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Innovative Applications of O.R.

Optimizing the open pit-to-underground mining transition

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ABSTRACT

A large number of metal deposits are initially extracted via surface methods, but then transition underground without necessarily ceasing to operate above ground. Currently, most mine operators schedule the open pit and underground operations independently and then merge the two, creating a myopic solution. We present a methodology to maximize the NPV for an entire metal deposit by determining the spatial expanse and production quantities of both the open pit and underground mines while adhering to operational production and processing constraints. By taking advantage of a new linear programming solution algorithm and using an ad-hoc branch-and-bound scheme, we solve real-world scenarios of our transition model to near optimality in a few hours, where such scenarios were otherwise completely intractable. The decision of where and when to transition changes the net present value of the mine by hundreds of millions of dollars.

1. Introduction and literature review

The mining industry contributes trillions of dollars annually to the global economy by providing minerals, metals, and aggregates. This, and volatile metal prices, make it critical that mines possess an efficient production schedule, which can be categorized as: (i) short-term (days to months), (ii) long-term (years), and (iii) strategic (life-of-mine) (Gershon, 1983). A short-term schedule might determine what material to process on a given day; a long-term schedule may examine production rate changes (Alonso-Ayuso et al., 2014; Epstein et al., 2014). Finally, a strategic schedule is used to evaluate large capital investments, and other decisions that have long-ranging impacts. Because the transition from open pit to underground extraction affects a mine for the remainder of its operational life, it falls into the category of strategic scheduling.

At the time of this writing, a large number of metal deposits are being extracted via surface methods, but plan to transition to concurrently or exclusively extracting ore via underground mining methods. For safety reasons, the underground mine must be sufficiently geographically separated, with horizontally positioned in situ rock, from the open pit mine via what is typically referred to as a crown pillar. Current industry practice places the crown pillar based on: (i) largest economically viable open pit mine, or (ii) the extraction method that results in the largest undiscounted profit for each three-dimensional discretization of the ore body and surrounding rock. Mine operators tend to delay the transition, leading to NPV losses of up to hundreds of millions of dollars. We provide a systematic means by which a mine operator can determine the highest value of a combined open pit and underground design.

The most common method used to extract material is open pit, or surface, mining. Open pit mines vary in both shape and size, and their design is based on the deposit's block model, a model which discretizes the orebody and surrounding rock, and assigns a series of attributes, including mining cost, degree of mineralization (referred to as grade), location, and the cost or profit associated with processing the specific block. Blocks can be categorized using a minimum cutoff grade; blocks at or above the cutoff grade are sent to the processing plant, referred to as a mill, while those below the cutoff grade are sent to a waste dump. The slope angle for the open pit mine, resulting from geotechnical constraints of the host rock, ensures the stability of the pit's walls (Crawford & Hustrulid, 1979).

Given the block attributes and slope angles, mine planners determine the largest economically viable pit for a given deposit, i.e., the ultimate pit limit (Lerchs, 1965; Underwood & Tolwinski, 1998). However, while the solution to the ultimate pit limit problem yields the size of the open pit mine, it provides no indication of the extraction sequence required to maximize its discounted value. Johnson (1968) originally formulated the open pit block sequencing problem as an integer program that schedules the

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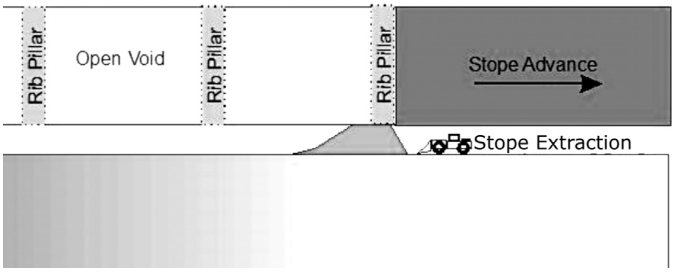

Fig. 1. (Open stoping) In this mining method, rib pillars provide stability, as does the backfilling of open voids left by extracted stopes. Stope advance shows the direction in which mining proceeds.

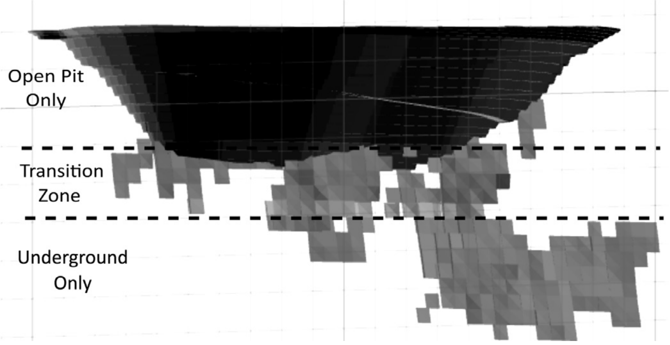

Fig. 2. (Transition zone) The transition zone is an area where it is economically viable to extract material via open pit or underground mining methods. We see the open pit, black, encroaching on the underground mine, gray, in the transition zone.

extraction of blocks such that the open pit's value is maximized subject to resource and precedence constraints.

Solution techniques for open pit block sequencing problems are still widely studied (Chicoisne, Espinoza, Goycoolea, Moreno, & Rubio, 2012; Osanlo, Gholamnejed, & Karimi, 2008; Ramazan, 2007; Shishvan & Sattarvand, 2015; Souza, Coelho, Ribas, Santos, & Merschmann, 2010; Topal & Ramazan, 2010). One such recent significant advance for the linear programming relaxation of a general version of the so-called precedence constrained production scheduling problem (PCPSP), i.e., the open pit block sequencing problem, is with the use of an algorithm outlined in Bienstock and Zuckerberg (2010), which exploits the problem structure (Muñoz et al., 2015). Lambert, Brickey, Newman, and Eurek (2014) present a guide to formulating and efficiently solving monolithic instances of the open pit block sequencing problem, i.e., without decomposition.

Underground mining is used when an economically viable deposit is situated sufficiently deep such that open pit mining is cost prohibitive. There exist many underground mining techniques: (i) open stoping (Fig. 1), (ii) room-and-pillar, (iii) sublevel caving, (iv) drift-and-fill, (v) longwall, and (vi) block caving. Determining which method(s) to use is typically based on geotechnical constraints, size, and shape of the deposit (Qinglin, Stillborg, & Li, 1996). For the purpose of this paper, we confine our discussion to open stoping mining and its associated sequencing options.

A stope is a large, three-dimensional, mineable volume whose maximum size is correlated with the geotechnical properties of the host rock, and is the basic unit for stoping methods. The void left by an extracted stope is sometimes filled with an aggregate to provide structural stability, a process referred to as backfilling. Most underground stoping mines are separated into vertically spaced levels based on the maximum stope height, creating a near-regular grid of possible stope positions (Alford, 2006).

After determining possible locations from which the ore can economically be extracted, i.e., possible stope locations, mine planners design the development (Alford, 2007; Brazil & Thomas, 2007), which is required to gain access to the ore, provide haulage routes, and maintain proper ventilation within the underground mine. All stoping activities require the completion of a specific set of development activities before that stope's extraction can commence. Underground sequencing constraints are created after the design, and provide rules for the order in which the development and stopes are extracted. Given a fixed design and sequencing method, we can schedule the underground mining activities to, e.g., maximize NPV, or minimize deviation from production targets (Brickey, 2015; Carlyle & Eaves, 2001; Martinez & Newman, 2011; Newman & Kuchta, 2007; O'Sullivan & Newman, 2015). Trout (1997) provides one of the first generalized formulations for underground stope scheduling; our formulation is a bit more streamlined than his in that we do not differentiate between scheduled and actual decisions, and because we assume that once an activity commences, it must continue at a prescribed rate until finished. The latter characteristic implies that our model contains no continuous variables. On the other hand, we determine sill pillar placement, i.e., locations in which material is left in situ to allow for a change in mining direction, which adds a layer of complexity.

An early transition model assigns large aggregated blocks to be extracted via open pit or underground mining methods in order to maximize the value of the deposit (Bakhtavar, Shahriar, & Oraee, 2008). This idea was later improved to include the time element and to capture underground capital costs (Newman, Yano, & Rubio, 2013). In both previous transition models, there is little differentiation between the mining units used above and below ground. The mining industry comments on the difficulty of modeling the transition correctly (Finch, 2012); however, decisions regarding the transition are becoming increasingly relevant (Araneda, 2015). Fig. 2 shows an open pit atop an underground mine. The transition zone is depicted as the material that would be extracted were it done via underground methods; the corresponding amount of material would be greater were open pit methods used in the transition zone.

We present a new model and corresponding solution techniques to determine the timing of a transition from open pit to underground mining in both a spatial and a temporal sense. This transition incorporates a crown pillar placement that separates the open pit from the underground mine, and of the sill pillars, i.e., levels left in situ that can grant earlier access to stopes by creating a false bottom. Our methodology is based on an ad-hoc branch-and-bound approach that incorporates decomposition methods for solving PCPSP linear programming relaxations, and that includes rounding heuristics. We outline underlying models for the transition in Section 2. Mathematical reformulations to enhance tractability are presented in Section 3, and the solution strategy in Section 4. Sections 5 and 6 provide the numerical results and conclusions, respectively.

2. Underlying models

In this section, we introduce three models that underlie our computationally tractable transition model. We first present a surface extraction formulation, followed by an underground formulation, and conclude with a preliminary transition formulation which is essentially a combination of the two.

2.1. Surface model

We consider a surface model based on open pit mining with a multi-phase pit design (Fig. 3), in which a phase corresponds to a sub-region of the pit. A block within a phase consists of all of the material in the phase that resides within a predefined vertical distance. (Note that some mine operators refer to our blocks

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