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A multivariate destination policy for geometallurgical variables in mineral value chains using coalition-formation clustering

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ABSTRACT

Complex polymetallic mining projects with multiple processing streams tend to require tight blending constraints, with different operational and processing targets. These blending requirements are generally not focused solely on metal grade, but rather on a set of geometallurgical variables that affect the performance of the operation and its ability to meet targets and maximize project value. Because of this, a multivariate destination policy is developed here, based on coalition formation clustering (a line of study of cooperative game theory), which avoids the use of cut-off grades and defines where material is sent by accounting for the value and relation of groups of blocks being processed together. This allows improving investment decisions as a result of optimizing project performance, because the variables that affect blending and processing requirements are actively accounted for in the optimization process. A case study on a copper-gold mine with six destinations is presented, where the method proposed shows significant improvements in meeting processing requirements and increases the expected net present value by 5.6% when compared to a traditional method. This shows that complex processing requirements can be accounted for and respected without any loss of project value.

1. Introduction

In mining, orebodies define the design and the value of a project, based on the attributes of the rock and the operational characteristics of the project, the processing streams used along the life-of-mine (LOM), and the range of profit produced by the project. The over-simplification that arises in the conventional optimization of mining projects is the assumption that a block of materials (mining block) has an intrinsic dollar value, and that a given cut-off grade will define what is ore (to be processed for profit) or waste. However, there are various other parameters that effect the dollar value of a block. For example, the presence of deleterious elements (such as arsenic), hardness, spatial location (which will define when the material can be extracted), and so on, will all have an effect over block value. Because of this, these pertinent variables should be considered during planning to optimize to which processing stream a mining block will be directed to and with this, to realistically evaluate the project's performance and value.

This issue takes precedence in the increasingly complex deposits being presently developed, where processing plants' and refineries' performance depends greatly on how their different requirements are met (for example, blending constraints must be met in order to maximize metallurgical recovery). These hard constraints force the project to be optimized around them, making it necessary to consider from an early stage not only grade uncertainty, but also all the variability of relevant geometallurgical characteristics (rock hardness, material types, etc.) that affect the configuration of the different processing streams (i.e., energy consumption, metallurgical recovery, etc.). However, because of the high costs associated with exploration, the limited information obtained from sample composites and the inherent flaws in sampling and testing systems, obtaining reliable geometallurgical information is difficult and requires cross-disciplinary efforts (Figueiredo and Piana, 2016). In addition to this, the geology of a deposit (grades, material types, rock properties, other) is highly uncertain, being one of the main sources of technical risk in a mining operation (Godoy and Dimitrakopoulos, 2004). Thus, many efforts have been directed towards developing methods that account for this uncertainty and manage the related rick in the design and evaluation of a project. Two aspects are included in these efforts, stochastic or geostatistical simulation to quantify geological uncertainty and stochastic optimization that uses the quantified uncertainty to manage the related risk while optimizing mine design and planning. Methods developed have been successfully implemented in various mining projects (Goodfellow, 2014; Montiel, 2014; among others).

Geological uncertainty extends to uncertainty in the supply (mate-

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rials) to various processing streams, giving special importance to the process of re-distributing the extracted rock between the available destinations, so that the different constraints are met. This reordering and delivering process, referred to as *destination policy*, is especially important in poly-metallic mines with multiple processing streams, as there are increasingly complex constraints. Traditional mine planning models define destination policies solely based on the material's concentration with respect to different cut-off grades and treat a block as waste if its (assumed) value is negative. Although it is traditionally used given the methods available to date, this assumption is misleading, as blocks have different attributes and concentrations of elements (other than the grade of the main commodity), which must be extracted, transported, blended, processed, and sold in order to yield a financial gain. All these activities are also strongly affected by the geological uncertainty present in the deposit, which will ultimately define the performance of the mining system. Thus, the actual value of a mining block depends not only on the period when it is extracted, but, in addition, (i) to the quality of the elements and material types contained in it, as well as (ii) on the destination where the block is processed, which entails the blending requirements, processing costs, recovery curve of the metallurgical process, and so on. In other words, the actual "block value" cannot be calculated individually. For example, if the available sulphur content in the processed material is not enough to reach blending constraints in the plant, then lower grade material with higher sulphur content could be sent to the processor from areas of the deposit with higher sulphur content, even if this material is not profitable on its own. Disregarding these non-linear relations would result in failing to meet blending constraints, reducing expected metallurgical recovery, and ultimately decreasing project value.

This paper aims to tackle this problem by developing an optimal destination policy mechanism for polymetallic deposits in order to increase project value and the reliability of project evaluation. This destination policy is based on a multidisciplinary implementation, combining mine planning with coalition formation theory using the "Shapley Value" (which is a line of study of cooperative game theory), and considers within the decision process the deposit's geometallurgical variables, its blending requirements, and the uncertainty related to its geology. These considerations increase project value by improving the performance of the available processes, meeting the project's planned targets, as well as taking maximum advantage of the limited resource.

The next section of this paper reviews the existing literature on mining optimization, focusing on destination policy, as well as on the inclusion of geometallurgical variables. The description of the proposed method follows, with a brief introduction on game theory, and the concepts that will be used. The proposed method is then tested over a real life copper gold deposit with six possible destinations, showing that including complex variables of the processed material in the optimization not only allows the project to meet blending constrains, but also increases final project value without even changing the extraction schedule. Conclusions and future work follow.

2. Literature review

2.1. Mining optimization and destination policy

Thus far, the decision of defining where each block is sent after extraction is based mainly on two aspects: defining certain ranges of grades accepted at the different destinations (commonly referred to as cut-off grades, Lane, 1988; Rendu, 2014), or the general revenues expected from sending a block to each of the possible processing streams. However, these policies are based on a longstanding serious oversimplification in mine planning, which is to assume that a block has an inherent dollar value (Lerchs and Grossman, 1965; Tolwinski and Underwood, 1996; Ramazan, 2007; Meagher et al., 2010). This results in severe deviations from expected project revenues and performance, as well as clear suboptimal results (Wharton, 2004). By assigning a "dollar value," the formulation assumes a priori when a block will be extracted (i.e., the mining sequence), and what material is ore and what is waste (thus, where it should be sent), before any optimization has been done, bypassing the actual destination policy decision.

Some work has been done in designing dynamic policies, such as in Meagher et al. (2010), where the destination decisions are updated on a yearly basis according to new information that becomes available once a block is extracted. The possibility to re-optimize is considered as valuable flexibility, which is added to the block's value. In this paper, geological uncertainties, market uncertainties, and the time value of money in calculating the value of a block at its period of extraction are accounted for. However, the formulation proposed grows exponentially if multiple elements, deposits, and/or processing streams are considered, and the focus is still placed on assigning an individual dollar value to each block instead of on optimizing the mining complex as a whole. Asad and Dimitrakopoulos (2013) propose a heuristic approach to select an annual cut-off grade under geological uncertainty, which maximizes the net present value (NPV) of the mining operation and satisfies production constraints. Continuing on this line, Meagher et al. (2014) develop a dynamic cut-off grade policy to define block destination under geological uncertainty. Here, the optimal cut-off grade is defined on a yearly basis in order to optimize the pushback design and maximize project value. However, the model only considers one element with one processing facility and the optimization is done greedily by sequentially maximizing the NPV of each pushback, instead of optimizing the whole deposit simultaneously. Thompson and Barr (2014) generate a dynamic cut-off grade policy under stochastic prices and note the differences between considering uncertainty in the cut-off results when compared to traditional methods. However, the authors still assume an economic value of the block, and do not consider the geological uncertainty of the deposit.

Few methods have been presented in the literature that dynamically account for the destination policy in the optimization process and, at the same time, develop a global mine plan. The multistage stochastic optimization method developed by Boland et al. (2008) presents a destination policy mechanism that optimizes each geological scenario independently once the scenarios have "differentiated enough" along the LOM. Other studies have developed robust destination policies, such as Montiel and Dimitrakopoulos (2015), who proposes a mathematical programming model where destination policies are first stage variables (thus equal over all scenarios). Here, the author considers the optimization of the whole mining complex under geological uncertainty, with multiple material types and processing streams. The method presented is able to develop a mining schedule that defines when each block is mined and where it is sent, avoiding the need for pre-defined cut-off grades, and maximizing project value while meeting production constraints. However, in this case, the destination policy can only be optimized if the material type of a block is the same over all the simulations. In other words, the model might produce misclassification errors (i.e., where oxides are sent to processing streams that only accept sulfides), resulting in infeasible solutions. Menabde et al. (2007) also define a robust destination policy, but it is based on cut-off grade optimization. In their study, the authors account for geological uncertainty and present a MIP formulation where the destination policy is defined by classifying blocks into bins of "similar grades", where each bin is sent to the same destination. By doing so, they are able to avoid misclassification problems, as seen in the previous case. However, their formulation only accounts for a single mine, with one element and a single processing stream, and does not consider the problems that arise with blending requirements that entail more than one element.

As the complexity of mining projects increases (in terms of the number of deposits, processing streams, and elements), traditional destination policies, such as the ones presented in the previous