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Decision Support

A dynamic-material-value-based decomposition method for optimizing a mineral value chain with uncertainty

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ABSTRACT

A decomposition method is developed to optimize a mineral value chain composed of multiple mines and a material flow circuit. In the proposed decomposition method, the upstream mine production schedule and the downstream material flow plan are optimized simultaneously to maximize the expected NPV of the entire mineral value chain. The proposed approach is tested through a practical-scale case study and the test results show that the proposed method can effectively optimize the production schedule of each mine in consideration of downstream constraints and market uncertainty. Through the observation of the test results, we show that optimizing a mineral value chain in an integrative manner and considering market uncertainty can avoid overinvestment in strategic assets and overestimation of long-term profitability. The proposed decomposition method is not limited to the setting of a specific mineral value chain and can be easily extended to integrate more impacting factors.

1. Introduction

A typical mineral value chain (MVC) consists of single or multiple mines and a material flow circuit, as shown in Fig. 1. A material flow circuit includes waste dumps, material stockpiles and a complex value-added material processing system with a series of transformation processes that generate commodities from raw materials. Fig. 1 shows the material flow chart of a typical MVC. Optimizing a MVC includes optimizing the mine production schedules, the destination of extracted materials, the processing plans, and the transportation plans. The present work focuses on the integrative optimization of the entire MVC in consideration of both the upstream uncertainty in the pertinent aspects of mineral deposits and downstream uncertainty in the commodity market.

In the literature, optimization in the mining industry usually focuses on mine production scheduling (MPS) and material flow planning (MFP). MPS at a given mine optimizes which areas of the mine deposit should be extracted and when, while a MFP problem optimizes the downstream plans over the planning horizon, such as the transportation of materials, the processing rate and the capacity of mills, smelters, stockpiles, and so on. A multi-mine MVC, as in Fig. 1, includes multiple MPS problems and a single MFP problem.

In MPS, the objective is typically to maximize the expected net present value (NPV) of the valuable material mined during the planning horizon subject to mining precedence constraints and mining capacity constraints. In mining engineering, a mineral deposit is modeled by a large number of mining blocks, and the extraction of a block is a task to be scheduled. The number of binary variables used to model real-world MPS is in the order hundreds of thousands or millions. Ongoing research in MPS focuses on designing algorithms to search for a near optimal solution for the very large numbers of mining blocks involved. A review of research on MPS can be found in Hochbaum and Chen (2000) and Newman, Rubio, Caro, Weintraub, and Eurek (2010). When the uncertainty of characteristics of each block is considered, MPS becomes even more complex. A review of research on MPS with uncertainty can be found in Lamghari and Dimitrakopoulos (2012), Lamghari, Dimitrakopoulos, and Ferland (2015), Ramazan and Dimitrakopoulos (2013), and Chatterjee, Sethi, and Asad (2016).

In MFP, the production schedules of mines considered are typically treated as fixed. The objective of a MFP is to maximize the expected NPV given the fixed production schedules of the mines involved subject to the transport capacity of each arc and the processing capacity of each node in the material flow chart of MVC. The complexity of MFP depends on the structure of MVC and the factors considered. The structure of a MVC is determined by the material flow circuit, and can be expanded when other features, such as outsourcing, closed-loop processing, and so on, are considered. The details include the nonlinear relationship between input and output at each part in the MVC, resource

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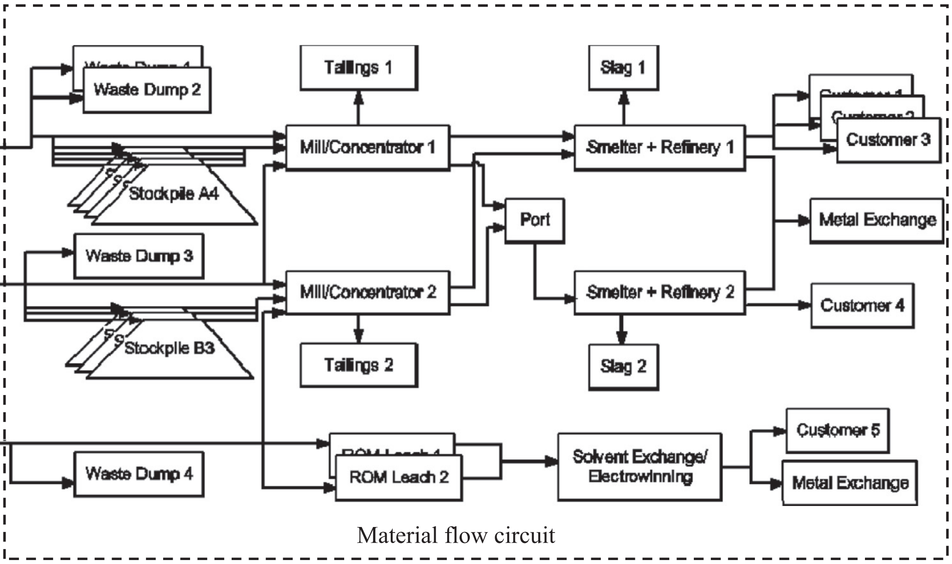

Fig. 1. The material flow chart of a typical MVC (Goodfellow, 2014).

allocations (e.g., labor, equipment, facilities, etc.), setup costs, operational risks, and so on. When market uncertainty is considered, a sufficient number of market scenarios have to be integrated in the model. Hence, the size of the MFP problem depends on the number of market scenarios considered.

The complexities described above make it difficult to integrate MPS and MFP to search for the best solution for the entire MVC. In the literature on MVC optimizations, some work can be found that optimizes part of a MVC by treating the outputs of the other parts as fixed. Hoerger, Seymour, and Hoffman (1999) formulate a model of optimizing a MVC for a gold-mining case with multiple mines, stockpiles and processing facilities. They consider 50 mines, for which the mine production schedules are assumed to be fixed. Thus, the MVC problem they study is equivalent to the MFP problem defined herein. The work that studies unified models for MVC optimization mostly focuses on heuristics that are designed to solve special forms of MVC. Souza, Coelho, Ribas, Santos, and Merschmann (2010) study MPS in consideration of truck allocation downstream. Caccetta and Hill (2003) optimize a MVC with the constraints of mill throughputs, mining capacities, blending requirements, stockpiles and transport system by using a branch and cut algorithm. Epstein et al. (2012) develop an algorithm that iteratively adds cuts to tighten the linear relaxation of a unified MVC optimization model so that the binary variables in the original model have binary solutions after solving the relaxed model. In order to solve the relaxed model efficiently, blocks are aggregated to benches or columns and the downstream MFP problem has to be linear. Asad and Dimitrakopoulos (2013) optimize the cutoff grade for MVCs with multiple processing streams in consideration of the uncertainty in material grades. Kizilkale and Dimitrakopoulos (2014) optimize the mining rate of multiple mines in consideration of the uncertainty of commodity prices. Montiel and Dimitrakopoulos (2015) study the optimization of a MVC with multiple processing and transportation options. Goodfellow (2014) uses meta-heuristic to optimize a general MVC model in consideration of geological uncertainty.

Most of the existing methods for MVC optimization described above are capable of optimizing very specific forms of MVCs, while ignoring some substantial impacting factors, thus leading to suboptimal plans. As a consequence, the resulting poor investments in strategic assets may have a considerable impact on a company's long-term profitability. In the work presented in the following sections, a dynamic-material-value-based decomposition method (DMVBD) is developed to allow the optimization of the MPS and the MFP models of a MVC to be synchronized through iteration. This leads to a final solution for each of the MPS and MFP close to the best solution for the entire MVC. DMVBD developed herein has the following advantages. First, it is easy to integrate DMVBD with the optimizers already employed by the company for solving independent MPS and MFP problems, such as Earthworks multimine scheduler, ECSI maximiser, MinMAX planner, Whittle strategic mine planning, and so on (Goodwin et al., 2006). In order to implement DMVBD, only the inputs to the MPS models are required to be changed. The MFP model requires the minimum-level modification and does not increase the complexity of applications. Second, it is easy to extend the MPS and MFP models of a MVC after adopting DMVBD. Given that the MFP and MPS models stay independent after DMVBD is employed, each model can be upgraded without considering the others. For example, if a user wishes to integrate operational risk for equipment, such as trucks, shovels, or crushers, into the MFP model, there is no need to change the MPS models, but, as the result of DMVBD, the final solutions of the MPS models will change as needed. Finally, with DMVBD, it is easy to insert new MPS models when new mines are added to MVC. When new MPS models are added, DMVBD will automatically change the optimal solution of other models to account for the change of the MVC structure.

The paper is organized as follows. In Section 2, a MPS model and a MFP model are formulated for a MVC, to elaborate on DMVBD. In Section 3, the detailed steps of DMVBD are presented. Section 4 presents a practical-scale numerical test conducted to assess the performance of DMVBD and show the integration of market uncertainty. Conclusions are presented in Section 5.

2. Models

The DMVBD proposed herein is applicable for optimizing MVC with single or multiple mines and a material flow circuit, as introduced in Section 1. In order to present DMVBD clearly, this section focuses on a typical MVC. Geological and market uncertainties are considered in the models developed. Note that the proposed DMVBD is not limited to the specific forms of models presented herein.

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