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Methodology for a Dump Design Optimization in Large-Scale Open Pit Mines

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Abstract: Dump design and scheduling are critical elements to effective mine planning, especially if several of them are required in large-scale open pit mines. Infrastructure capital and transportation costs are considerable from an early stage in the mining project, and through the life-of-mine as these dumps gradually become immense structures. Delivered mining rates, as well as certain spatial and physical constraints, provide a set of parameters of mathematical and economic relationship that creates opportunities for modelling and thus facilitates the measuring and optimization of ultimate dump design by using programming and empirical techniques while achieving economic objectives. This paper presents a methodology to model and optimize the design of a mine dump by minimizing the total haulage costs. The proposed methodology consists on: (i) Formulation of a dump model based on a system of equations relying on multiple relevant parameters; (ii) Solves by minimizing the total cost using linear programming and determines a 'preliminary' dump design; (iii) Through a series of iterations, modifies the 'preliminary' footprint by projecting it to the topography and creates the ultimate dump design. Finally, an example application for a waste rock dump illustrates this methodology.

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

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1. Introduction

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. 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 [1]. 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. Researchers and slope stability practitioners have achieved extensive progress and expertise in the areas of geotechnical engineering, establishing that a thorough knowledge of factors affecting the dump stability must be properly considered at the design stage [2]; especially the floor dip and foundation strength, from which the dump stability is highly sensitive [3]. 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 [4]. 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.

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 calculate the values that seek to maximize the satisfaction of a linear programming objective. As most of the dumps are emplaced on irregular topographies, a

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second approach has to contrast the values obtained 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 toe of the ramp to the dynamic dumping point. Figure 1 briefly illustrates the process. This methodology applies to dumps receiving a single type of 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 by Yu Li et al. [5]. In addition, an example illustrates the methodology.

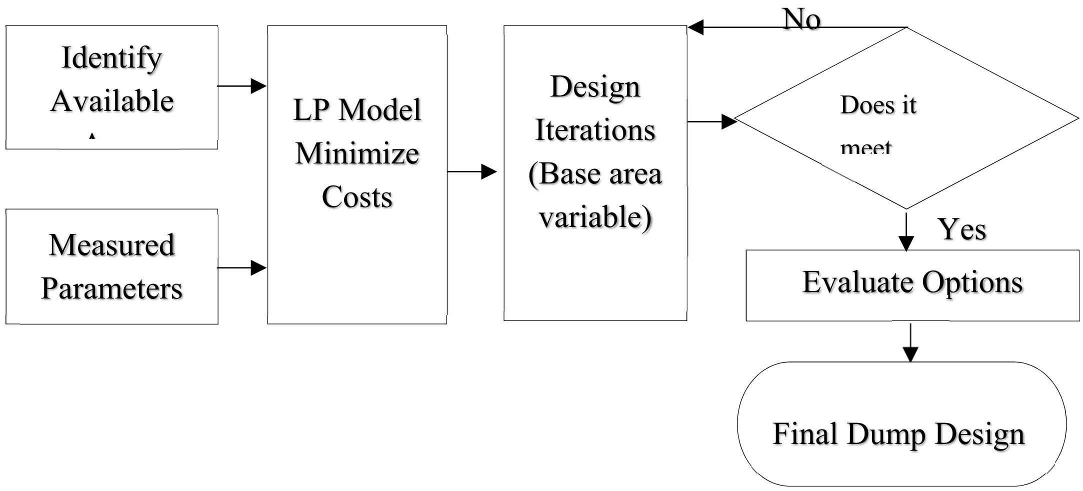

Figure 1. Schematic flowchart of the dump design process.

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 forms 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 lifts' height tend to be constant but are restricted to prevent shear stresses on the foundation and is a factor to control consolidations and permeability variations [6]. The total height of the dump is also restricted by formation mechanism [7] and carrying capacity limitations [8]. 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 stablishing ramps of a suitable width, super elevation and gradient in order to minimize travel distance and therefore to reduce haulage costs.

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. Over dimensioning can result in underutilization of valuable areas. Under dimensioning can result in 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 [9].
- 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.

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- 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 in order to maintain long-term stability, erosion control [10] and to avoid re-handling costs [11].

Although every dump is unique and some of its cost maybe be given by its own factors, the above description includes all of the general concerns one would have in order 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 of the other constraints can be achieved by using Linear Programming (LP). The method optimizes an outcome, such as lowest cost, in a mathematical model whose requirements are related by linear equations. Then a solver software (AMPL) will produce optimization problems from models and data, and will retrieve results for analysis. 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: (i) travel along the ramp and (ii) 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.

$$\text{Minimise} \sum_{i}^{n}(T_i * R_i * C_i \div S_i \div TC) + \sum_{i}^{n}(T_i * D_i * C_i \div SL_i \div TC) \quad (1)$$

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 distance flat distance from crest to the lift centroid; $S_i$and SL_i 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. 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.

$$r_i \geq 0 \quad (2)$$

3.3.2. Ramp distance from toe to crest of lift i

$$\text{Ri} = h * i * \sqrt{(\frac{1}{g})^2 + 1} \quad (3)$$

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

$$Di = ri\,;\; i = 1 \quad (4)$$

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$$Di = D_{i-1} - \frac{h}{Tan(\alpha)} \; ; i = 2, \ldots, n \qquad (5)$$

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

$$\text{Vi} = \pi \; ({r^2}_i + {r^2}_{i+1})\frac{h}{2} \qquad (6)$$

3.3.5. Tonnage of lift i

$$\text{Ti} = \; \text{V}i \; \div \; \text{TF} \qquad (7)$$

Where TF = Tonnage factor m3/ton of the broken rock.

3.3.6. Total tonnage required or stockpile capacity

$$\textstyle\sum_{i=0}^{n} \text{T}i \; \leq \; \text{TT} \qquad (8)$$

Where TT = Total tonnage capacity required

3.3.7. Non-negativity

$$\text{R}i, \text{D}i, \text{V}i, \text{T}i \; \geq \; 0; \qquad (9)$$

4. Model Implementation

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 indicates that the East pit will deploy uneconomical waste material in an approximate amount of at least 515 million tons during its 15 years life-of-mine operation. Land properties extend its limits on the East side over more than 6 Km2 of surface available. Results of the study will indicate more precisely the areas to conduct hydrological and hydraulic analyzes to estimate precipitation, runoffs and 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.

Table 1. Input parameters.

Parameter	Details
Operating cost (of a truck)	280 $/hr. (Operating, maintenance, labor & fuel)
Lift Height	10 meters
Speed Uphill	17.7 km/hr.
Speed Downhill	27.4 km/hr.
Speed Level surface	45 km/hr.
Grade of Ramp	10% gradient
Angle of repose	36.9 º
Density - Tonnage factor	0.467 m3/ton
Total Tonnage - Capacity	515 Million Tons [1]

[1] Minimum.

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Using AMPL/CPLEX the model has been code to solve the objective function, variables and set of inequalities and constraints [12]. 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. The optimal solution is found for a six lifts dump to optimize the objective function to a minimum of 42,713,023.2. Table 2 shows the optimization output. The result is presented for the total tonnage and costs – by lift, volume and summary of ramp and flat travel distances. The value of the optimal base radius r (0) equal to 1,170 meters is then compared with different cases of base radius values in order to investigate the effect of number of lifts and base area on generated haulage costs as shown in Figure 2. The ∑Total cost curve indicates that a wide base dump area with less than four lifts yield more expensive 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.

Table 2. Results for the optimal r (0) = 1,170 meters.

Lift Number (i)	R (i) (meters)	D (i) (meters)	V (i) (10^6 x m3)	T (i) (10^6xTons)	Total Cost (i) (10^6x US$)	∑ Total Cost (10^6x US$)	∑ T (10^6 x Tons)
Lift 1	100.5	1,156.2	42.5	90.9	5.6	5.6	90.9
Lift 2	201.0	1,142.9	41.5	88.9	6.2	11.8	179.8
Lift 3	301.5	1,129.6	40.6	86.8	6.9	18.7	266.6
Lift 4	402.0	1,116.3	39.6	84.8	7.5	26.2	351.4
Lift 5	502.5	1,103.0	38.7	82.8	8.0	34.2	434.2
Lift 6	603.0	1,089.6	37.8	80.8	8.5	42.7	515.0

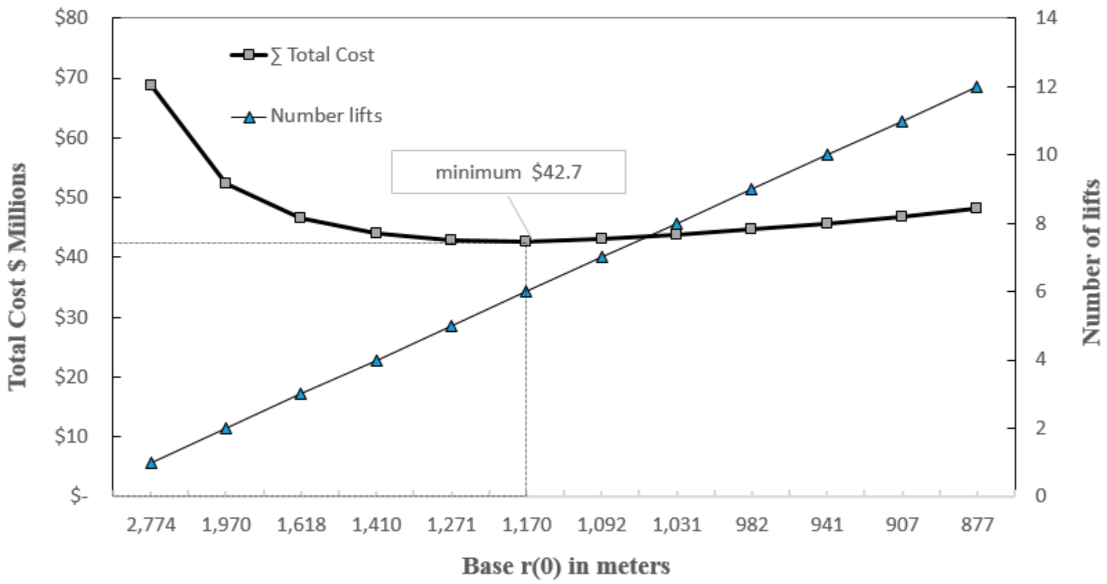

Figure 2. Minimum costs optimization results.

5. Iterative Design Process

Although linear programming optimizes the economic stockpile plan, it achieves this by assuming a regular inward dump shape but does nothing with respect to the irregular topography to be filled in. A process of iterative design over comes this draw back 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 limit area – limit 01 - given by the optimum radius π * r2 (0) which equals 4,297,212 m2. Table 3 summarizes the main characteristics of the three dump designs.

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Figure 3 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 iteratively with the purpose of creating a design that best meets the required capacity. In this case, reduction has an equal percentage value, but it can also be variable, depending on whether or not the LP result was over or underestimating. For the three limit areas, the west side and the horizontal axis are the same in order 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.

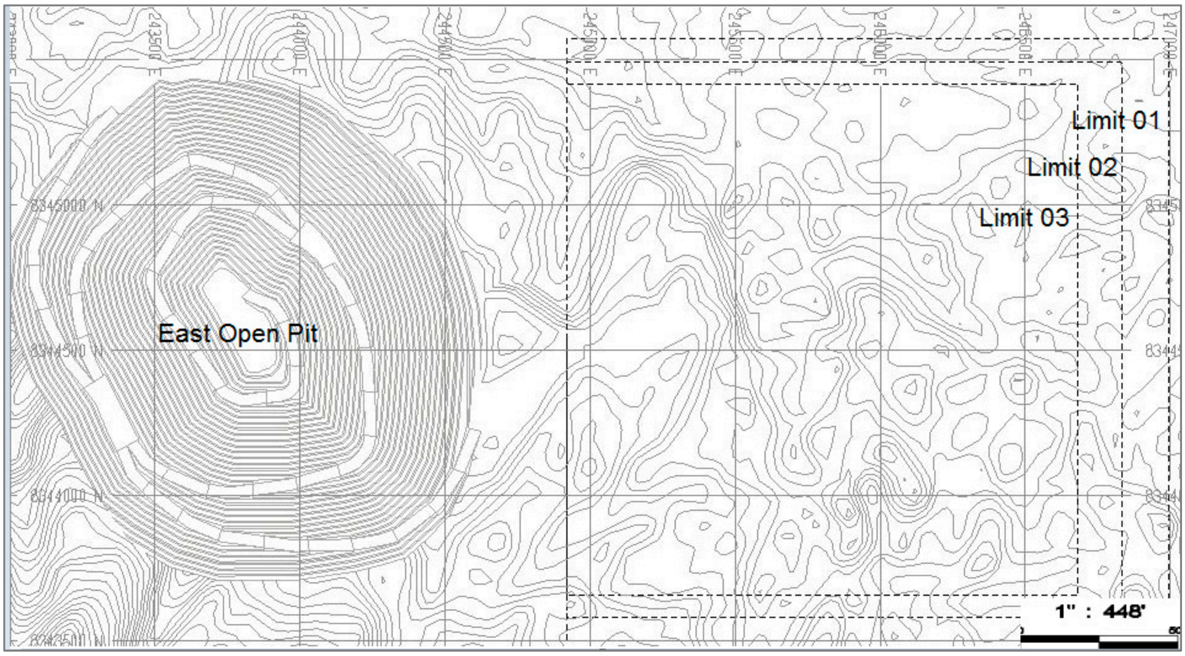

Figure 3. Three iteration limits for dump design.

Southern part of the dump is bounded by high elevated hill contours. Existing ground topography will require subgrade preparation and fine over liner fill and perimeter berms will be constructed at each lift to prevent the runoff of storm water. Figure 4, 5 and 6 represent the iterated design of the dumps 01, 02 and 03 respectively.

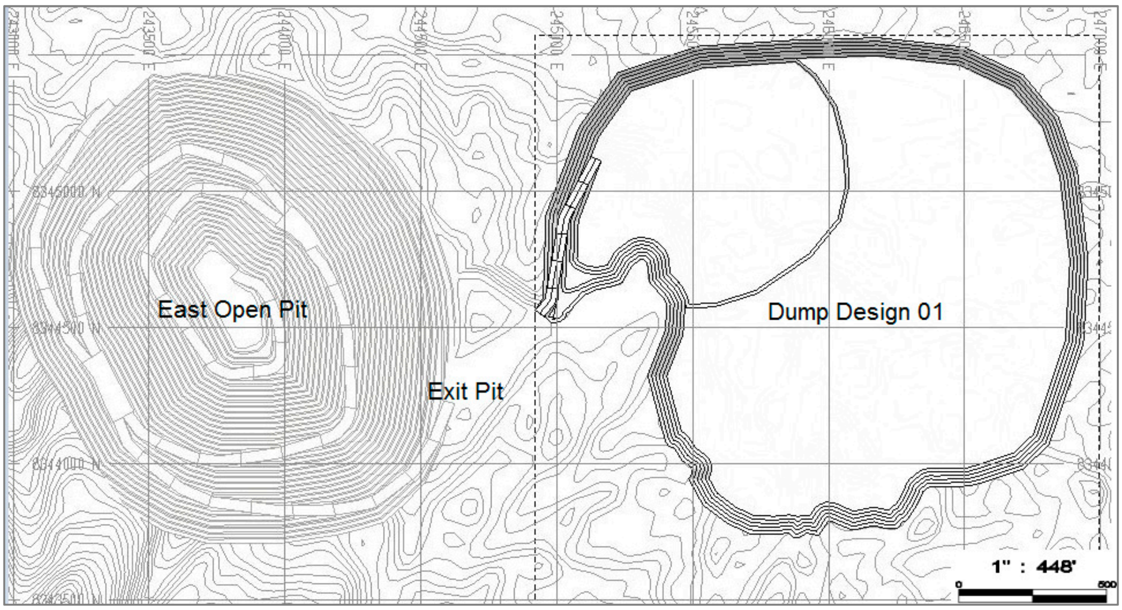

Figure 4. Dump design 01 – 6 lifts

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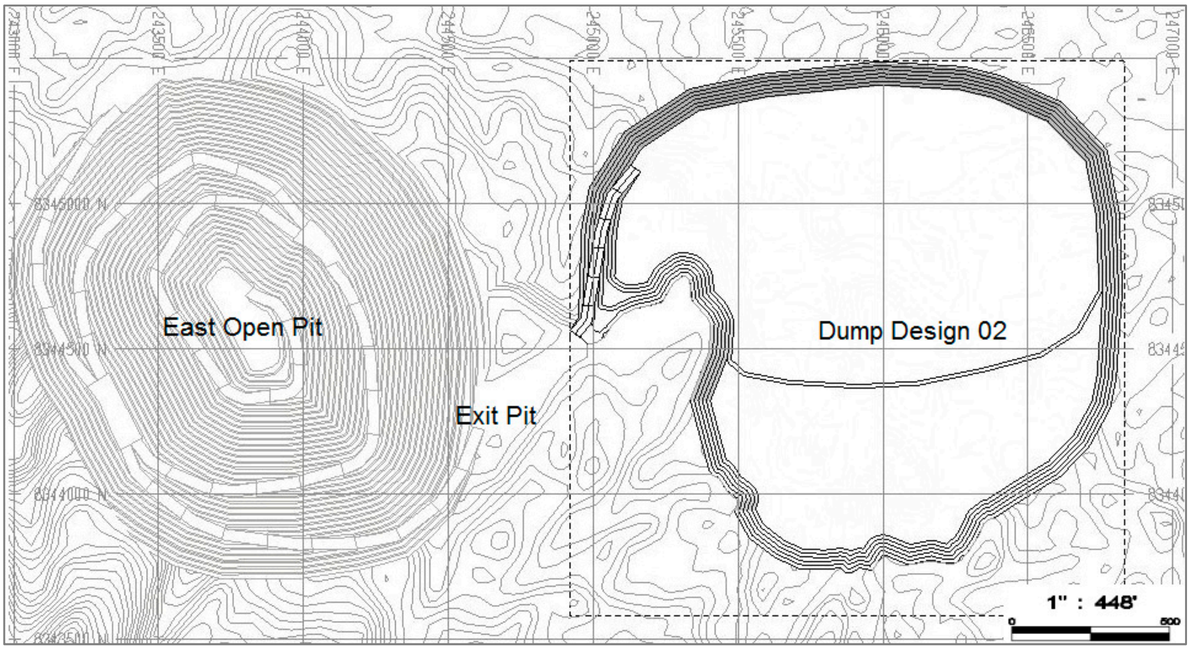

Figure 5. Dump design 02 - 6 lifts

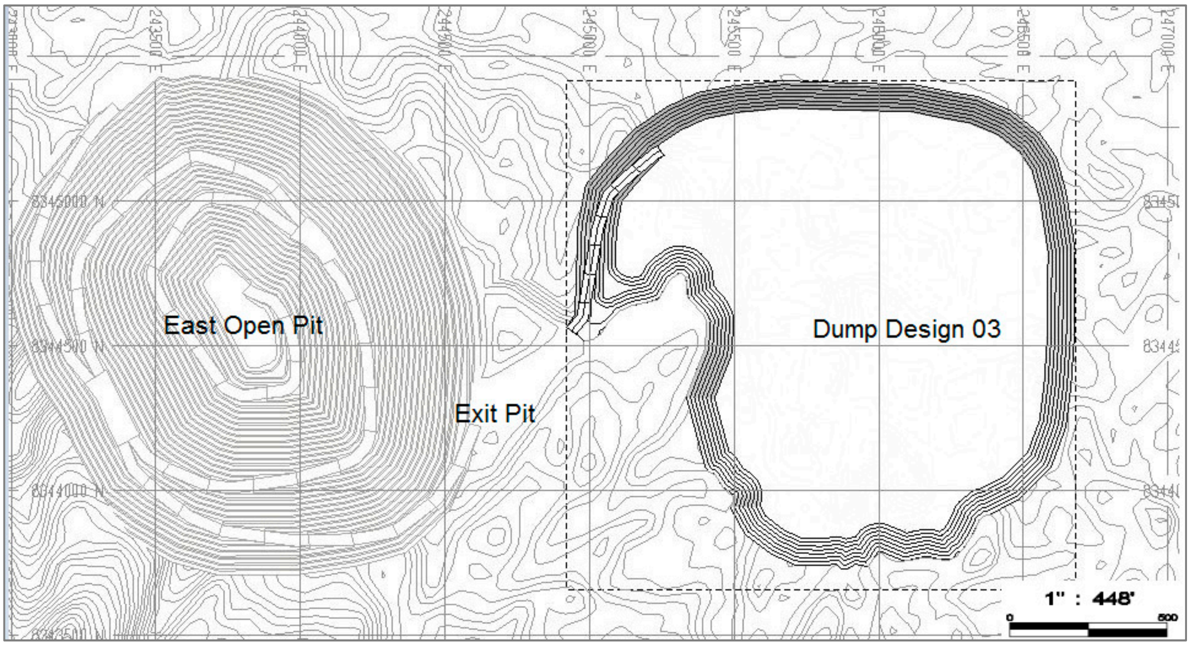

Figure 6. Dump design 03 - 7 lifts

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, respectively, 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). Methodology ends with the third iteration that provides insufficient tonnage capacity.

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Table 3. A summary of the three dump designs.

	Dump 1	Dump 2	Dump 3
Side (meters)	2,073	1,911	1,762
Base area m2	4,297,212	3,652,630	3,104,735
Side reduction %	--	0.92	0.92
Number Lifts	6	6	7
Deep dump (10^6xTons)	272.9	267.7	238.4
Lift dump (10^6xTons)	265.5	247.9	262.2
Total dump (10^6xTons)	538.4	515.6	500.6

6. Conclusions

Waste and leach dumps must be subjected to in-depth study from the very 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 following the availability principle [5], but this traditional approach, in the long term, results in under or over utilization of the mine surface and longer distances traveled by haul trucks. The present article outlines a methodology 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 in order 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 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 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.

Conflicts of Interest: “The author declares no conflict of interest." Jorge Puell Ortiz.

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