International Journal of Mining Science and Technology 23 (2013) 317–321

Contents lists available at SciVerse ScienceDirect

International Journal of Mining Science and Technology

journal homepage: www.elsevier.com/locate/ijmst

Multi-period mine planning with multi-process routes

Mustafa Kumral

McGill University, Department of Mining and Materials Engineering, 3450 University Street, Montreal, Quebec, Canada H3A 2A7

ARTICLE INFO

Article history:
Received 11 September 2012
Received in revised form 20 October 2012
Accepted 8 December 2012
Available online 4 June 2013

Keywords:
Mine planning
Multi-route
Sequencing
Production rates
Heuristics
Mixed integer programming

ABSTRACT

This paper attempts to optimize optimal capacities, block routing and mine sequencing problems in a mining system. The solution approach is based on a heuristics and the mixed integer programming (MIP). Unlike previous sequential solution approaches, the problems are herein solved at the same time. Furthermore, the proposed approach guarantees practical solutions because it considers ore material distribution within orebody. The paper has two main contributions: (a) the proposed approach generates production rates in a manner that the capacities are satisfied; (b) the proposed approach does not use pre-defined marginal cut-off grades. Thus, idle capacity problem is eliminated and different scheduling combinations are allowed. To see the performance of the approach proposed, a case study is carried out using a gold data. The schedule generated shows that the approach can determine optimal production rates, block destination and sequencing effectively.

1. Introduction

Mine production scheduling focuses on solving three sub-problems: (1) block sequencing that is the decision process of extraction period of each block; (2) block routing that is the decision process of the destination of blocks (waste dumps or processing routes); (3) optimal mining and processing production rates which correspond to economic considerations and grade heterogeneity within ore body.

These problems have been solved separately in the conventional approaches. The mixed integer programming (MIP), as an alternative to the approaches based on the graph theory and the network flows, has been used to solve the block sequencing problem [1–11]. They formulated the sequencing problem under pre-defined cut-offs and capacities. On the other hand, the techniques to determine cut-off grades based on the assumption of free selection (lack of access constraint) are mostly heuristics [12–14]. They were quite far away from real optimality. The capacities are installed on the basis of demand and financial resources of investor. Given that both the quantity and quality of the ore do not distribute homogeneously, the capacity installation based on financial reality may not be satisfactory. In other words, the capacities based on financial power of the investor may not be compatible with orebody heterogeneity.

In current practice, the mine production scheduling problem is heuristically solved in a subsequent fashion as follows:

Step 1. Pre-defined capacities which attributed to economic consideration and corresponding mining and mineral processing costs are initiated.
Step 2. Using this cost structure, marginal cut-off grade(s) are determined. Each block route is identified *a priori* by applying cut-off grade(s).
Step 3. Block economic values are calculated on the basis of the block identification. These values are used as the parameters in optimization process.
Step 4. The block sequencing problem expressed as MIP formulation is solved and the extraction time of each block is determined.
Step 5. Net present value (NPV) is recorded and this procedure is repeated for some numbers of capacities and corresponding costs. The sequence generating maximum NPV is accepted as optimal sequencing and production rates.

Although this approach suits the problem size and complexity, it has severe limitations:

(1) The approach does not consider ore material and grade heterogeneity within orebody. In other words, the capacity selection considering only economic concerns may not coincide with the characteristics of orebody. This leads to serious idle capacity problem, which adds indirect cost.

E-mail address: mustafa.kumral@mcgill.ca

2095-2686/$ - see front matter © 2013 Published by Elsevier B.V. on behalf of China University of Mining & Technology.
http://dx.doi.org/10.1016/j.ijmst.2013.05.001

(2) There could be difference between the selected capacities and the realized production rates. There may be unacceptable fluctuations in terms of production rate among the periods. It may be thought that a lower limit constraint into process capacity constraint can solve the unacceptable fluctuations. However, the initiation of lower limits may preclude from finding a solution.
(3) The approach cannot guarantee optimal production rates. To reach the optimality, search space (the number of iterations corresponding to capacities initiated) should be increased. There is no limit for the number of iterations.
(4) Ore-waste discriminated as a priory via cut-off grades may undervalue the venture. It is difficult to decide on types of costs to be used in the calculation of cut-off grades. Moreover, current cut-off grade strategies assume that ore price is stable, which is not realistic. A priory cut-offs make accessibility more difficult. For example, a block having slightly lower grade than cut-off can be assessed as ore to go into valuable areas within orebody in a manner that profit is higher.
(5) It was proved that varying cut-off grades in descending order generated more NPV in comparison with the marginal cut-off grade [12]. However, the calculation of cut-off schedule assumes free selection and uses grade-tonnage curves. Therefore, a cut-off grade schedule in descending order cannot be optimal.
(6) In the optimization model, process control (blending) constraint is required to control average grade in each period. However, this gives a rise to model size and thus, solution time. There is also a contradiction between process control constraint and the NPV maximization. In a very narrow upper and lower limits especially, the NPV loses the rationality as an objective function because the model generates homogenous products among periods because of ore material heterogeneity.

The block sequencing, the ore-waste discrimination and the production rates problems should be solved simultaneously rather than a sequential way to reach optimality. However, this is an extremely difficult task because block economic values cannot be calculated without initiating capacities (economies of scale). On the other hand, the capacities cannot be known without the block sequencing. Finally, the blocks cannot be sequenced without knowledge of present value of block economic values. This insoluble conundrum motivates us to solve the problem using a heuristics, which can be summarized as follows:

Step 1. Initialize input values: The destination capacities and corresponding mining and mineral processing costs are determined. Using these values, economic value of each block for each destination is calculated.
Step 2. Solve the problem through traditional approach, which considers economic characteristics. This solution may not satisfy capacities fully. This leads also to tonnage fluctuations among the periods.
Step 3. Solve the problem through the proposed approach, which considers orebody characteristics. Tonnage fluctuations can be controlled by this model. However, the NPV may be lower than that of previous approach.
Step 4. Compare solutions in terms of the NPVs and the rates. If differences are in acceptable limits, accept the solution. Otherwise, go to Step 1.

To generate a quick solution, Steps 2 and 3 can be unified for reasonable size of the problem such that maximum and minimum allowable deviations and destination capacity constraints are used in the same optimization model as given in Eqs. (4)–(7).

2. Problem formulation

In this model, the decision variables are not only extraction period but also the block destination. In other words, unlike the conventional approaches, ore-waste discrimination is made by optimization process in addition to the determination of block extraction period. Furthermore, the gap between the capacities and the production rates is controlled using additional constraints in a manner that optimal capacities can be determined. The objective is the maximization of the NPV of mining venture.

The objective is to maximize NPV of mining venture and given as follows:

$$\text{Max} \quad f(x) = \sum_{i=1}^{T}\sum_{j=1}^{N}\sum_{d=1}^{D} V_{ijd}^{c} * x_{ijd} \tag{1}$$

$$V_{ijd}^{c} = \begin{pmatrix} [price * recovery_d * ore\ tonnage\ of\ block\ j * \\ grade\ of\ block\ j] - [(mining\ cost_d + mineral\ proc.\ cost_d) * \\ tonnage\ of\ block\ j] \end{pmatrix} * (1+n)^{-i} \tag{2}$$

Subject to access constraint:

$$\sum_{d=1}^{D} x_{ikd} \geq \sum_{d=1}^{D} x_{ijd} \quad i = 1,\ldots,T;\ j = 1,\ldots,N \text{ and } k \in K_j \tag{3}$$

Destination capacity constraint:

$$\sum_{j=1}^{N} f_j x_{ijd} - Upp_d \leq 0 \quad i = 1,\ldots,T \text{ and } d = 1,\ldots,D \tag{4}$$

$$\sum_{j=1}^{N} f_j x_{ijd} - Low_d \geq 0 \quad i = 1,\ldots,T \text{ and } d = 1,\ldots,D \tag{5}$$

Maximum and minimum allowable deviations:

$$\sum_{j=1}^{N} f_j x_{ijd} - \sum_{j=1}^{N} f_j x_{i-1jd} \leq Mx \quad i = 1,\ldots,T \text{ and } d = 1,\ldots,D \tag{6}$$

$$\sum_{j=1}^{N} f_j x_{ijd} - \sum_{j=1}^{N} f_j x_{i-1jd} \geq Mn \quad i = 1,\ldots,T \text{ and } d = 1,\ldots,D \tag{7}$$

Block conservation constraint:

$$\sum_{i=1}^{T}\sum_{d=1}^{D} x_{ijd} \leq 1 \quad j = 1,\ldots,N \tag{8}$$

Binary constraint:

$$x_{ijd} \in \{0,1\} \quad i = 1,\ldots,T,\ j = 1,\ldots,N \text{ and } d = 1,\ldots,D \tag{9}$$

where $i = 1, 2, \ldots, T$, T is the number of periods; $j = 1, 2, \ldots, N$, N the number of blocks; $d = 1, 2, \ldots, D$, D the number of destinations (at least one waste dump and one processing destination); x_{ijd} the binary variable (if block j is sent to destination d in period i, the variable is one. Otherwise, it is zero); V_{ijd}^{c} the net present value of block j in period i if it is sent to destination d for capacity c; K_j the set of blocks that must be extracted prior to the mining of block j; f_j the tonnage of block j; n the discount rate; Upp_d and Low_d the upper and lower capacity limits in destination d used in traditional approach; Mx and Mn the maximum and minimum allowable deviation limits among periods.

3. Case study

In order to demonstrate the performance of the approach proposed, a case study is conducted. The initial data comprised a set of 10 drillholes, the cores from which had been assayed for Au. A