Optimal Selection and Assignment of Loading Equipment for the Compliance of an Open Pit Production Plan

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Abstract. Open pit mining is a resource-intensive process, since the profitability of the business is strongly related to the magnitude of the tonnage extracted. Therefore, it is necessary to use large equipment to extract and transport material from the mine. The decision of what and how much equipment to buy and where it should be operating, strongly impacts the value of the mining business. Generally, the estimation of the material movements is made using various planning software based on a movement capacity of certain material in tonnes extracted per day, which not necessarily represents what happens in the operation.

In this paper, a multi-objective optimization model is presented, which aims to determine the optimal shovel-bench allocation for the operation and also show that the equipment allocation obtained can estimate a production plan that fits the reality better than the conventional methodologies. Several operational factors and restrictions are considered including mechanical availability, utilization, space restrictions and precedence among benches of different pushbacks. Divers experiments were carried and for all cases, fluctuations were obtained in the tonnages extracted per month that were not predicted in the mine plan with a production defined by a constant flow of tons. The presence of these fluctuations can indicate that a greater number of variables can still be considered within the planning that could allow building of more robust plans to guarantee a reliable operation in terms of production and feed to the plant.

Keywords: Mine Planning., Equipment, Assignment, Production Plan, Optimization.

1 Introduction

1.1 Motivation

Mine planning is a process in which, among other things, the volumes of material to be extracted at a given time and with a specific destination are defined. The decision on the material movements is a complex process with several stages which are present from the beginning of a project through selecting the blocks to be extracted in a block model to the last stage of the bench. However, the moment in which material extraction is conceptualized occurs in intermediate stages to those mentioned.

Material transport is a highly important process in the mining business, mainly due to the high costs associated with it [1]. This is a consequence of: a large number of equipment involved in the operation, both for loading and transport; a high degree of mechanization and, above all, the presence of this process throughout the life of the mine.

Removing the rock from the mine is not the same as extracting blocks in a model. Consideration should be given to aspects related to the mechanical equipment that will be used to extract the material and equipment that will move it from the mine to its destination. The decision about which equipment to use, how many and what type to buy and where it should be operating has a strong impact on the value of the mining business. For these reasons, a model was created to determinate and evaluate various scenarios of material handling with different type and number of shovels.

The optimization of the equipment is strongly related to the optimization of the pit: improving the selection of equipment decreases mine costs and increases productivity, which influences the planning and design of pit limits [2]. It is possible to separate the planning process into levels, according to the characteristics of the decisions made [3]:

- *strategic:* refers to the selection of exploitation methods, mine capacity, processing and, in general, to the estimations of mining reserves. The main objective of strategic planning is to synchronize the market with the available resources and the mission of the company.
- *tactics:* corresponds to the specification of the processes to be carried out throughout the life of the mine, such as long-term production programs and programming models for the use of equipment and processing plants. Tactical or conceptual planning determines the way to achieve the objective previously established by strategic planning. Its´s result is the mine plan, which defines how the resources will be extracted.
- *operational:* involves the delivery of the material to its destination (for example using trucks) or the change of location of a shovel. The operational processes and indexes resulting from the mining plan are included in the operational planning.

The objective of this work is the creation of a methodology to support the development of an allocation plan for loading equipment in an optimal way that allows compliance with a production plan. In this way, a bridge between the level of tactical planning with the operational can be created. A base production plan from a real mine was used to compare the results obtained.

1.2 Related Work

Over the years, many techniques associated with operations research have been developed to assist in decision-making in mining. Temeng, Otuenye and Frendewey (1997) proposed an equipment dispatch system. Their work describes a model, which main limitation is the exclusion of the short-term production and the location of the shovels. Gurgur, Dagdelen and Artittong (2011) propose a linear optimization problem that provides the location of trucks and shovels to minimize deviations from the progress of the mine provided by strategic planning. However, it only considers the long-term information, leaving aside costs of production and movement of the equipment.

S. P. Upadhyay & H. Askari-Nasab (2016) propose a model that includes both long-term and short-term objectives, as well as movement costs and allocation of loading equipment and trucks. However, it performs this assignment based on the sequencing obtained in a previous stage using a clustering and scheduling algorithm.

Linear optimization applied to the optimization of the mining operation reveals the following:

1. the allocation of the shovels has not received enough attention in the literature.
2. the models do not present communication between strategic planning and production in the operation.
3. the models depend on multiple stages to find a solution.
4. the sequencing of the extraction in many cases is an input for the assignment of shovels and trucks.

The model proposed in this paper seeks to incorporate the aforementioned points (single stage optimization, communication between strategic planning and production, the sequencing of the extraction as result of the shovel assignment) into the optimization problem to obtain a one-stage solution that is interpreted as planning at the operational scale and which leads to meeting long-term goals.

1.3 Problem Statement

Data from a real mine operation were used to validate the model. The name remain confidential at the request of the suppliers. The optimization problem was addressed using the Python programming language.

The data used included:

- the material movements per period determined by the long-term plan, as well as the destinations associated with each block, without modification
- the pushbacks (without modification) and the sequence of extraction of the blocks conditioned at the level of years as it is considered in the block model with the solution delivered by the optimization problem on a monthly scale.
- the extracted mineral was quantified in proportion to the *extracted tonnage* and the *mineral/total tonnage* ratio of each bench.
- equipment operational and investment costs as well as equipment characteristics (obtained from catalogs).

2 Methodology

A review of the data obtained from the mine site was performed to determine the mineral depletion throughout the mine life. Since the assignment of loading equipment to the particular workplace is sought, a catalog of equipment was used to obtain data regarding equipment characteristics, costs and capabilities, among others. The construction of the optimization model that determines the allocation of the loading equipment to the production pushbacks over time to minimize production costs was made.

The equipment assignment was made manually as well as using the model to measure the differences. The results obtained using modelling were compared with the manual assignment and the base production plan.

3 Optimization Model

Within the dynamics in which the loading equipment operates in a mining operation, numerous factors that affect productivity were considered:

- mechanical Availability.
- operational factors.
- available operating space.
- precedencies between bench of the same and different pushbacks.
- feed requirements to the processing plant.
- production goals.
- cost of production and acquisition of equipment.
- productivity of the equipment.

3.1 Variables

The decision variables for the model made according to Equations 1 through 6:

$$x_{pbft} = \text{percentage of period } t \text{ that shovel } p \text{ is in bench } b \text{ of phase } f \quad \textbf{(1)}$$

$$\bar{x}_{pbft} = \begin{cases} 1, \text{if the shovel } p \text{ is in bench } b \text{ of phase } f \text{ of period } t, \\ 0 \text{ if not} \end{cases} \quad \textbf{(2)}$$

$$z_{bft} = \begin{cases} 1,, \text{if bench } b \text{ of phase } f \text{ is active in the period } t, \\ 0 \text{ if not} \end{cases} \quad \textbf{(3)}$$

$$\bar{z}_{bft} = \begin{cases} 1, \text{if bench } b \text{ of phase } f \text{ was extracted in period } t \text{ or later}, \\ 0 \text{ if not} \end{cases} \quad \textbf{(4)}$$

$$w_{pt} = \begin{cases} 1, \text{if the shovel } p \text{ is bought in period } t \text{ or earlier}, \\ 0 \text{ if not} \end{cases} \quad \textbf{(5)}$$

$$\bar{w}_{pft} = \begin{cases} 1, \text{if the shovel } p \text{ is assigned to phase } f \text{ in period } t, \\ 0 \text{ if not} \end{cases} \quad \textbf{(6)}$$

Equation (1) is the decision variable that quantifies the production associated with each equipment in operation while the variables (2) to (6) are used to regulate the precedencies and assignments of the equipment to the operation.

3.2 Objective Function

The final objective function is given by equation (7):

$$min: \sum_t K_p \cdot w_{pt} \cdot FD_t + \sum_{p,t,f,b} C_p \cdot x_{pbft} \cdot Q_p \cdot D_p \cdot Fll_p \cdot FO_{bf} \cdot T_t \cdot FD_t \quad \textbf{(7)}$$

The objective function of the model (Equation 7) seeks to minimize the costs associated with the acquisition of loading equipment (K_p) and the operational cost based on the extracted tonnage (C_p). The tonnage extracted in each period is expressed by the multiplication of the capacity per hour of the equipment (Q_p) by the corresponding operational factors (D_p: mechanical availability, Fll_p: filling factor, FO_{bf}: utilization), the fraction of the period the equipment is operating (x_{pbft}) and the duration of the period (T_t). The values are discounted in time using the discount factor (FD_t) that corresponds to the duration of the period. In this way you can use the model with periods of days, weeks or months.

The variables are subject to different restrictions to ensure that the solution obtained represents the operation in the best possible way. In particular, the restrictions indicate that:

- variable (1) cannot exceed the duration of the assigned period;
- the movement of material associated with the variable (1) must meet the productive goal for the end of the total periods;
- the equipment can only be assigned if the variable (5) indicates that the equipment is available;
- to begin work on a new bench all the material of the predecessor benches must be extracted, which is indicated by the variable (4);
- the precedencies are given by the sequence of benches of the same phase and different pushbacks according to operational criteria;
- to assign working time to a bench, the bench must be marked as active according to the variable (3) and with an equipment assigned according to the variable (2);
- in order to assign an equipment to a bench, space must be available for its entry, which is entered as an input for each bench and is updated period by period according to the material extracted in that sector;
- the total extracted mineral must comply with the requirements of the plant;
- there is a limit of assignment of the same equipment to different pushbacks of work in each period.

4 Model Inputs

The model seeks to generate an equipment allocation plan for each month of a year of production. The optimization is applied to a long-term plan (Fig. 1) obtained with the software Whittle, which considers a constant production rate for each period. By incorporating the model developed at the production bench scale, the tactical plan and the operational plan can be linked. Data associated with the equipment, benches to be extracted within the period of 4 years and operating parameters, specified in Sections 4.2 and 4.3 were considered.

4.1 Material to be extracted

The material to be extracted associated with each bench is entered into the model. The data entered also includes: the phase to which it corresponds, the number of the bench (growing with depth), the total tonnage to be extracted, the tonnage of ore present in the bench and the revenue per ton that presents its extraction.

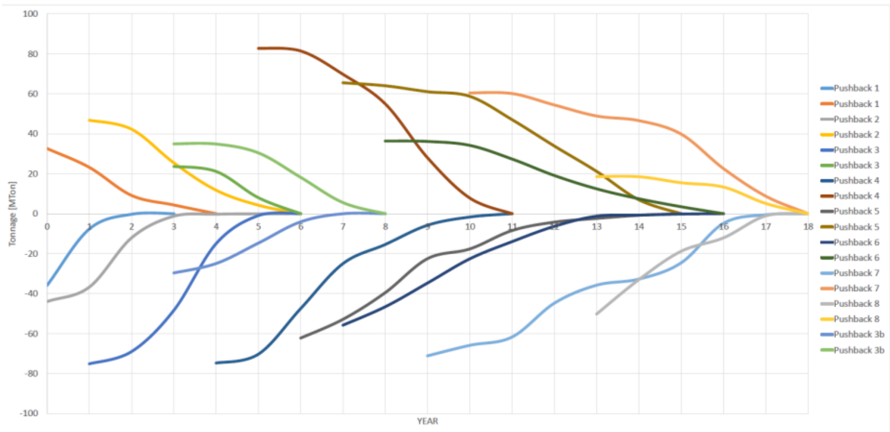

Fig. 1. Graph of depletion of material for the whole life of the mine. In the upper part of the horizontal axis are the mineral tonnages and in the lower the sterile. Year 4 was the basis for the study.

4.2 Loading Equipment

The model sought to complete the production plan with the total extraction of the material entered in each bench; it made decisions regarding shovel selections to minimize costs. The information required for each equipment was: an associated name (P0X), the cost of acquisition, the capacity in tons, the utilization and fill factor in percentage and the operational cost in dollars per hour.

Given the way in which the model was built it is necessary to express the operational cost of the equipment in USD / hour. To achieve this, the following assumptions will be considered:

- the fleet of trucks allows the blades to be saturated.
- each truck will be filled with three buckets of the shovel that loads it.

The first assumption was made to express the productivity of the shovel in relation to itself without depending on the cycle of the transport equipment while the second was done to express productivity directly from the bucket capacity of each shovel. This last assumption is quite strong and works well when the shovels chosen for production do not differ so much in size, but in the case of a considerable difference, the assumption implies that the truck fleet must be different in order for the condition of cargo to be fulfilled.

4.3 General parameters

Data associated with the mining operation: the ore tonnage requirement for the plant's feeding, the discount rate, the bench height and the density of the material were incorporated within the model.

5 Results

5.1 Model Simulations

To facilitate the representation and form in which the results are presented, the results referring to the manual allocation of equipment and that obtained with the model are displayed simultaneously. The following scenarios were considered:

- case A: Manual assignment of equipment selecting the lowest cost per ton.
- case B: Manual assignment of equipment selecting those with the lowest investment.
- case C: Assignment of equipment according to model considering lower investment equipment.
- case D: Assignment of equipment according to model.
- case E: Assignment of equipment according to model with restriction of area.

Scenario D resulted in the lowest global cost because the model did not have restrictions associated with equipment usage nor with space restrictions. Table 1 shows the equipment assignment and the percentage difference in resulting cost between each exercise with exercise D. Despite both scenarios B and C use the same loading equipment the Case C manages to obtain lower costs. This reveals the great impact of the allocation of equipment and the sequence of extraction on costs and how a better strategy for the use of equipment can help reduce the costs of the mine.

Between the cases C and D, it can be seen that by giving the model freedom to choose the equipment to be used, it selects other equipment than equipment chosen manually, thus achieving the production goal in the same way. The difference between case A and B indicate that for the evaluation period of 1 year, the operational cost less relevant than the acquisition cost. This may be reversed when several years of operation are evaluated while the large tonnage to be moved allows the operational cost to become an important part of the total costs.

Table 1. Type and quantity of equipment selected for each scenario: the percentage difference in costs obtained in relation to case D.

Scenarios	Selected Equipment	Δ% to scenario D
A	2 P01 – 2 P12	+162.2
B	2 P01 – 2 P04 – P05	+42.4
C	2 P01 – 2 P04 – P05	+14.3
D	2 P01 – 2 P02 – 2 P03	-
E	2 P01 – 2 P03 – P04	+0.6

Fig. 2 shows the production plan generated by the assignment of equipment from scenario E. It can be seen that the material movements have a ramp-up during the first periods before stabilization; this is due to the area restrictions imposed on benches. It is also possible to notice variations in the tons of waste and ore extracted from one month to another. This is because production is conceived as the result of a particular equipment assigned to a specific sector and not as a constant flow of tons. In this way the model manages to capture and better represent what happens in the operation allowing to create more feasible plans.

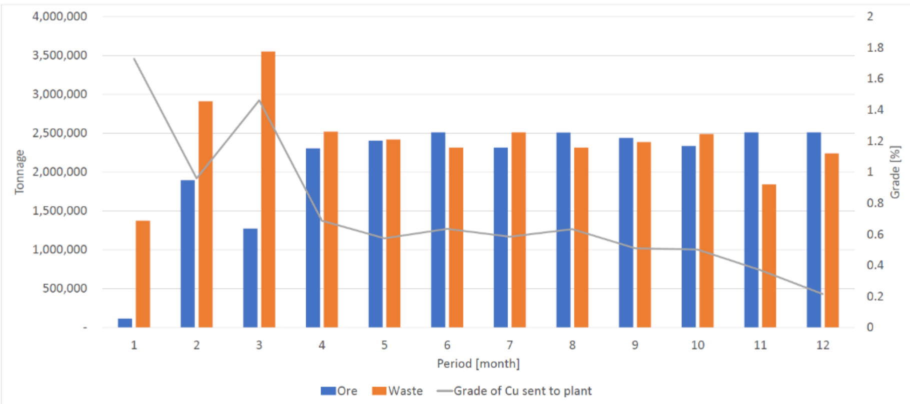

Fig. 2. Production plan for Scenario E.

5.2 Scenario E versus Long Term Plan

The comparison of the results obtained with Scenario E with the production plan obtained in the Long Term planning is shown in Fig. 3, where it can be seen that, for the ore in Pushbacks 2 and 4, the extraction was slower than estimated according to the Long Term plan while Phase 1 does it faster after period 4 (the line graph obtained by the model goes below the Long term line). This may mean that when the plan was put into operation, there were problems with the mineral feed to the plant, especially in the first 4 months.

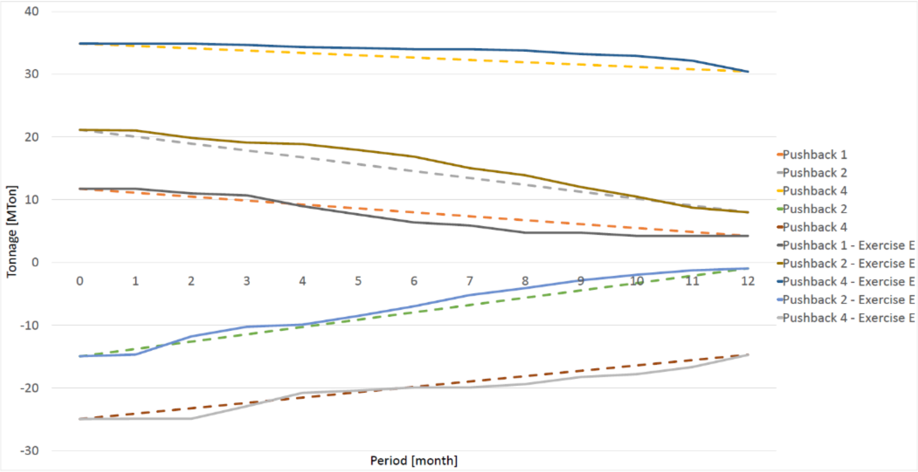

Fig. 3. Material depletion comparison of scenario E with the initial plan. Base case is represented by dotted line while model by the continuous line. Only selected pushbacks are presented given the difference of order of magnitude between the movements among pushbacks.

6 Conclusion

The developed methodology allows to obtain an assignment for a fixed fleet of shovels to the workplaces that meets operational and production restrictions for the short and medium terms. It provides a guide for the planner, which saves time and resources. The model also allows to evaluate different fleet investments options, in the case of greenfield operations, based on their productivity in different work sector.

The consideration of the movement capacity associated with real equipment instead of a defined daily movement allows obtaining a plan that is better adjusted to what actually happens in the mining operation, allowing to estimate revenues and costs more accurately as well as determining the vulnerabilities in the plant feed.

The model also delivers an operational plan that complies with the projected production in the long-term plan, serving as a tool capable of incorporating the characteristics of the mining operation and obtaining a sequencing that serves as a bridge between the different levels of planning

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