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Innovative Applications of O.R.

A hybrid heuristic algorithm for the open-pit-mining operational planning problem

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A B S T R A C T

This paper deals with the Open-Pit-Mining Operational Planning problem with dynamic truck allocation. The objective is to optimize mineral extraction in the mines by minimizing the number of mining trucks used to meet production goals and quality requirements. According to the literature, this problem is NP-hard, so a heuristic strategy is justified. We present a hybrid algorithm that combines characteristics of two metaheuristics: Greedy Randomized Adaptive Search Procedures and General Variable Neighborhood Search. The proposed algorithm was tested using a set of real-data problems and the results were validated by running the CPLEX optimizer with the same data. This solver used a mixed integer programming model also developed in this work. The computational experiments show that the proposed algorithm is very competitive, finding near optimal solutions (with a gap of less than 1%) in most instances, demanding short computing times.

1. Introduction

This work deals with the Open-Pit-Mining Operational Planning (OPMOP) problem, which involves to determine extraction rate of material from ore and waste rock pits, and to assign the equipments (shovels and mining trucks) to these pits. The objective is to determine the extraction rate at each pit in a way that production and quality goals are satisfied, and to minimize the number of trucks needed for the production process.

We are considering dynamic truck allocation in the OPMOP problem, that is, the trucks are not fixed to specific pits/or shovels. Instead, a truck can be assigned to different pits, which increases the fleet productivity, allowing smaller fleets to perform the operations.

The problem in focus has the Multiple Knapsack Problem (MKP) as a subproblem. In fact, the analogy can be made by considering each shovel like a knapsack and the loads (ore or waste rock) of the trucks as the items. In this analogy, the goal is to determine which loads are the most attractive to allocate to each knapsack, respecting its capacity (productivity). Thus, as MKP belongs to the NP-hard class (Papadimitriou and Steiglitz, 1998), OPMOP does too. Since in real cases the decision must be fast and it is unlikely that optimal solutions would be obtained by exact techniques in a short space of time, it is proposed to find sub-optimal solutions for the problem by means of heuristic techniques. The proposed heuristic algorithm is based on the procedures Greedy Randomized Adaptive Search Procedures – GRASP (Resende and Ribeiro, 2010) and General Variable Neighborhood Search – GVNS (Hansen et al., 2008a,b; Hansen and Mladenovic, 2001; Mladenovic and Hansen, 1997).

These algorithms have been applied with success to solve several hard combinatorial problems (Glover and Kochenberger, 2003). We propose here a hybrid heuristic with the aim of combining good features found in each one of these metaheuristics. From GRASP we used the construction phase to quickly produce good quality solutions and accelerate the improvement phase. GVNS was chosen due to its simplicity, efficiency and the natural capacity of its local search (VND method) for handling different neighborhoods.

To test the efficiency of the proposed heuristic, its results were also validated by using the state-of-the-art commercial optimization software CPLEX 11.0.1 applied to a mathematical programming model also proposed in this work.

The contribution of this work is the presentation of a more complete mathematical programming model of OPMOP than those found in literature. This model seeks to more faithfully depict a real operational mining industry environment. Moreover, it presents a new heuristic model not yet found in literature in order to solve the problem in focus.

The remainder of this paper is organized as follows. Section 2 shows the related work. Section 3 describes the problem considered in this work. Section 4 presents a mathematical programming formulation to OPMOP, while Section 5 presents a heuristic approach to the problem in focus. The testing scenarios are described

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in Section 6, while in the following section, the computational experiments are presented and analyzed. Section 8 concludes the work.

2. Related works

White and Olson (1986) proposed an algorithm that is the basis for the DISPATCH System, which operates in many mines around the world. A solution is obtained in two steps. The first, based on linear programming, handles the problem of ore mixture optimizing by minimizing costs considering the mining rate, the quality of the mixture, the ore feed rate to the plant for beneficiating, and the material handling. The restrictions of the model are related to the production capacity of the shovels, the quality of the mixture and the minimum feeding rate to the processing plant. The second stage of the algorithm, which is solved by dynamic programming, uses a model similar to White et al. (1982), differing from this by using a decision variable for the volume of material transported per hour on a given route, instead of the truck working rate per hour. Also considered is the presence of storage piles. In this second stage of the algorithm, the objective is to minimize material transportation in the mine.

Sgurev et al. (1989) described an automated system for real-time control of truck haulage in open-pit mines. This system is called TRASY and it is designed towards the improvement of the technical–economical indices of the loading–unloading process in open-pit mines where trucks are used as vehicles. The authors described the two ways of organizing the trucks work: on a closed-circuit system and on an open-circuit system, so-called dynamic allocation system. The benefits of the open-circuit system are shown and the authors described the four modules of the TRASY system: configuration, control, monitoring and report. The authors concluded that the increase of the operation productivity in open-pit mines may be achieved by improving the effectiveness of the loading-haulage process control, so the introduction of automated systems for haulage vehicles control is one way to accomplish this goal. However, this system does not take into account the quality goals of the ore control parameters.

Chanda and Dagdelen (1995) developed a linear programming model that solves the problem of mixed minerals in the short-term planning of a coal mine. The objective function of this model is the weighted sum of three distinct objectives: to maximize an economic criterion, to minimize production deviations, and to minimize quality deviations from the desired values of the control parameters. No allocation for the loading and transport equipment was considered in this model.

Ezawa and Silva (1995) developed a system for dynamic truck allocation with the objective of reducing variability in the levels of the ore and increasing transport productivity. The system uses a heuristic to sequence the trucks in order to minimize changes in the levels. To validate it, the authors used a simulation and the theory of graphs for the mathematical modeling of the mine. Deploying this system transport productivity increased by 8% and management obtained more accurate data in real time.

Alvarenga (1997) developed a program for the optimal dispatch of trucks in the iron mining of an open-pit mine, with the objectives of minimizing the queue time of the trucks in the fleet, increasing productivity and improving the quality of the extracted ore. In the work, which is the basis of the SMART MINE system widely used in various Brazilian mines, a technique of stochastic optimization was applied, using the genetic algorithm with parallel processing. Basically, the problem is to indicate the best point of tipping or loading and the trajectory for the movement, when there is a situation of choice to be made. The author pointed to productivity gains of 5–15%, proving the validity of the proposal.

Merschmann (2002) developed an optimization system and simulation for analyzing the production scenario in open-pit mines. The system, called OTISIMIN (Simulator and Optimizer for Mining), was developed in two modules. The first is the optimization module where a linear programming model is constructed and solved, while the second is a simulation module that allows the user to use the results obtained by solving the linear programming model as input for the simulation. The optimization module was developed with the aim of optimizing the process of mixing the ores from the mining of several pits in order to meet the quality specifications imposed by the treatment plant and allocating equipments (trucks, shovels and/or excavators) to pits, considering both static and dynamic truck allocation. The developed model does not consider production optimization and quality targets, or reduction of the number of trucks required by the production system.

Godoy and Dimitrakopoulos (2004) dealt with the open-pit mine design and production scheduling problem, with a view to find the most profitable mining sequence over the life of a mine. According to the authors the dynamics of mining ore and waste and the spatial grade uncertainty make predictions of the optimal mining sequence a challenging task. The authors show a risk-based approach to life-of-mine production scheduling, including the determination of optimal mining rates for the life of mine, whilst considering ore production, stripping ratios, investment in equipment purchase and operational costs; and the generation of a detailed mining sequence from the previously determined mining rates, focusing on spatial evolution of mining sequences and equipment utilization. The production scheduling stage uses a specially-developed combinatorial optimization algorithm based on the Simulated Annealing metaheuristic. A new risk-based, multistage optimization process for long-term production scheduling is presented, and the results show the potential to considerably improve the valuation and forecasts for life-of-mine schedule.

Guimaraes et al. (2007) presented a computational simulation model to validate the results obtained by applying a mathematical programming model to determine the mining rate in open-pit mines. LINGO solver, version 7.0, was used for optimizing the problem and ARENA, version 7.0, simulated the solver's solution. Contrary to belief, the modeling demonstrated that by increasing the number of vehicles, the production goal was not met and was further deterred due to increased queue time. Thus, increasing the number of vehicles does not necessarily optimize mining operations.

Boland et al. (2009) dealt with the open-pit mining production scheduling problem (OPMPSP). The treated problem consists of finding the sequence in which the blocks should be removed from pits, over the lifetime of the mine, such that the net present value (NPV) of the operation is maximized. Due to the large number of blocks and precedence constraints linking them, blocks are aggregated to form larger scheduling units. The authors investigated the characteristics of the problem and showed how the aggregates can be systematically divided into bins (groups of blocks) so that the solution of the linear programming (LP) relaxation with all processing decision variables fully disaggregated to block level (D-LP) can be recovered from the solution of our compactly disaggregated LP relaxation (B-LP) with processing decisions made at the level of bins. As the number of bins is much smaller than the number of blocks, using their binning approach, D-LP can be solved to optimality for much larger data instances than by a direct disaggregation