Incorporation of geometallurgical modelling into long-term production planning

A. Navarra\textsuperscript{a,c}, T. Grammatikopoulos\textsuperscript{b}, K. Waters\textsuperscript{c}

\textsuperscript{a} Universidad Católica del Norte, 0610 Angamos, Antofagasta, Chile  
\textsuperscript{b} CSGS Canada Inc., 185 Concession Street, Lakefield, Ontario K0L 2H0, Canada  
\textsuperscript{c} McGill University, 3610 University Street, Montreal, Quebec H3A 0C5, Canada

\begin{abstract}
Strategic decisions to develop a mineral deposit are subject to geological uncertainty, due to the sparsity of drill core samples. The selection of metallurgical equipment is especially critical, since it restricts the processing options that are available to different ore blocks, even as the nature of the deposit is still highly uncertain. Current approaches for long-term mine planning are successful at addressing geological uncertainty, but do not adequately represent alternate modes of operation for the mineral processing plant, nor do they provide sufficient guidance for developing processing options. Nonetheless, recent developments in stochastic optimisation and computer data structures have resulted in a framework that can integrate operational modes into strategic mine planning algorithms. A logical next step is to incorporate geometallurgical models that relate mineralogical features to plant performance, as described in this paper.
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1. Introduction

Geometallurgy is the analysis of spatially correlated geological data, for the predictive modelling of extractive metallurgical operations (Alruiz et al., 2009; Suazo et al., 2010; Navarra et al., 2017a). It contributes to a system-wide perspective of the mineral value chain (Navarra et al., 2017b), thus it coordinates mining, stockpiling and blending, with the individual unit operations that occur within mineral processing plants. This perspective overcomes traditional interdisciplinary barriers, leading to more effective strategic decisions and operating practices.

At some mines, the logic employed by managers and engineers may be fundamentally correct, but could benefit from quantitative fine-tuning of operational settings, or by streamlining the incoming data. In particular, geometallurgical models have been developed to relate grinding circuit throughput to incoming mineralogical data (Alruiz et al., 2009), and then to predict flotation kinetics (Suazo et al., 2010). With recent advances in digitization (Chambers and Thornton, 2016), modern information systems are now a means to integrate geometallurgical models into daily, monthly and longer-term decision-making processes.

Decision-makers must consider a range of data, which is available under different timeframes, and with differing levels of confidence (Lamghari and Dimitrakopoulos, 2016). To mitigate risk, long-term production plans must be sufficiently flexible to allow for optimal short-term decisions, as more detailed information becomes available. Plans should not be overly dedicated to a single possible scenario (e.g. the “mean” scenario). Rather, they should be configured so that they may perform well for the entire distribution of possible scenarios. This is particularly true for mine production, which is subject to various forms of environmental and market uncertainty.

Geological uncertainty is especially crucial for mineral processing plants that are fed by nearby orebodies (Montiel and Dimitrakopoulos, 2015; Goodfellow and Dimitrakopoulos, 2016). This type of uncertainty is related to the sparsity of drill core samples used to characterize the orebody. As depicted in Fig. 1, traditional techniques consider only a single geological scenario (i.e. the kriging mean) for long-term production planning, hence they do not measure the confidence of net present value (NPV) estimates, under geological uncertainty. Newer techniques consider a sequence of possible scenarios obtained through conditional simulation (Remy et al., 2009), described in the following section; these techniques employ two-stage stochastic optimisation, described later in this paper. In comparison to the traditional deterministic approaches (Fig. 1), the current stochastic approaches (Fig. 2) have been shown to produce more adaptable mine plans, thereby increasing the expected NPV of mining operations by over 20%, which may correspond to hundreds of millions of dollars (Goodfellow and Dimitrakopoulos, 2016).
An important mechanism to mitigate uncertainty is to develop alternate modes of operation (Navarra et al., 2017b). For instance, a geometallurgical model may determine that a certain type of ore is economical if it undergoes a coarse grind. However, the change from a fine grind to a coarse grind may involve emptying the semi-autogenous grinding mill (SAG mill) and introducing larger steel balls, which would correspond to a change of operational mode. This type of alteration should not be done every day, for instance, but only according to tactical criteria, which considers forecasts from the long-term mine plan, as well as the incoming geometallurgical data. Generally, operational modes can harmonize various segments of the mineral value chain, e.g. an operational mode prescribes milling parameters, while simultaneously prescribing the corresponding upstream parameters for stockpiling and blending, as well as the corresponding downstream parameters for flotation. Thus, operational modes are a fundamental consideration within a system-wide perspective.

Fig. 3 is an extension of Fig. 2 that illustrates the incorporation of geometallurgical modelling into long-term mine planning. The additional modelling step is to categorize (or cluster) the blocks in terms of how conducive they are to the proposed operational modes; the resulting categories are known as geometallurgical units (Alruiz et al., 2009; Suazo et al., 2010). Even in the early stages of mine development, the approach of Fig. 3 may be used to determine whether or not an operational mode is economically viable; the stochastic optimisation is run with and without the additional mode. Typically, the additional mode would require more processing capacity and/or equipment, and hence a greater capital expenditure. The mode is economically justified if it leads to a statistically significant increase in operational NPV that offsets the additional capital expense (Navarra et al., 2017a).

The establishment of distinct geometallurgical units depends on advanced characterization techniques, such as quantitative evaluation of minerals by scanning electron microscopy (QEMSCAN). As described in the following section, the compositional and morphological features, which can be observed with the QEMSCAN provide insight to determine which combination of blending, milling and concentration parameters might constitute operational modes that are economically viable (e.g. Grammatikopoulos et al., 2013; Jordens et al., 2016; Little et al., 2016). Different sources of ore can be regarded as distinct geometallurgical units, depending on whether or not they exhibit categorically different responses to the viable operational modes (Navarra et al., 2017a).

Geometallurgical modelling and stochastic optimisation are active areas of research. There is substantial economic incentive to merge these areas in the development of long-term mine plans that mitigate geological uncertainty (Goodfellow and Dimitrakopoulos, 2016); indeed, the current paper presents a new computational framework that incorporates geometallurgical models into long-term strategic mine plans (Fig. 3), which is demonstrated using sample calculations. Considering the diverse challenges that are observed at different mine sites, it is important to establish unifying concepts, which serve as a starting point for customized quantitative solutions (Alruiz et al., 2009). Continued collaboration between industry and academia will provide the next generation of tools that employ a system-wide perspective to evaluate and optimise mining projects.

2. Conditional geometallurgical modelling

Current mine plan algorithms assume a simple relation between head grade and recovery. For different ore classes, the recovery is often taken to be constant, as is the milling cost per tonne. Indeed, a valid starting point for geometallurgical modelling (transition from Fig. 2 to Fig. 3) is to determine the milling costs for these classes in order to attain a prescribed recovery; this usually involves empirical hardness- and-throughput studies. Ultimately, the objective of this modelling phase is to determine the economic value and time required to process individual blocks through the proposed set of operational modes.

Geometallurgical models are developed by considering the following four aspects, which are listed in increasing level of detail:

- Mineralogy: Distribution and correlations between mass fractions of different minerals
- Liberation: Distribution of minerals into separate particles as a function of particle size, exposure and degree of freedom
- Texture: Distribution, shape and orientation of crystal grains within the mineral matrix
- Mineral Chemistry: Correlations between the preceding aspects and the presence of elements of interest, or penalty elements
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