Methodology for a dump design optimization in large-scale open pit mines

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Abstract: Modern large-scale open pit mines move hundreds of thousands of tonnes of material daily, from the loading sources to the destination zones, whether these are massive mine dumps or, to a lesser extent, to the grinding mills. Mine dumps can be classified as leach or waste dumps, depending upon their economic viability to be processed in-place, a condition that has experienced great progress in the last decades and has reconfigured the open pit haulage network with an increase in the number of dumps. Therefore, new methods for dump design optimization are of the highest priority in mine planning management. This paper presents a methodology to model and optimize the design of a dump by minimizing the total haulage costs. The location and design of these dumps will be given mainly by the geological characteristics of the mineral, tonnage delivered, topographical conditions, infrastructure capital and transportation costs. Spatial and physical design possibilities, in addition, provide a set of parameters of mathematical and economic relationship that creates opportunities for modelling and thus facilitates the measurement and optimization of ultimate dump designs. The proposed methodology consists of: (1) Formulation of a dump model based on a system of equations relying on multiple relevant parameters; (2) Solves by minimizing the total cost using linear programming and determines a “preliminary” dump design; (3) Through a series of iterations, changes the “preliminary” footprint and creates the ultimate dump design.
footprint by projecting it to the topography and creates the ultimate dump design. Finally, an application for a waste rock dump illustrates this methodology.

Subjects: Engineering Project Management; Mining Engineering; Planning & Design; Sustainable Mining

Keywords: mine planning; dump design; open pit; optimization

1. Introduction

Three major destination groups, characterized by a cut-off grade criteria and ore type, represent the places in the mine where the material receives specific treatment after its delivery from the pit: leach dumps, waste dumps and mill (Hustrulid, Kuchta, & Martin, 2013). Dump leaching facilities are built to receive and treat low-grade ore by the use of solution agents, while waste rock dumps store uneconomic material. Dump leaching technologies have developed over the last decades, allowing the mining industry to build larger and higher dumps faster than ever (Smith, 2002), since they have proven to be an efficient method of treating oxide and sulfide ores, an attractive way to treat large low-grade deposits (Dorey, Van Zyl, & Kiel, 1988). As a result, an increase in the number of dumps, which are the most visual landforms left after mining (Hekmat, Osanloo, & Shirazi, 2008) has reconfigured the open pit mines network organization and landscape.

Contributions to this progress have come from the mineral and metallurgical processing field (hydrometallurgy), geo-synthetics, slope stability, and best construction practices of solution collection systems, notably prompted by environmental requirements. Researchers and slope stability practitioners have achieved extensive progress and expertise in the areas of geotechnical engineering (Ureel, 2014), establishing that a thorough knowledge of factors affecting the dump stability must be properly considered at the design stage (Upadhyay, Sharma, & Singh, 1990); especially the floor dip and foundation strength, from which the dump stability is highly sensitive (Rosengren, Simmons, Maconochie, & Sullivan, 2010). Along with the geotechnical, several other attributes, such as the topography, final pit limit, haul road distances, landform, among others, have been ranked, subjectively and objectively, by multi-criteria decision methods with the specific aim of selecting the dump location (Hekmat et al., 2008). However, few studies have attempted to integrate the safety and environmental factors with the haulage costs in order to elaborate a strategic plan for the location and ultimate dump design, whether it is leachable or for waste. The general practice for a dump design consists on the availability principle (Li, Topal, & Williams, 2013) driven by the short-term planning needs to make production by seeking the shortest haul to the dump, although this approach can be detrimental to the long-term scheduling and dump development.

In large-scale open pit mines, the mining process is rather complex and often involves different run-of-mine (ROM) ore and waste material treatment downstream. Appropriate areas to place these large amounts of material are limited and their selection and design must serve the environmental factors and economic goals of the long-term mine plans. Normally, construction of the leach or waste dumps results by creating a footprint base via deep dumping and subsequently, ramping up a determined lift height to accumulate the ex-pit material.

In designing the dump, there are many ways to assign values and combine the different geometric and size parameters while respecting the safety and environmental constraints. The total tonnage capacity required can have as many geometrical representations as its limitations allow. In this situation, building a mathematical optimization model is the best option to interrelate certain key variables and the first approach to calculating the values that seek to maximize the satisfaction of a linear programming objective. As most of the dumps are emplaced on irregular topographies, a second approach has to contrast the values got by the generalized model and correct them, if necessary, by a series of successive iterations and projections to the field.
This paper presents a methodology to optimize the ultimate dump design in a mining operation by minimizing the unit haulage cost using a linear algorithm and subsequent iterations on variables such as the footprint base, number of lifts and haulage distances from the toe of the ramp to the dynamic dumping point. Figure 1 briefly illustrates the process. This methodology applies to dumps receiving a single material target as it is usual in large-scale open pit mines; hence, there is no need for any special material blending or encapsulation, as the models proposed to handle waste rock dumping causing acid mine drainage (Li et al., 2013). In addition, an example illustrates the methodology.

2. Dump design considerations

A mine dump can be defined as a massive structure formed by placing large amounts of material in lifts of a restricted vertical expansion that laid one on top of each other and form a stable slope at the angle of repose. A dump so formed, however, needs a horizontal base at first, which is built by push dumping material from a certain elevation and levelling off the required footprint area. Generally, this first phase of the dump construction takes the irregular shape of the topography where is placed. Subsequent lift height is constant, though is restricted to prevent shear stresses on the foundation and is a factor to control consolidations and permeability variations (Zanbak, 2012). The total height of the dump is also restricted by formation mechanism (Zhang et al., 2014) and carrying capacity limitations (Peng, Ji, Zhao, & Ren, 2013). As in most of the large open pit operations, haulage is performed by heavy trucks, the access to the successive dump lifts is achieved by establishing ramps of a suitable width, super elevation and gradient in order to minimize travel distance and therefore to reduce haulage costs (Figure 2).

In dump designing, costs may be governed by any or all of the following factors:

- Geometry: Usually designed to handle a total capacity throughout the life-of-mine. Overdimensioning can cause underutilization of valuable areas. Under dimensioning can result in the increase of the total haulage distances.
- Operating costs: Costs resulting from fuel, energy, maintenance and labour of the haul trucks.
- Haulage distances: Minimizing the total haulage distance while meeting the required capacity by strategic placing of the ramps, exits, entrances and dumping sequence.
- Stability control: It will define the angle of repose and the nature of the underlying material. Maintaining the stability of the dump may require relocation of weathered rock or material blending, especially if water is present (Russell, 2008).
- If it is a dump leach, a leaching cycle time will define the mining delivery rate and dumping schedule. Ideally, deliveries rate from the mine should match the leaching cycle times of the dump. Otherwise, there is a risk of short cycling and losing on mineral recoveries. In addition, costs of building the leaching facilities are factored in (Kappes, 2002).
- Acquisition of the land permit for dumping purposes as specified by law.
- Environmental factors: costs of implementing and maintaining effective systems to reduce and eliminate loses and contamination. Design considerations for reclamation and closure to maintain long-term stability, erosion control (Piteau Associates Engineering Ltd, 1991) and to avoid re-handling costs (Sommerville & Heyes, 2009).
Although every dump is unique (Zástěrová et al., 2015) and some of its cost maybe be given by its own factors, the above description includes all the general concerns one would have to elaborate the most economical dump design.

3. **Linear programming (LP) formulation of the dump model**

   Formulation of a model where the cost is to be minimized while meeting all the other constraints can be achieved by using Linear Programming (LP). The method optimizes an outcome, such as the lowest cost, in a mathematical model whose requirements are related by linear equations. Linear Programming, as one of the most widely used operations research tools (Wright, 1996), has been largely applied in the mining industry to solve production scheduling problems (Newman, Rubio, Caro, Weintraub, & Kelly, 2010). Then a solver software (AMPL) will produce optimization problems from models and data and will retrieve results for analysis (Figure 3).

   The model is expressed as follows.

3.1. **Sets**

   \[ L_i^n \] = Set of the number of lifts of the dump from lift \( i \) to lift \( n \).

3.2. **Objective function**

   The objective is to minimize dumping costs of the open pit operation by finding the shortest haulage distances for the haul trucks in two round trips: (1) travel along the ramp and (2) travel the flat surface from the crest of the ramp to the lift centroid. Such distances are multiplied by the operating
cost and tonnage dumped at that lift and then divided by the average speeds and haul truck capacity.

\[
\text{Minimise } \sum_{i=1}^{n} \left( T_i \times R_i \times C_i \div S_i \div TC \right) + \sum_{i=1}^{n} \left( T_i \times D_i \times C_i \div S Li \div TC \right)
\]  

(1)

where \( T_i \) = tonnage dumped at lift \( i \); \( R_i \) is the distance of the ramp for lift \( i \) from toe to crest; \( D_i \) is the flat distance from the crest to the lift centroid; \( S_i \) and \( S Li \) are the average speed up/down hill and at flat surface, respectively; \( C_i \) and \( TC \) are the operating cost and capacity of the standard haul truck.

3.3. Constraints

3.3.1. The radius of the base of lift \( i \)
The generalized dump model is formulated within the context of making the most efficient theoretical dump and establishes a circular base which maximizes the use of the property surface and meets the slope angle along its boundaries.

\( r_i \geq 0 \)  

(2)

3.3.2. Ramp distance from toe to crest of lift \( i \)

\[ R_i = h \times i \times \sqrt{\left( \frac{1}{g} \right)^2 + 1} \]  

(3)

where \( h \) = height of lift \( i \) and \( g \) is the grade (%) of the ramp.

3.3.3. Distance from crest to the centroid of lift \( i \)

\( D_i = r_i; \quad i = 1 \)  

(4)

\( D_i = D_{i-1} - \frac{h}{\tan(\alpha)}; \quad i = 2, \ldots, n \)  

(5)

where \( \alpha \) = angle of repose.

The centroid is the best approximation to the average distance travelled by haul trucks until the lift is fully filled as long as the material dumped has uniform density.

3.3.4. Volume of lift \( i \)

\[ V_i = \pi \left( r_i^2 + r_{i+1}^2 \right) \frac{h}{2} \]  

(6)

3.3.5. Tonnage of lift \( i \)

\[ T_i = V_i \div 1F \]  

(7)

where TF = Tonnage factor m³/tonne of the broken rock.

3.3.6. Total tonnage required or stockpile capacity

\[ \sum_{i=0}^{n} T_i \leq TT \]  

(8)

where TT = Total tonnage capacity required.

3.3.7. Non-negativity

\( R_i, D_i, V_i, T_i \geq 0; \)  

(9)
4. Model implementation

4.1. Field input data
The proposed dump model concept has been applied to optimize the ultimate design of a waste dump in an open pit copper mine. Mine production plan shows that the East pit will deploy uneconomical waste material in an approximate amount of at least 515 million tonnes during its 15 years life-of-mine operation. Land properties extend its limits on the East side over 6 Km² of surface available. The results of the study will show the areas to conduct hydrological and hydraulic analyzes to estimate precipitation, runoffs and the presence of aquifers. As the waste material deployed will remain un-leached, its density and angle of repose will correspond to a broken and un-saturated (dry) material. Table 1 presents an overview of the input parameters used for the dump model optimization. Round-travel speeds are given by the technical specifications of the equivalent fleet truck in route; and operating costs include maintenance, fuel consumption, and labor. Ramp grade and lift height comply with the internal mine haul road design manual of the mine operation.

4.2. Linear programming coding and solving
Using AMPL (Fourer, Gay, & Kernighan, 2003) and CPLEX (2016) the model has been codified to solve the objective function, variables, sets of inequalities and constraints. The data-set is accessed from Microsoft Access. The program is executed on a computer of 2.80 GHz and 32 GB installed memory RAM, and the results are displayed for base radius, the number of lifts, tonnes, volume, and distances. The optimal solution is found for a six lifts dump to optimize the objective function to a minimum of $42,713,023.2. The result is presented for the total tonnage and costs-by lift, volume, and summary of the ramp and flat travel distances. Table 2 shows the optimization output. It should be noted that these results give us only a first idea of the total costs and values of the main variables. The design is still subject to adjustments to be made during the engineering and construction phases of the project. Likewise, be noted that the case studied does not include in its costs the use of geomembranes to isolate the dump due to state regulations regarding waste overburden that was not and will not be subject to leaching processes.

The value of the optimal base radius \( r(0) \) equal to 1,170 m. The ramp distance between the toe and crest of every lift is 100.5 m (a berm of 0.5 m is left at every lift perimeter). A particularity of dumps is that the haulage cost increases considerable from lift to lift (For instances, from lift 1 to lift 2, it increases 12%) while the number of tonnes is reduced by only 2% for the same movement from lift 1 to lift 2. The sum of the accumulated total tonnes gets the minimal required capacity, but leaves the dump open for further unplanned deliveries on top of the lift 6 level. Furthermore, the optimal radius \( r(0) \) equal to 1,170 m is then compared with different cases of base radius values in order investigate the effect of the number of lifts and base area on generated haulage costs as shown in Figure 4. The \( \Sigma \)Total cost curve indicates that a wide base dump area with less than four lifts yield more expensive

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Details</th>
</tr>
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<tbody>
<tr>
<td>Operating cost (of a truck)</td>
<td>280 $/h (operating, maintenance, labor and fuel)</td>
</tr>
<tr>
<td>Lift height</td>
<td>10 m</td>
</tr>
<tr>
<td>Speed uphill</td>
<td>17.7 km/h</td>
</tr>
<tr>
<td>Speed downhill</td>
<td>27.4 km/h</td>
</tr>
<tr>
<td>Speed level surface</td>
<td>45 km/h</td>
</tr>
<tr>
<td>Grade of ramp</td>
<td>10% gradient</td>
</tr>
<tr>
<td>Angle of repose</td>
<td>36.9°</td>
</tr>
<tr>
<td>Density – tonnage factor</td>
<td>0.467 m³/tonne</td>
</tr>
<tr>
<td>Total tonnage – capacity</td>
<td>515 Million Tonne(^{a})</td>
</tr>
</tbody>
</table>

\(^{a}\)Minimum.
plan scenarios. However, cost decreases when the number of lifts varies between five and seven. After eight lifts and smaller base areas, the haulage cost increases gradually.

4.3. Iterative design process

Although linear programming optimizes the economic stockpile plan, it achieves this by assuming a regular inward dump shape, but does nothing regarding the irregular topography to be filled in. A process of iterative design overcomes this drawback through the use of calculated areas of interest, prioritizing the base area found by the linear programming and building successive dump structures until meeting the tonnage capacities. The first design 01 is framed inside a limited area—limit 01—given by the optimum radius $\pi r^2$ which equals 4,297,212 m$^2$. Table 3 summarizes the main characteristics of the three dump designs.

![Figure 5](image-url) Figure 5 shows the three iterative limits. The innermost areas are reduced by eight percent while retaining the same west side and horizontal axis. This gradual area reduction of eight percent is done with the purpose of creating a design that best meets the required capacity. Here, the reduction has an equal percentage value, but it can also be variable, depending on whether the LP result was over or underestimating. For the three limit areas, the west side and the horizontal axis are the same to keep the shortest distance from the open pit exit. For operational convenience, property limits have been made squared, although the dump design maintains smoothed boundaries.

![Figure 4](image-url) Figure 4. Minimum costs optimization results.
The southern part of the dump is bounded by high elevated hill contours. The existing ground topography will require subgrade preparation and fine over liner fill. Also, perimeter berms will be constructed at each lift to prevent the runoff of stormwater. Figures 6–8 represent the iterated design of the dumps 01, 02 and 03 respectively.

### Table 3. A summary of the three dump designs

<table>
<thead>
<tr>
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<th>Dump 1</th>
<th>Dump 2</th>
<th>Dump 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Side (m)</td>
<td>2,073</td>
<td>1,911</td>
<td>1,762</td>
</tr>
<tr>
<td>Base area (m²)</td>
<td>4,297,212</td>
<td>3,652,630</td>
<td>3,104,735</td>
</tr>
<tr>
<td>Side reduction (%)</td>
<td>-</td>
<td>0.92</td>
<td>0.92</td>
</tr>
<tr>
<td>Number lifts</td>
<td>6</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Deep dump (10⁶ x tonne)</td>
<td>272.9</td>
<td>267.7</td>
<td>238.4</td>
</tr>
<tr>
<td>Lift dump (10⁶ x tonne)</td>
<td>265.5</td>
<td>247.9</td>
<td>262.2</td>
</tr>
<tr>
<td>Total dump (10⁶ x tonne)</td>
<td>538.4</td>
<td>515.6</td>
<td>500.6</td>
</tr>
</tbody>
</table>

Figure 5. Three iteration limits for dump design.

Figure 6. Dump design 01–6 lifts.
Upon iteration of the design process, the total tonnage for each dump is calculated (see Table 3), which determines that Dump 02 meets the required minimum capacity and is, therefore, the optimal design in the economic and operational aspect. Dump 01 and Dump 03 are over and under dimensioned and therefore are discarded as solutions. Notice that the base area calculated by the linear programming output corresponds to Dump 01, but when projected against the topography increases its tonnage capacity and makes it necessary to reduce the base area by eight percent to run the next design option (Dump 02). The methodology ends with the third iteration that provides insufficient tonnage capacity.

5. Conclusions
Waste and leach dumps must be subjected to in-depth study from the start of the mining project since they are among the most significant costs for the mine operation, and therefore their designs must be properly located and optimized. Traditionally, dumps have been intuitively sized and placed driven by short-term objectives, but this traditional approach, in the long term, results in under or overutilization of the mine surface and longer distances traveled by haul trucks. The present article outlines a method where a theoretical dump model is built based on geometrical and economic relationships of its main parameters, an LP algorithm is formulated as an optimization problem where
the objective function minimizes the total haulage costs and the base dump radio and lifts number are defined as variables, solved and used to create alternative dump designs through successive iterations. Finally, the methodology compares and selects the ultimate dump design that best meets the requirements. The proposed methodology differs from the traditional approach in its orientation towards the economic value of the different combinations of the base area, lifts number and projection to the field that makes the optimal dump design.

This paper presented an application from an actual waste dump in an open pit copper mine. The LP model is prepared to minimize haulage cost while handling a required tonnage capacity and solved. Results showed that the larger the footprint base, the higher the haulage cost until the curve reaches an inflection point (lowest cost) where the curvature changes. Afterwards, haulage cost increases slightly if the footprint area is reduced. Proposed designs are built iteratively by reducing eight percent the previous area until getting the ultimate dump design.

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