

General approach to distribute waste rocks between dump sites in open cast mines

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Abstract

In most surface mining operations, waste rocks are removed from the pit and deposited on adjacent areas. Mine optimization is a key step in the viability of a surface mining project. Definition of approaches for selection of haulage tracks and waste distribution to dumps on the basis of minimizing the haulage cost is one of the main parameters in optimization. Cost estimation, linear programming and decision-making tools are applied in optimization. Cost estimation is performed to obtain the primary information for the linear programming process. In order to ensure high operating efficiency, linear programming has focused on haulage optimization. The waste distribution program is a complex engineering decision of enormous economic significance. This paper presents an approach to minimize transportation costs of waste rocks. Finally, a real mining operation is demonstrated that highlights the advantages of such approach.

Keywords: Cost estimation; Linear programming; Dump site; Waste distribution

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Introduction

The mining industry is characterized by a need for large up-front investment, with low success rates, and long lead times on new projects. It also faces significant back-end costs, when mines are eventually closed, in decommissioning the processing facilities, rehabilitating the sites, dealing with residual environmental issues, and managing obligations to the workforce and local communities. In addition, there are many activities in mining which result in saleable production and also contribute towards the development of the mine, and hence deliver longer term benefits as well.

On the other hand, the mining industry is currently subject to unprecedented demand for its products. Worldwide, the economics of mining is in a state of great change. Sales opportunities and prices are continuing upwards for most commodities. Profits are at levels not seen in decades. Capital is pouring into exploration, development and expansion of resources. Both operational and economic efficiency are needed to make the most out of the opportunities in these frantic times. In order to ensure appropriate capital and production decisions, accurate understanding and forecasting of the cost and revenue structures of operation are crucial.

The success of a mining venture in a competitive market depends on many factors. Combining technical design with economic parameters in a way that will best satisfy the interests of the various stakeholders is the most important problem that a mining company faces in the launch of any project.

Today, mining industry faces an increasing pressure set by stockholders to reduce production expenditures. Mining operations involve the management of waste rock and tailings that must be disposed of in a way that minimizes cost. Companies often have to demonstrate in advance of exploitation both their ability to respect rules during operation and their liability to engineering decision-making based on costs.

The main objective in any commercial mining operation is the exploitation of the mineral deposit at the lowest possible cost with a view of maximizing profits.

Open-pit mining and strip mining are the two preponderant categories of surface mining which account for more than 90% worldwide surface mining production. Production method is the conventional cycle of drilling-blasting-loading-transport. Drilling, loading and transport are day-to-day operations, blasting is done when it is need. These operations are designed in advance and follow the relevant plans, so for every cycle that the new blasting operation yields a face of ore or waste the loading spots and the volume of rocks to be loaded and transported to stockpile and dump are predetermined.

Cost estimation

Optimizing mining projects is a challenging task, as the best answers are rarely known exactly, and are thus based largely on estimates derived from sample data.

Cost estimation, mine planning, measurement of mine performance and the reconciliation of production results with original expectations are continuous processes during the operation of a mine. These activities involve members of several disciplines over an extended period. Although operating conditions, policies and personnel may change, estimating and reporting practices must be applied consistently to achieve accuracy in periodic evaluations and reconciliation.

Mining and mineral processing have the potential to be important sources of income and driving forces behind broader economic development. But this potential is not always realized.

Surface mining normally involves the haulage of moderate to large amounts of waste and ore out of the pit for relatively long distances at steep grades. Large-scale surface mining operations are increasingly employing large-capacity equipment for achieving economic bulk production.

Haulage in open-pit and strip mines is most generally achieved by dump trucks. The role of haul trucks in many surface mines is restricted to cycling between the loading zone and the transfer point such as the dumping station. Haul trucks are favoured based on their flexibility of operation, which were the preferred haulage method until the 1960s. However, the cost of transporting materials in surface metal and non-metal pits is generally greater than 50% of the total operating cost of the mine.

Now that the ownership and operating costs associated with haulage equipment are high, thus, concrete efforts must be made to achieve reasonable reduces on investors' capital.

Table 1 provides a comprehensive list of the capital and hourly costs associated with owning and operating equipment typically used in haulage operations by trucks.

The cost of equipment consists of two parts: capital and operation. The exact ownership cost is hard to estimate, as purchase price varies with sales' volumes, equipment life is hard to quantify and salvage or re-sale value is unknown. Operating costs contribute thirties of total cost for trucks. Table.1 shows the ownership and operating cost versus the size evaluation based on the manufacturer's data for a single truck on an hourly basis.

Tire consumption has an enormous impact on overall truck operating cost. Tire cost for a haulage truck is equal to its capital cost during its operating life.

Maintenance and overhaul accounts for a large portion of total operating cost in an open pit mine. The maintenance cost to operating cost ratio in open pit mines is about 45%. Increasing truck size requires bigger bays and special tools. Due to the size and complexity of truck, down-time for regular maintenance and repair may be longer, and, in the case of unscheduled repairs, the time consumed for troubleshooting may be longer. In the case of an in-pit break-down, equipment may have to be brought to the maintenance shop when specialized tools and equipment are required to complete repairs.

Table 1: The capital and hourly costs for rigid-frame and articulated trucks

TYPE	CAPACITY Ton	CAPITAL COST \$	LIFE hr	CAPITAL RECOVERY \$/hr	OVER HEAD \$/hr	OVERHAUL		MAINTENANCE		FUEL Lit/hr	LUBE Lit/hr	TIRES \$/hr
						PARTS \$/hr	LABOR hour	PARTS \$/hr	LABOR hour			
Rigid-Frame	34	331,820	37,500	8.8	0.31	1.05	0.042	1.96	0.078	1.8	0.14	0.45
Rigid-Frame	40	565,000	37,500	15.1	0.53	1.79	0.072	3.33	0.133	2.3	0.22	0.35
Rigid-Frame	55	532,600	37,500	14.2	0.5	1.69	0.068	3.14	0.126	3.3	0.23	0.59
Rigid-Frame	70	603,800	37,500	16.1	0.56	1.92	0.077	3.56	0.142	3.4	0.25	0.56
Rigid-Frame	85	1,032,900	37,500	27.5	0.96	3.28	0.131	6.09	0.244	4.3	0.41	0.44
Rigid-Frame	100	1,110,000	37,500	29.6	1.04	3.52	0.141	6.55	0.262	4.4	0.44	0.41
Rigid-Frame	150	1,571,000	37,500	41.9	1.47	4.99	0.150	9.26	0.278	6.8	0.63	0.53
Rigid-Frame	170	1,591,200	37,500	42.4	1.49	5.05	0.152	9.38	0.281	6.1	0.62	0.51
Rigid-Frame	220	1,945,000	37,500	51.9	1.82	6.18	0.185	11.47	0.344	9.0	0.79	0.99
Rigid-Frame	260	2,285,000	37,500	60.9	2.13	7.26	0.218	13.48	0.404	10.9	0.93	0.99
Rigid-Frame	360	3,470,000	37,500	92.5	3.24	11.02	0.331	20.46	0.614	17.2	1.42	0.56
Articulated	20	240,000	37,500	6.40	0.22	0.85	0.038	1.57	0.071	0.806	0.094	2.37
Articulated	25	264,059	37,500	7.04	0.25	0.93	0.042	1.73	0.078	1.166	0.108	2.79
Articulated	27	295,000	37,500	7.87	0.28	1.04	0.047	1.93	0.087	1.276	0.120	4.21
Articulated	30	339,999	37,500	9.07	0.32	1.2	0.054	2.23	0.100	1.276	0.135	3.55
Articulated	35	486,265	37,500	12.97	0.45	1.72	0.077	3.19	0.144	1.276	0.184	3.55
Articulated	40	545,261	37,500	14.54	0.51	1.92	0.087	3.57	0.161	1.725	0.211	6.32

Decision analysis

Technological development has enabled the mining industry to deploy more complex and capital intensive equipment to increase productivity, but misfit selection and inefficient operation often prevent utilization of its full capacity.

There is an increasing requirement for mines to compare investment alternatives that require different capital and result in different production. An economic criterion involves engineering decision-making based on costs.

The decision-making process may be qualitative, quantitative or a combination of the two. The problem structuring and analysis process is conceptualized in Figure 1.

Qualitative analysis is based primarily on the judgment, knowledge and experience of an expert or team of experts. When experience and expertise is strong within an analytical team, then an emphasis can often be placed upon a qualitative analysis. However, in cases where there is limited experience or high complexity, then a quantitative analysis may be more appropriate. In a quantitative analysis, the focus is on facts and data associated with a problem and a mathematical formulation that encompasses the objectives, variables and constraints of the particular problem. Quantitative analysis has traditionally been the subject of operations research and management science.

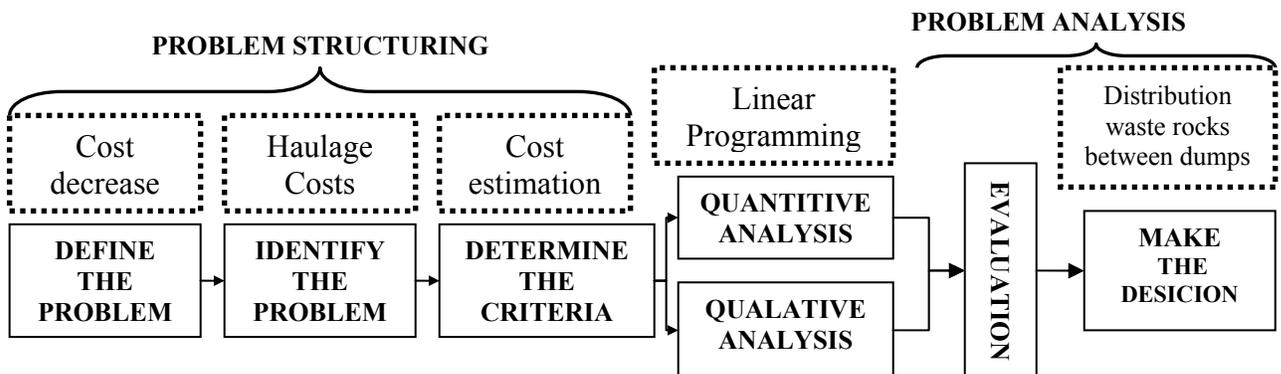


Figure 1: Problem structuring and problem analysis in making decision

This paper focuses on quantitative decision making analysis in mining haulage operations.

Decision analysis can be used to develop an optimal strategy when a decision maker is faced with several decision alternatives.

For example, in the haulage system for a surface mine, the location of the mine facilities (such as dumps), cannot be varied. However, there is considerable flexibility in the distribution of the waste rocks between the dump sites. The objective of decision-making, in the systems analysis framework, is to select from the entire set of controllable and no controllable factors, those combinations of controllable factors which contribute most to the overall growth of the company.

Estimation of discounted average cost for key elements of any cost effective mining scheme and using this method as a mechanism to compare several alternative decisions with a differing mix of capital and operating costs are essential for the effect of increased revenue from product sales biasing or enhancing the evaluation in favor of one alternative.

Waste dump sites

A waste dump is an area in which a surface mining operation can dispose of low grade and barren material that has to be removed from the pit to expose higher grade material. The area required for waste disposal is usually equal to or greater than the pit area because the disturbed waste material has a greater volume than in situ.

By its nature mining exposes largely innocuous, stable materials, breaks them down and stores them as close to the mining operations as possible but at surface. Waste rock has been trammed up the open pit ramps directly onto the dump.

By weight, volume or height, waste dumps are the largest structures built by man. Facilities may be most appropriate as the dump to fill are: valley, side hill, ridge crest, heap and other fills such as backfilled pit or in-pit fill, road fill or dual terms.

During the last decade, many mines have researched planning and operating activities designed to minimize costs, improve transport and disposal of waste.

Construction of a waste rock dump is considered to entail the preparation of the site to receive the waste rock as part of the overall mining process. A contractor may be employed to construct access roads, strip the site, prepare foundations, place under drains and install surface water management facilities.

Operation of the waste rock dump, generally done by the mining employees, involves these activities:

- Waste transports from the mine to the dump.
- Off-loading of the waste at the dump in accordance with the planned dump development and operating plans, including lift height and location.
- Access road construction and maintenance.
- Clearing of new areas for dumping, foundation preparation and drain construction as required in new areas.
- Maintenance, upgrade and expansion of surface water management facilities.
- Environmental monitoring of conditions at the dump including seepage water, surface water, groundwater quantities and quality.
- Dump performance monitoring and documentation including stability, erosion, consolidation and creep.

Transport in these items causes a considerable expense typically and beside its other shares seems small, therefore the decision maker must provide a clear, transparent and defensible evaluation tool for alternatives assessments and attempts to reach consensus in ranking of alternatives based on cost.

The dump sites are not permanent mining facilities and their location may change several times in the mine life then it is important of all that the presented procedure can be carried out for each different mine layout.

Linear programming

Linear programming can be viewed as a part of the great revolutionary development which has given mankind the ability to state general goals and to lay out a path of detailed decisions to take in order to “best” achieve its goals when faced with practical situations of great complexity.

Linear programming is the optimization technique most frequently applied in real-world problems and therefore it is very important to introduce new tools in the approach that allow the model to fit into the real world as much as possible.

Tools for doing this are ways to formulate real-world problems in detailed mathematical terms (models), techniques for solving the models (algorithms) and engines for executing the steps of algorithms (computers and software).

Obviously, by doing so companies are moving into a more efficient production scenario, based on sound mathematical principals and for which benefits have been clearly stated. Since the problem of linear programming was first developed and applied in 1947 by George B. Danzig, Marshall Wood and others in the US and UK military, applications have been extended in virtually all areas of the economy, including many areas in the mining industry.

The optimization of a linear function subject to linear constraints is simple in mathematical structure but powerful in its adaptability to a wide range of applications. The mathematical technique of linear Programming is a search routine where the utility to be optimized is expressed as a linear equation and the domain in which the search takes place, is confined by boundary or constraint linear equations.

Linear programming can produce an accurate model of haulage operations to dumping sites and can be used to predict the operational performance that will result from changes to the mine layout or system upgrades.

In the case presented modeling of a haulage operation has enabled alternative designs to be evaluated and compared at an early stage and the impression of a wide range of parameters, such as truck numbers, dump capacities, haulage times, to be investigated.

A mining scenario

One of the aims involved in the economic analysis consists in establishing a link between the qualitative and quantitative aspects of the field on the basis of approaches that are inevitably simplifying.

A methodology for quantitative decision-making in economic evaluation using the cost estimation and the linear programming is presented herein.

The following mining decision-making scenario was considered in order to distribute load among the waste dump sites. A description of the goal and choosing the best alternative used in analysis that is presented.

The first method is transporting materials by trucks, specifically in a mining operation. In a mining open pit, excavators load materials from faces into dump trucks and trucks transport material to destinations. They transport ore to mineral processing factory to be processed and prepared for the sale and transport waste rocks to waste dumps. This method requires a model to dispatch trucks in an efficient way, minimizing the cost and making sure the system will achieve the transport goals based on available facilities. Figure 2 illustrates a typical open pit section with five active loading points.

Locations of dumps are not permanent places and these points have to be removed several times in a mine life.

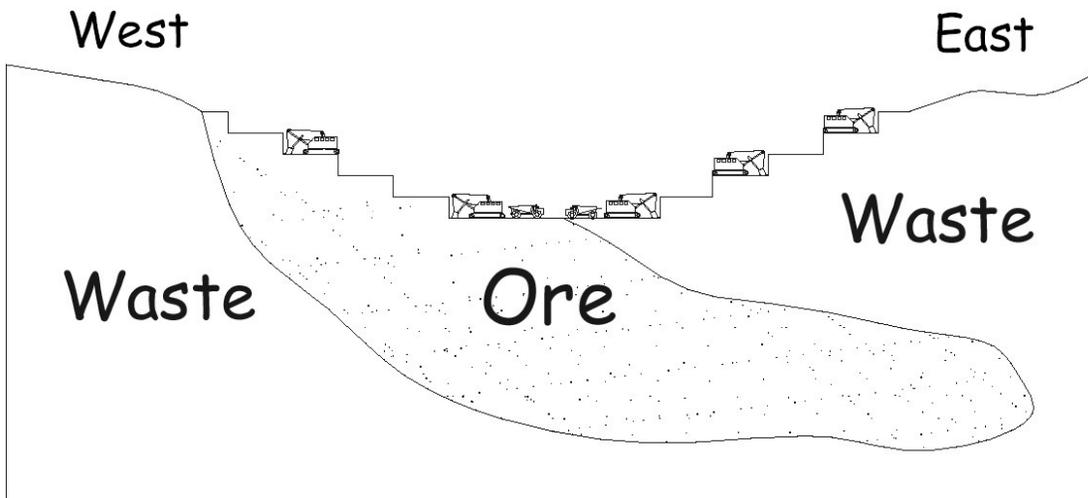


Figure 2: The section of mining scenario

Let us assume that, three excavators (W_1 , W_2 , and W_3) are working within the waste zone and two others are excavating within the ore zone. There are four waste dumps where are located at the North West (D_1), the north east (D_2), the south east (D_3), and the south west (D_4) of pit (figure 3).

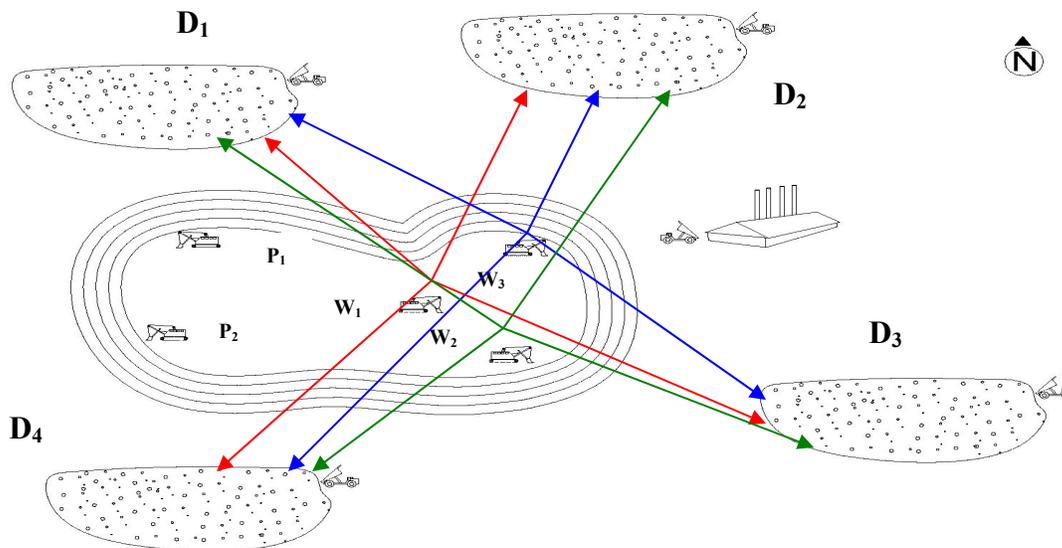


Figure 3: The plan of mining scenario (The site plan)

The distances between the faces and the dumps are given in table 2. Although distance is the main factor in the cost of transportation per ton but the overall cost of transportation depends heavily on haulage time and hourly operating costs for fleet. The haulage time is concerned with the roads condition and performance of trucks.

Table 2: The distances between the faces and the dumps

Face \ Dump	D ₁	D ₂	D ₃	D ₄
	km	km	km	km
W₁	4	5	8	6
W₂	6	5	4	3
W₃	4	2	5	7

Loaded speed in the order of 20 km/h and unloaded speed of 40 km/h are assumed in this scenario. The forecast of round trip times is based on table 3.

Table 3: The forecast of round trip times for trucks

Face \ Dump	D ₁			D ₂			D ₃			D ₄		
	Haulage time (hour)			Haulage time (hour)			Haulage time (hour)			Haulage time (hour)		
	Fill truck	Empty truck	Total time	Fill truck	Empty truck	Total time	Fill truck	Empty truck	Total time	Fill truck	Empty truck	Total time
W₁	0.2	0.1	0.3	0.25	0.125	0.375	0.4	0.2	0.6	0.3	0.15	0.45
W₂	0.3	0.15	0.45	0.25	0.125	0.375	0.2	0.1	0.3	0.15	0.075	0.225
W₃	0.2	0.1	0.3	0.1	0.05	0.15	0.25	0.125	0.375	0.35	0.175	0.525

If trucks capacity are used in the mine equals 85 ton, the operation and recovery costs are extracted from table 1. The performance of cost estimation presupposes the average wage of a mechanic laborer is \$10 per hour; the fuel is \$ 0.1 per liter and the lubricant is \$ 1 per liter. Capital recovery, overhead and hourly operating costs for rigid frame truck with a capacity of 85 tons are presented in table 4.

Table 4: The costs for rigid frame truck with a capacity of 85 tons

Items	Costs per hour
Capital-recovery	27.5 \$
Overhead	0.96 \$
Overhaul-parts	3.28 \$
Overhaul-labor	$0.131 \times 10 = 1.31$ \$
Maintenance-parts	6.09 \$
Maintenance- Labor	$0.244 \times 10 = 2.44$ \$
Fuel	$4.3 \times 0.1 = 0.43$ \$
Lubricant	$0.41 \times 1 = 0.41$ \$
Tire	0.44 \$
Sum	42.86 $\frac{\\$}{hr}$

The information thus calculated is used in definition of haulage cost for each path from the faces to the dumps (Table 5). This table shows the coefficients matrix.

Table 5: The haulage costs for each path per a round trip

Face \ Dump	D ₁	D ₂	D ₃	D ₄
	\$	\$	\$	\$
W₁	12.86	16.07	25.72	19.29
W₂	19.29	16.07	12.86	9.64
W₃	12.86	6.43	16.07	22.50

The linear programming scheme allows constraints to be set in terms of a minimum and maximum limit on any output. Setting these upper and lower bound requirements needs careful attention and should be subject to properly designed procedures, audited by consultants from the relevant disciplines.

The scenario is a minimization of haulage cost under the constraints associated with the dumps capacities and the waste production.

Conditions for a hypothetical mine are presented:

$$\sum_{i=1}^4 D_i = 12,0000 \frac{\text{ton}}{\text{day}}, D_1=1,000 \frac{\text{ton}}{\text{day}}, D_2=2,000 \frac{\text{ton}}{\text{day}}, D_3=5,000 \frac{\text{ton}}{\text{day}}, D_4=4,000 \frac{\text{ton}}{\text{day}}$$

$$\sum_{j=1}^3 W_j = 12,0000 \frac{\text{ton}}{\text{day}}, W_1=6,000 \frac{\text{ton}}{\text{day}}, W_2=4,000 \frac{\text{ton}}{\text{day}}, W_3=2,000 \frac{\text{ton}}{\text{day}}$$

Finally, the scenario must formulate to linear programming problem from contextual problem. There is one objective function in the above model that made from table 5: X_{ij} equals daily tonnage that must remove from the excavator (W_i) to the dump (D_j).

Objective function:

$$\text{Min } Z = 12.86X_{11} + 16.07X_{12} + 25.72X_{13} + 19.29X_{14} + 19.29X_{21} + 16.07X_{22} + 12.86X_{23} \\ + 9.64X_{24} + 12.86X_{31} + 6.43X_{32} + 16.07X_{33} + 22.50X_{34}, X_{ij} \geq 0$$

Subject to:

$$\left\{ \begin{array}{l} X_{11} + X_{12} + X_{13} + X_{14} + 0 + 0 + 0 + 0 + 0 + 0 + 0 = 6,000 \\ 0 + 0 + 0 + 0 + X_{21} + X_{22} + X_{23} + X_{24} + 0 + 0 + 0 + 0 = 4,000 \\ 0 + 0 + 0 + 0 + 0 + 0 + 0 + 0 + X_{31} + X_{32} + X_{33} + X_{34} = 2,000 \\ X_{11} + 0 + 0 + 0 + X_{21} + 0 + 0 + 0 + X_{31} + 0 + 0 + 0 = 1,000 \\ 0 + X_{12} + 0 + 0 + 0 + X_{22} + 0 + 0 + 0 + X_{32} + 0 + 0 = 2,000 \\ 0 + 0 + X_{13} + 0 + 0 + 0 + X_{23} + 0 + 0 + 0 + X_{33} + 0 = 5,000 \\ 0 + 0 + 0 + X_{14} + 0 + 0 + 0 + X_{24} + 0 + 0 + 0 + X_{34} = 4,000 \end{array} \right.$$

A decision maker could not actually solve the problem yet, but it is formulated as linear programming problem that the objective is to minimize costs. Linear programming problems have to be solved by computer usually. We can solve them using Mathematica software.

Mathematica is a general computing environment, organizing many algorithmic, visualization, and user interface capabilities within a document-like user interface paradigm. Besides addressing nearly every field of classical mathematics, it provides cross-platform support for a wide range of tasks such as numerical computation and operations research. The Mathematica attempts to uniformly capture all aspects of mathematics and computation, rather than just specialized areas.

The linear programming problem should be formatted as the input of information into the Mathematica package.

The mining scenario is summarized as a Mathematica form below:

$$\left(\begin{array}{l} \text{Clear}[x, A, b, c, Xvec] \\ Xvec = \text{Table}[x[i, j], \{i, 1, 3\}, \{j, 1, 4\}]; \\ c = \{12.86, 16.07, 25.72, 19.29, 19.29, 16.07, 12.86, 9.64, 12.86, 6.43, 16.07, 22.50\}; \\ b = \{6000, 4000, 2000, 1000, 2000, 5000, 4000\}; \\ A = \{\{1, 1, 1, 1, 0, 0, 0, 0, 0, 0, 0, 0\}, \{0, 0, 0, 0, 1, 1, 1, 1, 0, 0, 0, 0\}, \{0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 1\}, \\ \{1, 0, 0, 0, 1, 0, 0, 0, 1, 0, 0, 0\}, \{0, 1, 0, 0, 0, 1, 0, 0, 0, 1, 0, 0\}, \{0, 0, 1, 0, 0, 0, 1, 0, 0, 0, 1, 0\}, \\ \{0, 0, 0, 1, 0, 0, 0, 1, 0, 0, 0, 1\}\}; \\ Xvec = \text{LinearProgramming}[c, A, b] \end{array} \right)$$

“c” is a goal vector, “b” is a constraint vector, and “A” is a coefficients matrix. The decision vector is earned after running program.

The decision vector is **{1000, 1000, 0, 4000, 0, 0, 4000, 0, 0, 1000, 1000, 0}**.

The decision vector allocates a quantity of waste to each of the dump site. The results of this study are given in table 6.

Table 6: The waste allocation table to the dumps

Face \ Dump	D ₁	D ₂	D ₃	D ₄	Sum
	<i>ton</i> <i>day</i>	<i>ton</i> <i>day</i>	<i>ton</i> <i>day</i>	<i>ton</i> <i>day</i>	
W₁	1,000	1,000	0	4,000	6,000
W₂	0	0	4,000	0	4,000
W₃	0	1,000	1,000	0	2,000
Sum	1,000	2,000	5,000	4000	12,000

There are three breasts the interior of waste (W₁, W₂, and W₃) in this scenario. The daily product rate is 6,000 ton from W₁. This amount must share among the dumps based on results (table 6). One thousand tons of waste rocks are consigned to the D₁ and another one thousand tons of waste rocks are also consigned to the D₂. Finally, four thousand tons of waste rocks that were excavated from W₁, were sent to D₄. This producer can be generalized to other dumps.

Conclusion

Since most activities generally involve processing a relatively large quantity of rock to recover a relatively small amount of valuable product, large quantities of waste are produced as a by-product. By-products must haulage to the dumps based on intake capacities and available facilities in the dump sites, such as the bulldozers to level the ground and distributing the waste evenly over the land. It is very important that the transport cost must be reduced to a minimum.

Limitations of conventional approaches have necessitated the development of new approach specifically for large haulage equipment.

Cost estimation and linear programming can produce an accurate model of haulage operations in surface mining and can be used to predict the operational performance that will result from changes to the mine layout or system upgrades.

This method provides a flexible platform for the development of such computer simulations. In the case presented modeling of a haulage operation has enabled alternative designs to be evaluated and compared at an early stage and the influence of a wide range of parameters, such as truck numbers, truck capacity, haulage times and passing bay spacing, to be investigated.

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