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Open pit waste removal optimization through equipment fleet scheduling

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Abstract: A neighborhood search algorithm was proposed to simultaneously schedule the waste removal quantity and the equipment fleet profile over the mine life for open pit mines. An initial search domain was first defined and a good schedule was obtained as the current best schedule by searching in this domain. Then, progressively narrower neighborhood search domains were constructed around the current best schedule to search for better schedules. The objective is to minimize the present value of waste removal costs over the mine life. The resulting schedule from this algorithm provides a complete fleet profile for each year over the mine life: the selected equipment models, the number of equipment units of each model, the age of each unit, as well as the quantity of waste removed. A numerical example of application was provided to demonstrate the feasibility and merits of the algorithm.

Key words: open pit; waste removal; equipment fleet; scheduling; neighborhood search

1 Introduction

Having an effective long-term production schedule and assigning proper fleets of mining equipment to fulfill the schedule are crucial to an open pit operation's economic outcome. Consequently, great research efforts have been devoted to these topics with the aim of obtaining optimal solutions.

The long-term open pit production scheduling problem (LTOPSP) consists of determining the quantity and sequence in which the blocks should be mined in each year over the mine life, so that the overall net present value is maximized. Various approaches have been proposed to get optimal solution to the LTOPSP. Linear programming has been a popular approach where the LTOPSP is usually formulated into mixed integer programming (MIP) or pure integer programming (IP) models [1−4]. The sheer size of such models prohibits the straightforward application of standard solution techniques, and much effort has been spent on finding ways of solving the models in acceptable time frames. Two ways of block aggregation [5,6] and Lagrangian relaxation [7,8] frequently appear in the literatures. Dynamic programming is another frequently used approach to the LTOPSP [9−11]. A relatively new development in this area is the incorporation of geological and market uncertainties in solving the LTOPSP [12−15].

Fleets of mining equipment must be operated to carry out the scheduled production. Materials handling takes a lion's share of the total equipment requirement, in terms of both capacity and cost outlay. According to Refs. [16,17], haulage cost constitutes 50%−60% of the total operating cost, and the capital cost of a truck-shovel system is in the order of hundreds of millions of US dollars for large operations. Therefore, the truck-shovel system has been the subject of extensive research to address various issues, including fleet sizing and scheduling.

Queuing network models have been used to obtain performance parameters of open pit truck-shovel systems. Analyses of these parameters may indicate deficiencies in the system and suggest improvement measures. By solving queuing network models for different truck-shovel fleet configurations, the best fleet

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configuration can be found for an operation. Some examples of publications in this area can be found [18−21]. Simulation is also a widely used tool for analyzing the performance of open pit truck-shovel systems. Through many runs of simulation, statistics on performance measures of a truck-shovel system can be obtained and analyzed to pinpoint bottlenecks and to devise possible improvements. Sensitivity analyses may be conducted using simulation with respect to certain system configurations in an attempt to optimize the system. A large number of publications in this area exist, and these are some examples of recent ones [22−25].

Fleet scheduling in open pit mines mainly concerns the determination of the number and models of trucks and shovels to be used in each period to meet the scheduled production targets. BURT et al [26,27] formulated the fleet scheduling problem as a MIP model. The model determines the number and models of trucks and loaders as well as their purchase and salvage policies, and allocates the trucks to routes and the loaders to mining locations. The objective is to minimize the present value of materials handling cost while meeting the scheduled production requirements. TOPAL and RAMAZAN [28] also used a MIP formulation to schedule truck fleet, with an objective of minimizing the overall discounted maintenance cost while achieving the scheduled production targets. FU et al [29] extended this formulation to incorporate new truck purchase. TOPAL and RAMAZAN [30] used stochastic IP to schedule the truck fleet by treating the truck maintenance cost as a stochastic parameter.

Although a large number of publications exit on the open pit production and equipment fleet scheduling problems, the two problems have been treated separately. In fact, they are closely interrelated and can be seen as the same and one problem, because the quantity of material mined (the production) in each period is normally equal to the capacity of the mining equipment fleets operating in that period, unless the mine operator is willing to let some of the available equipment capacity be idle. Separate, optimal solutions to the two problems will not be optimal when the two are considered together. Therefore, production and equipment fleet should be scheduled together or, putting it another way, production should be scheduled through equipment fleet scheduling. Unfortunately, very few publications addressed the problem in such a way. WANG et al [31] solved the waste removal and truck fleet scheduling problem as a whole, but used a fixed truck replacement rule and allowed only a single truck model. GODOY and DIMITRAKOPOULOS [32] proposed a production scheduling approach that considers the purchase cost of added equipment capacity and the ownership cost of idle capacity. This approach implicitly incorporates equipment feet sizing in production scheduling, but the fleets are represented by capacities rather than specific equipment units.

In this work, an optimization approach was presented, where open pit waste removal scheduling and equipment feet scheduling were integrated. The approach can deal with heterogeneous fleets, preexisting equipment, and considers the effective capacity and operating cost of an equipment unit as discrete functions of its age. The objective is the minimization of discounted waste removal costs.

2 Waste removal problem and its solution domain

In open pit mines, sufficient quantity of waste must be removed each year to expose enough ore to meet the ore production target. Figure 1 shows an illustration of the relationship between waste removal and ore mining, where the ultimate pit is not divided into intermediate pits as commonly practiced in China. One can see that waste (w) must be removed with the mining of ore (q). For given annual ore productions, the required quantity of waste removal may vary dramatically over the mine life, depending on the orebody geometry, the ultimate pit, the topography, and the working slope α. Supposing that the annual ore production is a constant equal to the throughput of the processing plant, the required annual waste removal may vary with time as shown by the solid curve in Fig. 2. For given orebody geometry, the ultimate pit and topography, this waste removal curve depends on the working slope, α, which in turn depends mainly on the working bench width b. The smaller the b is, the higher the α is, and the more waste will be postponed in most cases. The steepest feasible working slope corresponds to the minimum b required for operating mining equipment at normal efficiency. We use the term required waste removal to refer to the quantity of waste to be removed to meet the specified ore production with the minimum b.

It seems that accomplishing just the required waste removal each year over the mine life (the solid curve in

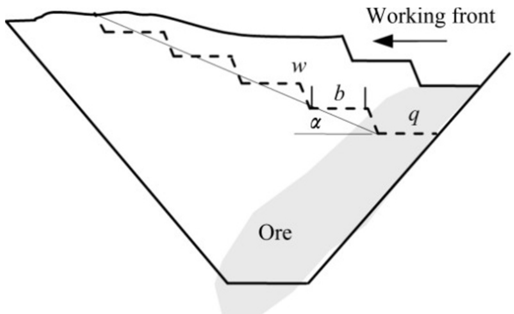

Fig. 1 Illustration of relationship between ore mining and waste removal