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Designing an optimal stope layout for underground mining based on a heuristic algorithm

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ABSTRACT

An optimal layout or three-dimensional spatial distribution of stopes guarantees the maximum profitability over life span of an underground mining operation. Thus, stope optimization is one of the key areas in underground mine planning practice. However, the computational complexity in developing an optimal stope layout has been a reason for limited availability of the algorithms offering solution to this problem. This article shares a new and efficient heuristic algorithm that considers a three-dimensional ore body model as an input, maximizes the economic value, and satisfies the physical mining and geotechnical constraints for generating an optimal stope layout. An implementation at a copper deposit demonstrates the applicability and robustness of the algorithm. A parallel processing based modification improving the performance of the original algorithm in terms of enormous computational time saving is also presented.

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1. Introduction

The availability of adequate supply of mineral resources is the requirement for commencement of a mining operation. Geological and geostatistical investigations delineate the spatial (size, shape, depth, etc.) characteristics of these resources, define mineable reserves, and create a three-dimensional ore body model by dividing these reserves into thousands of mining blocks [1–5]. Apart from the economic parameters, this ore body model becomes an input to subsequent mine planning process. Given these inputs, mine planning process may suggest recovery of these reserves either through a surface or an underground mining operation. If the decision is in favor of an underground mining operation, then the development of an optimal production plan that maximizes the discounted value of the operation subject to the production capacity, physical, and geotechnical constraints, follows the selection of a stope layout [6,7]. The procedure to generate an optimal stope layout combines thousands of mining blocks into a set of stopes, such that, the undiscounted value of operation is maximized by satisfying the physical and geotechnical requirements [8,9]. Consequently, for a decision, whether a mining block is included in a stope or otherwise, it requires evaluation of all possible combinations of thousands of mining blocks. This establishes the computational complexity of the stope optimization problem, and as a result, generating solution to this problem, is a challenge. Therefore, this paper describes and implements an efficient heuristic approach to develop an optimal stope layout in underground mining operations.

Physical and geotechnical constraints relate to the size and orientation of the ore body, extent of mine development openings (levels) that provide access to stopes, mining equipment size, and an appropriate ore pillar size ensuring stability of these underground excavations [10,11]. Given these constraints, a realistic stope layout may constitute fixed (i.e. all stopes of similar size) or variable size stopes with or without pillars. Consequently, a procedure that caters for variable stope sizes and availability of pillars within the underground mine, supplements the computational complexity of the stope layout problem. Fig. 1 establishes the context of computational complexity in a simple two-dimensional hypothetical ore body model containing 64 mining blocks.

As shown in Fig. 1a, the stope size is defined as $3 \times 3 = 9$ mining blocks, i.e. the number of mining blocks along *x* and *y*-axis is equal to 3, respectively. Given the defined stope size, a candidate mining block *b* may become part of 1 out of 9 possible stope combinations (for example, stopes 1 and 2). This reflects that there are numerous possible combinations for all 64 mining blocks within this hypothetical ore body model. Similarly, Fig. 2b relates the stope size and possible stope combinations for a mining block *b*. It shows that an increase in stope size escalates the number of stope combinations, resulting in the computational complexity of the stope layout problem. In realistic ore body models, an evaluation of these

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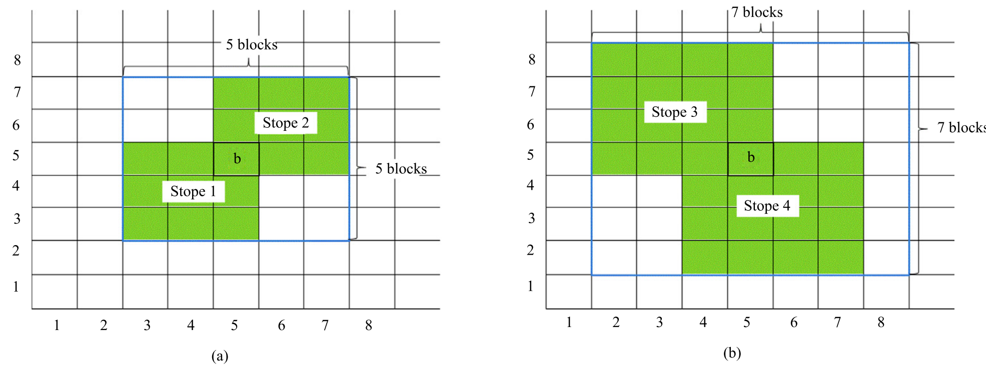

Fig. 1. Complexity of stope layout problem.

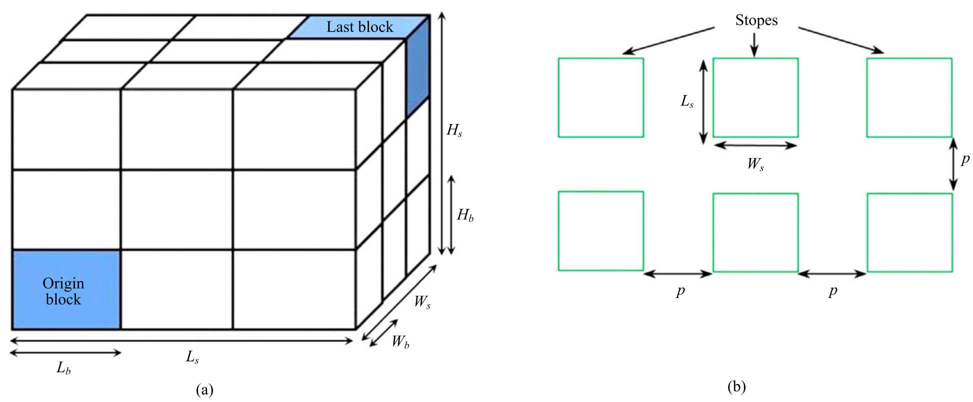

Fig. 2. An illustration of the stope and pillar layout notations.

combinations is required in three-dimensional space, leading to an exponential increase in the computational time and complexity.

Moreover, if a mining block is shared among a number of possible stopes, i.e. the mining block exists in more than one stope sets, such combinations are categorized as overlapping stopes. Physical mining constraint restricts the generation of overlapping stopes, and accordingly, avoiding such stope sets requires implementation of the additional computational steps of the algorithmic. In summary, it is established that the computational complexity of the stope layout problem is manifolds, and the development of a stope optimization algorithm that evaluates multiple combinations of non-overlapping stope sets and selects the best stope layout is a challenge.

Given these intricacies, a few algorithms offer solution to the stope layout problem, however, a majority of these algorithms does not generate the optimum solution [12]. Ovanic and Young propose the branch and bound algorithm to optimize the stope boundary along a row of mining blocks, i.e., in one dimension, using two piecewise linear cumulative functions [13,14]. These two functions identify the optimal starting and ending locations for mining within each row of mining blocks. As such, the algorithm cannot be implemented in three-dimensional ore body models. Imitating the open pit optimization procedures, Alford shares a floating stope procedure, and given the structure of the algorithm, it violates the non-overlapping stopes requirement [15]. Cawrse suggests a multi-pass floating stope process as an improvement/extension in the original floating stope process; however, the algorithm fails to address the violation of non-overlapping stopes requirement [16]. Ataee Pour proposes the maximum neighborhood value algorithm that relies on individual mining blocks in delineating the stope boundaries, consequently, ignores the shape of the mineable stopes, leading to limited applicability in realistic scenarios [17]. Grieco and Dimitrakopoulos develop a mixed integer programming based stope optimization algorithm under geological uncertainty, and given the size of the stochastic framework, the algorithm focuses only on the profitable stope locations, and valid solution to the entire ore body does not exist [18]. Topal and Sens suggest a heuristic procedure that derives the most profitable stopes from the ore body model, however, the procedure fails to analyse all alternative solutions [9]. Bai et al. propose an implementation of the maximum flow algorithm for stope optimization problem [19]. However, it is limited to use for small mineralized ore bodies and sub-level stoping mining method.

Realizing that the earlier studies do not offer a holistic approach to solve this challenging problem, this paper contributes: (1) a new and efficient heuristic algorithm that maximizes the economic value of the operation, honors the physical mining and geotechnical constraints, incorporates fixed and variable stope sizes with and without pillars, and solves the problem in three-dimensional space; (2) an implementation of the original algorithm at a copper deposit; and (3) a parallel processing based modified algorithm improving the performance of the original procedure in terms of enormous computational time savings.

2. Proposed heuristic algorithm

The proposed heuristic algorithm solves the stope layout problem sequentially in five distinct steps. It standardizes the ore body model, creates stopes, assigns attributes to these stopes, generates sets of stopes as possible solutions, and identifies the optimal solution among all possible solutions. More specifically, it converts the ore body model into an economic block model that constitutes

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