may be to place it directly in the free spaces within the pit, instead of storing all waste and tailings materials in stockpiles and/or waste/tailings dumps. This paper presents a new mathematical formulation integrating to life-of-mine planning and the maximization of net present value, with the related waste and tailings disposal kept within the mined-out parts of a pit, using a stochastic integer program that manages geological uncertainty including metal grades, material types and related chemical compositions. In addition to the traditional variables related to the materials being extracted from the ground in the form of mining blocks, strips of ground following the dip of a pit are considered within the pit as decision variables, and the optimization process aims to optimally define both the sequence of extraction of mining blocks and the reservation of strips needed to store waste materials. An application at an iron ore mine demonstrates the feasibility, applied aspects and advantages of the proposed method.

1. Introduction

Life-of-mine (LOM) planning is a core element of production forecasting, financial valuation and environmentally responsible development of open pit mining projects and operations. The optimization of the ore and waste extraction sequence and generation of related performance forecasting are undertaken based on operational research methods with the objective of maximizing discounted cash flows over the LOM while accounting for operational constraints and considerations (Whittle, 1999; Hustrulid and Kuchta, 2006; Ramazan and Dimitrakopoulos, 2004; Newman et al., 2010; Dimitrakopoulos, 2018). Among the core LOM planning considerations, waste management is a particularly important concern. Waste dumps and stockpiles represent significant volumes of material that substantially impact the local environment, while the available space for waste storage is often limited. As a result, material is first moved to a stockpile and then moved back to the open pit during the rehabilitation phase, leading to considerable costs and efforts. An alternative approach is to store waste and tailings directly into the mined-out areas of the open pit during its operation, which reduces the usage and size of external stockpiles as well as waste transportation and related costs. However, disposing material inside the pit during mining operations can have severe consequences on production, as an in-pit areas of storage may automatically sterilize potential underlying ore. As a result, it is critical to simultaneously optimize the extraction sequence of materials represented by mining blocks and the in-pit waste disposal to optimally define the mining production policy. The literature on this topic is limited, and some related work is found in Zuckerberg et al. (2007), who present an extended version of BHP's mine planning software Blazor, named Blasor-InPitDumping (BlasorIPD). Their concept is the following: a period of extraction is assigned to aggregates of mining blocks (or AGGs), and different processing decisions are assigned to subdivisions. Then, the percentage of an AGG going to waste can either go to an external stockpile or to a zone inside the pit. If it goes to the pit, it is associated with a “refill AGG”, which is an aggregate larger than an AGG, but that also respects precedence constraints. BlasorIPD produces a schedule that reduces the

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external stockpile by taking advantage of the free space in the open pit. However, the sparse disposition of waste material within the pit that can result from the optimization may be problematic from an operational point of view. In addition, aggregating mining blocks can misrepresent mining selectivity and provide misleading forecast results. Furthermore, this approach, like traditional mine planning methods, relies on a deterministic optimization in which all parameters used in the related mathematical model are considered known with certainty. In mine planning, geological information describing the pertinent properties of materials being mined is critical and at the same time largely uncertain, introducing substantial risks in mine plans, production forecasts and assessments. The adverse effects of uncertainty associated with the geological attributes of interest of mineral deposits (meal grades, material types, geometallurgical and other rock properties, deleterious materials and so on) have been repeatedly documented in the past (Ravenscroft, 1992; Dowd, 1994; Vallée, 2000; Dimitrakopoulos et al., 2002; Godoy, 2002; Dimitrakopoulos, 2011; others). The problem originates from the sparse drill hole data on which the mined orebody model is based. Deterministic optimization methods, such as the conventional ones frequently employed in LOM planning, use as input an orebody model generated from the available drilling data using estimation techniques and base the optimization process on this average-type (estimated) single representation of the mineral deposit at hand. Estimated orebody models of a deposit are smooth representations of reality and underrepresent both global proportions of materials and their local variability (eg. Dimitrakopoulos et al., 2002; Godoy, 2002), leading to poorly informed mine plans and production schedules. In terms of waste management, a smoothed representation of the grade distribution of a deposit tends to minimize the waste tonnage forecasts and results in unexpected additional material sent to the waste dump. To avoid this and address inevitable uncertainty, a set of stochastic simulated realizations of the mineral deposit may be used. These simulated models of the mineral deposit are equally probable representations of the actual orebody, given the available data, and reproduce the variability of the deposit's grade (Goovaerts, 1997; Journel and Kyriakidis, 2004). Instead of basing the optimization on a single representation of the ore body, a stochastic optimizer uses this set of simulated scenarios of the orebody to obtain a life-of-mine production schedule that maximizes net present value while minimizing risk in meeting production forecasts. Ramazan and Dimitrakopoulos (2005, 2013) propose a two-stage Stochastic Integer Programming (SIP) model with fixed recourses, which successfully optimizes the open pit mine scheduling under geological uncertainty. Several applications of such models with diverse solution approaches can be found in the literature. Most of these studies focus on heuristic methods to solve this complex problem: the aggregation of blocks technics (Menabde et al., 2007; Ramazan, 2007; Boland et al., 2009; Del Castillo and Dimitrakopoulos, 2016), the sliding time window method (Dimitrakopoulos and Ramazan, 2008; Cullenbine et al., 2011) and the topological sorting algorithm (Chicoisne et al., 2012). Metaheuristic methods have also been developed to tackle larger scale problems and full mining complexes, which account for the whole mineral value chain with multiple mines and processing streams. For example, Montiel and Dimitrakopoulos (2015), Montiel et al. (2016) and Goodfellow and Dimitrakopoulos (2016, 2017) use variations of simulated annealing and manage to optimize the mineral value chain. The notion of mining complexes is promising in terms of waste and tailings management, since the opportunities given by the diverse processing streams and the modelling of stockpiles can allow a better representation of the material exchanges between the different components of a mine.

The topic of in-pit waste disposal was also addressed in Zuckerberg et al. (2007); however, the present study considers a stochastic framework and additional operational considerations. The proposed method is tested in an iron ore mining project that aims to limit the space required for the external stockpiles for the waste and tailings material by refilling the pit during exploitation. The motivation for applying in-pit waste disposal originates from different factors, including limiting environmental impacts, accounting for constraints in available space surrounding the pit, and reducing the cost of waste transport and rehabilitation. In the deposit illustrated in this study, the shape of the deposit (low dip layers and long strike length) is used as an advantage, allowing for the material to be stored in bands or strips oriented toward the dip; the corresponding storage zone remains continuous and grows from one period to another. This orientation assures that the storage location remains contained without occupying space around the open pit, with the condition that the ore below an individual zone must also have been extracted prior to using it for storage. In general, all of the required constraints must be jointly addressed, starting with those associated with the extraction sequence of mining blocks, such as block accessibility, production capacity and blending constraints. The novelty of the proposed approach explicitly considers in-pit storage considerations and simultaneously accounts for geological uncertainty within the stochastic optimization framework, a topic particularly relevant in terms of waste production forecasts and management.

In the following sections, the description of the proposed SIP model, referred to as the open pit mine planning stochastic integer program with in-pit tailings disposal (OMPSIP-ITD), is presented. Subsequently, a case study at an iron ore deposit located in Labrador, Canada, details the applied aspects and contributions of the proposed model. The results are presented in terms of the material disposal inside the pit and the quality of production forecasts, including discounted cash flows and production targets along with their quantified risk in terms of meeting forecasts due to geological uncertainty. Finally, conclusions and insights for future research are presented.

2. The OMPSIP-ITD mathematical model

In this section, the proposed stochastic mathematical programming formulation for open pit mine production planning including the integration of in-pit waste disposal (OMPSIP-ITD), is detailed. The mathematical model is a two-stage stochastic integer program with fixed recourse (Birge and Louveaux, 2011) that simultaneously optimizes the extraction sequence and destination policy (Ramazan and Dimitrakopoulos, 2005, 2013; Spleit and Dimitrakopoulos, 2017; Rimélé et al., 2017) and the in-pit storage, which introduces several new notations, variables and constraints. In particular, at each period, a top and a bottom strip are considered to delimitate the storage zone in the pit. All the strips in-between are reserved for storage. Several hypotheses are made and described in the model.

2.1. Notation

The diverse sets, indices, parameters and variables used in the following OMPSIP-ITD formulation are described below.

2.1.1. Sets

$\mathscr{B} = \{i = 1, \ldots, N\}$Set of blocks in the ore body;
$\mathscr{P} = \{p = 1, \ldots, P\}$ Set of considered periods for the schedule;
$\mathscr{D} = \{0, 1\}$ Set of destinations available for the blocks $= 0$(waste dump) $d = 1$(mill);
$\mathscr{S} = \{s = 1, \ldots, S\}$Set of scenarios (equiprobable ore body stochastic simulations);
$\mathscr{C} = \mathscr{C}_1 \cup \mathscr{C}_2$ Set of blocks' characteristics, $\mathscr{C}_1 = \{c_1 = 1, \ldots, C_1\}$ linear characteristics (tonnages, trucks hours…), $\mathscr{C}_2 = \{c_2 = 1, \ldots, C_2\}$ non-linear characteristics (grades);

$\boldsymbol{G}(\mathscr{B},\boldsymbol{A})$Oriented graph representing the precedence relationships between blocks. On Fig. 1, $(\boldsymbol{b}, \boldsymbol{e}) \in \boldsymbol{A}$, which means that block $\boldsymbol{b} \in \mathscr{B}$ is a predecessor of block $\boldsymbol{e} \in \mathscr{B}$;

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