ARTICLE IN PRESS

Resources Policy xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Resources Policy

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

A review of underground stope boundary optimization algorithms

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ARTICLE INFO

Keywords:
Optimization
Stope boundary
Deterministic
Stochastic
Algorithm
Underground mining

ABSTRACT

Optimization is a key aspect of the mine design and planning process. A number of algorithms and techniques have been developed to optimize mines. However, most of these techniques focus on open pit optimization to an extent that some authors argue that open pit limit optimization has reached saturation level. Optimization of underground mines only received attention in recent decades and has been focused on three main areas including stope boundary optimization. This paper reviews and analyzes literature on algorithms developed to date for stope boundary optimization. There has been an increase in the number of algorithms developed to optimize stope layout. Most of these algorithms are heuristic, consider stope dimension as one of the constraints and optimize layouts in three dimensional space. However, all these algorithms are based on deterministic orebody models, therefore, fail to consider uncertainty intrinsic in ore deposits. Also, none of these algorithms guarantee optimal stope layout solution in three dimension. Consequently, there is a need for further research in the field of stope boundary optimization.

1. Introduction

Optimization in general involves either maximizing or minimizing an objective function against a given set of constraints. The objective can be minimizing inputs to a process because they are scarce, minimizing undesired outputs such as waste or maximizing desired outputs such as Net Present Value (NPV). Irrespective of the objective, the basis of optimization is a mathematical model that represents the problem that is then solved using an algorithm. To date, optimization algorithms have played an important role in mine planning and decision-making though more faster and efficient techniques still require to be developed (Little, 2012).

Optimization techniques for mining operations date back to the 1960s with initial research developments and application in surface mining. In open pit mining, considerable strides have been made in developing algorithms for open pit optimization. In contrast however, fewer algorithms have been developed for underground mine optimization resulting in most underground mines operating on sub-optimal mine plans particularly in the area of optimization of stope boundary and layout definition (Little, 2012). Optimization in underground mines only started in the 1970s as an extension of open pit optimization applications and to date only a few optimization techniques have been developed to solve underground optimization problems. However, Ataee-Pour (2005) indicated that most of those few optimization techniques for underground optimization have proved not to provide optimum solutions. This is because the optimization of underground mines is computationally more complex than open pit mines and hence the less algorithms that give optimum solutions for underground mines. Unlike in open pit mines, the main challenge in developing a generic methodology for the optimization of underground mines is that there is a wide range of underground mining methods available and their application varies among mine sites, hence each deposit requires a specialized optimization solution (Alford et al., 2007; Sandanayake, 2014).

Underground mines also require consideration of other constraints not applicable to open pit mines including ventilation and size of equipment to fit into stopes. Also, in open pit mines, for any given slope angle there is a single option available to remove a given block. Nevertheless, for underground mines there are several options available (Sandanayake, 2014). All these factors make developing optimization solutions for underground mines more computationally complex and hence the lesser amount of research work currently available compared to open pit mines. Alford et al. (2007, p. 574) stated that "*the complexity of the underground mine design problem and the unique mine design solutions sought for each ore body suggest that there will never be an elegant solution method analogous to that which exists for open pit mining*". Musingwini (2016) stated that because of this computationally complex nature of optimizing underground mines most of the current work on optimization in underground mine planning is mostly academic. Topal and Sens (2010) mentioned that optimization techniques in underground mines have been mainly focused on three main strategic mine planning areas:

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https://doi.org/10.1016/j.resourpol.2017.12.004
Received 31 July 2017; Received in revised form 1 December 2017; Accepted 6 December 2017

Please cite this article as: Nhleko, S., Resources Policy (2017), https://doi.org/10.1016/j.resourpol.2017.12.004

1. Optimization of stope boundaries;
2. Optimization of location of development and infrastructure; and
3. Optimization of production schedules.

A number of optimization techniques and algorithms have been developed for optimization of each of those areas in underground mines. However, this paper focuses on stope boundary optimization because stope boundary optimization provides the first opportunity to mine planners to optimize and maximize the NPV of a mining project. It is therefore, the aim of this paper to review and analyze literature available on underground stope boundary optimization algorithms. In this paper the phrases 'stope boundary', 'ultimate stope limits', 'stope envelope' and 'stope layout' are used interchangeably.

2. Orebody modelling

Irrespective of the mining method, either underground or surface, mining starts with prospecting and exploring for mineral resources of economic interest. Based on borehole data and geological information, a geological block model is created. The geological modelling process starts by dividing the orebody into regular blocks in three dimensions, with each block containing its characteristic data; most importantly grade, volume and density. From the geological block model subsequent evaluation processes are done including geostatistical techniques applied to estimate the quantity and quality of the mineral deposit and economic evaluation to convert the geological block model to an economic block model which is one of the key input for optimizing stope boundaries. However, there are other algorithms that generate a stope layout solution based on cut-off grade and head grade such as Floating Stope Algorithm.

As mentioned earlier, stope boundary optimization is one of the first opportunity available to mine planners to optimize the long term value of a mining project. Erdogan et al. (2016) mentioned that it may be considered as the starting point in the full optimization process for underground mines when both development and production schedule are considered. The economic orebody limits must be defined first which then allows the optimal location of key development access routes such as shafts, declines, tunnels and raises to be identified. Therefore, incorrect definition of stope boundaries results in incorrect placement of underground infrastructure which may require that the mine design be modified later in the life of the mine (LOM). In other words, an optimum stope boundary determines the efficacy of the mine design and subsequently, the long term production schedule, which then informs the cash flow profile and ultimately, the NPV of a project. Therefore, it is important that its in-situ representation is accurately modelled and understood.

Traditionally, to determine whether it will be economic to mine a particular block, the geological block model is converted to an economic block model by applying geological and economic parameters to each block to determine all economically mineable blocks to be included in the ultimate mining limits. The economic modelling process is based on calculating the revenue derived from each block and the cost of mining each block, comparing these two values on a block by block basis to get Block Economic Values (BEVs). For each set of cost and revenue parameters applied, the BEVs distinguish payable and unpayable ore blocks. A block will be economic to mine if the revenue from mining is greater than the cost of mining and processing, that is, if the block economic value is positive. From the economic block model, stopes are created and the following section review algorithms that have been developed to optimize stope boundaries.

3. Algorithms for stope boundary optimization

A stope is a mining area in underground mining which consists of a number of mining blocks. An optimum stope boundary is the limit for material that can be mined economically through underground mining methods; equivalent to an ultimate pit limit in open pit mining. Defining an optimum stope limit is fundamental in optimizing value from the extraction of a mineral deposit. It is a critical element of strategic mine planning. Little (2012) mentioned that the aim of stope boundary optimization is to select the best combination of blocks to form a series of stopes based on value measures such as grade or profit while satisfying physical mining and geotechnical constraints. The process to define an optimum stope layout combines thousands of blocks into a set of stopes, such that, the undiscounted value is maximized whilst satisfying physical and geotechnical constraints (Sandanayake et al., 2015). Algorithms that have been developed for the optimization of ultimate stope limits are categorized as either rigorous or heuristic (Ataee-Pour, 2006). These exact/rigorous and heuristic algorithms are reviewed in the following sub-sections.

3.1. Exact algorithms

Exact algorithms are those algorithms based on a mathematical model and hence they guarantee an optimum solution. These include the Dynamic Programing, Downstream Geostatistical and Branch and Bound algorithms. This section reviews the exact algorithms with the main focus being their shortfalls concerning generation of optimal solutions in 3 dimensional (3D) space.

3.1.1. Dynamic Programming algorithm

Riddle (1977) developed an algorithm based on the dynamic programming technique in order optimize stope layouts for block caving mines. The algorithm is a modification of the Dynamic Programming algorithm for optimizing open pit limits by Johnson and Sharp (Shahriar et al., 2007). In the algorithm the relation of height mined is constrained by draw control.

Riddle (1977) describes the optimization process by the algorithm mentioning that it starts by first assuming that there is no footwall region and then a minimum number of adjacent draw-points that should be mined in any discrete mining unit are established. The algorithm then assumes that one footwall region is added within the section and then it also establishes a minimum number of adjacent draw-points that should be left in a discrete, non-mined footwall region. Each combination of mined and non-mined draw-points is investigated and the profit of each combination is taken. If the profit with a footwall is greater or equal to the maximum profit obtained for the no-footwall case then a more optimum layout exists with a footwall case and the process is repeated to the two areas divided by a footwall. For example, if the north block is more optimal with a footwall, the process is continued by adding the southern region to the previous optimal condition analyzing the north end for further footwall (Riddle, 1977). This process is continued until no more optimum footwall case is found or it is no longer practical to add further footwalls.

In his review of stope layout optimization techniques Ataee-Pour (2005) highlighted the limitations of the algorithm. DP generates optimum stope layouts in two dimension. The optimum 2D sections can be combined to generate a 3D stope layout. However, stope constraints can be violated during the process, thus, optimality in 3D is not guaranteed. The other limitation is that the algorithm is only applicable to block caving mines and is not applicable to other mining methods.

3.1.2. Downstream Geostatistical approach

Developed by Deraisme et al. (1984), the approach defines an optimal economic stope design based on downstream geostatistics. Downstream geostatistics is defined by Deraisme p. 583) et al. (1984) as "the methodology for the study of the influence of mining constraints on mining recovery and ore quality". This approach introduces the application of geostatistics to determine the boundary of mineable ore in an orebody. It can be applied when the mining method to be used is cut and fill or sublevel stoping. It uses downstream geostatistics to build 2D sectional numerical models of the orebody and delineate the ore to