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Innovative Applications of O.R.

Long term production planning of open pit mines by ant colony optimization

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ABSTRACT

The problem of long-term production planning of open pit mines is a large combinatorial problem. Application of mathematical programming approaches suffer from reduced computational efficiency due to the large amount of decision variables. This paper presents a new metaheuristic approximation approach based on the Ant Colony Optimization (ACO) for the solution of the problem of open-pit mine production planning. It is a three-dimensional optimization procedure which has the capability of considering any type of objective function, non-linear constraints and real technical restrictions. The proposed process is programmed and tested through its application on a real scale Copper–Gold deposit. The study revealed that the ACO approach is capable to improve the value of the initial mining schedule regarding the current commercial tools considering penalties and without, in a reasonable computational time. Several variants of ACO were examined to find the most compatible variants and the best parameter ranges. Results indicated that the Max–Min Ant System (MMAS) and the Ant Colony System (ACS) are the best possible variants based on the required less amount of memory. It is also proved that the MMAS is the most explorative variant, while the ACS is the fastest method.

1. Introduction

A global challenge in the years to come is the environmental-friendly and financially attractive provision of exhaustible resources (minerals) to meet the ever-increasing demand by the today's high-tech society. Currently surface mining accounts for a significant proportion of the produced minerals. Surface or open pit mining is a mineral exploitation method by which the deposit is accessed by digging a large opening in the ground surface, called a pit, to expose the ore. The mining operation initially starts with a small pit and develops to a larger pit enclosing the previous one. The process proceeds until a final shape of the mine called "the ultimate pit limit" (UPL) is reached. These sequences of pits are known as mining sequences or pushbacks.

The last 30 years have seen a widely-publicized revolution in the application of the numerical methods in the mining industry in order to produce better mine plans on more complicated and often lower grade deposits. Recent researches in the field of open-pit optimization have been focused on developing new algorithms which are (Sattarvand, 2009):

- firstly less complex in terms of comprehensibility and programming;
- secondly require high computational efficiency in order to be applicable to the large deposits;
- finally allow the incorporation of real mining complexities such as variable slopes, working slopes, time value of money, quality and quantity of planned material and related uncertainties.

A core concept to address this complex and large-scale optimization problem is the block model, where the ore body is discretized into a three dimensional array of regular size blocks. The model may have millions of blocks depending on the size of the deposit and the size of the blocks. A set of attributes such as tonnage and grade, using different geostatistical techniques and economic parameters, are assigned to the each block.

The long-term open-pit mine production planning problem can be defined as specifying the sequence in which the blocks should be removed from the mine as a certain material type, in order to maximize the total discounted profit from the mine subject to a variety of economical and physical constraints.

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This paper presents a new metaheuristic approximation approach based on the Ant Colony Optimization (ACO) for the solution of the problem of open-pit mine production planning. The process has the proficiency to optimize the UPL and the long-term planning problem simultaneously considering the multi-objective targets and the complex constraints. It merges the constraints into the objective function as a set of the penalties for deviations from the targets. The next section gives a brief review on state of the art, short description of the metaheuristic algorithms and reviews the former developed metaheuristic approaches in the field of open pit optimization. Thereafter, fundamental structure of the ACO modeling and its applicable variants in the open pit optimization are described. Finally, the proposed procedure of long-term open pit planning is explained and the results of its application on a real scale Copper–Gold mine are presented and discussed.

2. Problem statement

2.1. Mathematical formulation

At late 60s, researchers were only focused on the UPL problem. Lerchs and Grossmann's algorithm based on graph theory (Lerchs & Grossmann, 1965) and Maxflow algorithm based on network flow concept (Johnson, 1969) are the first attempts to solve this problem. Subsequent studies motivated to a more general problem namely the problem of production planning. Gershon (1983) presented a Mixed Integer Linear Programming (MILP) model. The model has binary variables and its objective function could be expressed as a maximization of Net Present Value (NPV) of the mining operation. The MILP model is subjected to the variety of technical constraints. For instance, the total tonnage of extracted material, the quantity of each material type and the average grade of each production element should be within predefined ranges of limits. Moreover, sequencing constraints are necessary to ensure that a block can be extracted if all immediate successor blocks have been removed. Finally, reserve constraints are applied to mathematically guarantee that a block is mined only once.

Several approaches have been proposed in literatures to solve this MILP model. Dagdelen and Johnson (1986) and Caccetta, Kelsey, and Giannini (1998) used Lagrangian parameterization in order to relax the mining and milling constraints into the objective function. Consequently, the problem could be handled by repetition of any UPL algorithm such as the (Lerchs & Grossmann, 1965)'s graph theory based algorithm. Later Caccetta and Hill (2003) proposed a branch and bound technique to solve the formulated scheduling problem. Dowd and Onur (1993) and Onur and Dowd (1993) formulated the problem as a dynamic programming model. Ramazan (2007) described the application of fundamental tree algorithm to reconstruct the mining blocks and decrease the number of variables in scheduling problems without reducing the resolution of the model or optimality of the results. They defined the fundamental tree as any combination of the blocks that can be profitably mined respecting slope constraints. Boland, Dumitrescu, Froyland, and Gleixner (2009) proposed an iterative disaggregation method that refines the aggregates (with respect to processing) up to the point where the refined aggregates defined for processing produce the same optimal solution for the Linear Programming (LP) relaxation of the MILP as the optimal solution of the LP relaxation with individual block processing. Bley, Boland, Fricke, and Froyland (2010) presented an integer programming formulation which is strengthened through adding inequalities derived by combining the precedence and production constraints. The addition of these inequalities decreases the computational requirements to obtain the optimal integer solution. Chicoisne, Espinoza, Goycoolea, Moreno, and Rubio (2012) developed a new algorithm for this problem based on a well-known integer programming formulation which called C-PIT method. The proposed method used a new decomposition process for solving the linear programming relaxation of the C-PIT when there is a single capacity constraint per time period. They denoted that this is just a proof of a concept and next step would be extending the critical multiplier method to work explicitly with multiple side constraints.

All these exact approaches are limited by the amount of decision variables and can solve relatively small problems, excluding many practical implications.

2.2. Metaheuristics

A metaheuristic is a set of algorithmic concepts that can be used to improve the heuristic methods to become applicable for difficult problems. These concepts are usually inspired by biology and nature. The use of metaheuristics has significantly increased the ability of finding very high quality solutions for large combinatorial problems (that are often easy to state but very difficult to solve) in a rational time. This is particularly true for large problems which are difficult to understand. The family of the metaheuristics includes, but is not limited to, Genetic Algorithm (GA), Simulated Annealing (SA), Tabu Search (TS), ACO, and Particle Swarm Optimization (PSO).

Denby and Schofield (1994) described the process of the application of the GA in optimization of an open-pit mine production planning shown in Fig. 1a. The main advantage of their method was in its ability to solve the ultimate pit limit and the long-term planning problem simultaneously. By choosing proper values for the genetic parameters, this method is capable to produce good results for a small block model in an acceptable time. Later Denby and Schofield (1995) continued to consider risk assessment in their scheduling process. They also extended the algorithm from 2D to 3D (Denby & Schofield, 1996) and used it for a flexible scheduling operation (Denby, Schofield, & Surme, 1998).

Kumral and Dowd (2002, 2005) investigated the solution of the open pit mine production scheduling problem by means of the SA as shown in Fig. 1b. The main advantage of this routine is that it utilizes a multi-objective function comprised of three minimization components. On the other hand, the separate determination of UPL and production schedule would be counted as a drawback

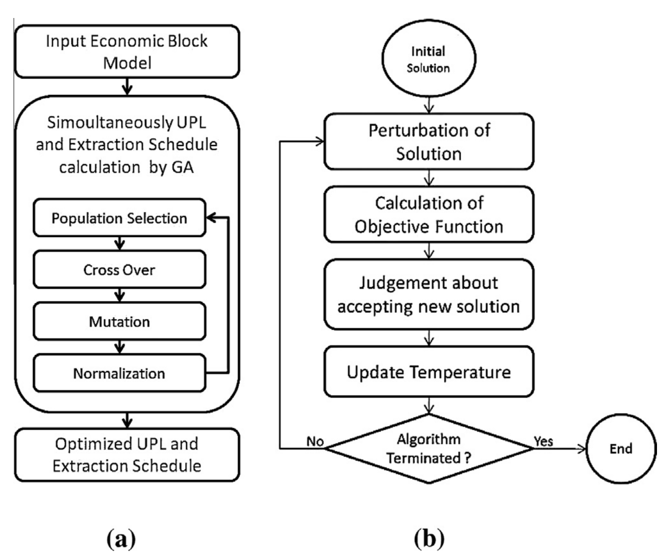

Fig. 1. (a) The process of open pit scheduling by genetic algorithm and (b) simulated annealing (Sattarvand, 2009).