Professional paper

Sizing equipment for open pit mining – a review of critical parameters

E. Bozorgebrahimi, R. A. Hall and G. H. Blackwell

Over the past century, open pit mines have steadily increased their production rate. Larger equipment and new technologies make it possible to mine larger batches of materials in a shorter time. Low commodity prices have forced companies to decrease their unit cost, by using new technologies and improving productivity. In the late 20th century, with companies facing low commodity prices and competing with strong rivals globally, larger equipment with lower unit costs ensured survival. As a result, mine geometry and mining equipment have dramatically increased in size. To date, in terms of productivity, the mining industry continues to adhere to the 'bigger is better' mentality. There are indications that this strategy may not always be advantageous. This paper will discuss on-going research into understanding the effects of equipment size on surface mining. The research includes investigation of mine and mill construction and operating costs, mine productivity, mine design, and economic optimisation. It identifies the significant variables that need to be considered and suggests an approach to quantify their impact on the mine. The paper also proposes a new view to mine planning and equipment selection with respect to the sensitivity to equipment size factors.

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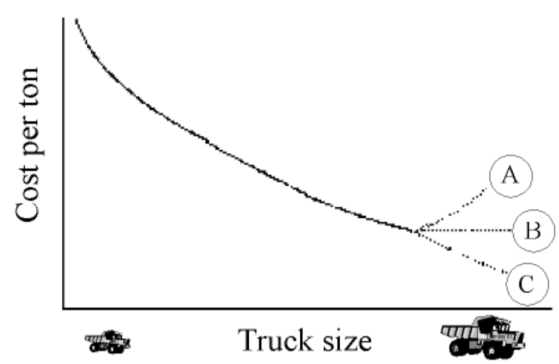
INTRODUCTION

The mining and mineral industries are an enormous and vital contributor to the global economy. For example, about 3.7% of the gross Canadian domestic product (GDP) is contributed by the mining and mineral processing industries.[16] In the last 50 years, mining equipment in general and particularly trucks have gradually increased in size and capacity. For example, the 380-t trucks of today are about 10 times the size of the 35-t trucks of the 1950s. For every 10 years during this period, there has been a 50% increase in truck payload.[14] Experience has shown that larger equipment has reduced total cost by improving productivity in big mines.[3,14] By the end of 2000 there were 253 'ultra' trucks (capacity bigger than 272 t) around the world and it is estimated that there will be potential for 1200 more of these trucks to be purchased during the next 10 years.[13]

At the close of 20th century when mines were facing a decline in commodity prices, implementing larger equipment became the preferred way to decrease unit cost. It seems that there is an over-riding interest in operating trucks with higher payload capacity,[13] but the overall effects of this approach have not been clarified. The new generation of larger equipment is too new to be evaluated completely and there are indications that some difficulties have accompanied the use of large equipment (*e.g.* complexity, dilution, lost production and the lack of flexibility). These difficulties may limit the overall benefit of implementing larger equipment, and there may be a maximum threshold beyond which truck capacity should not increase, at least in the shorter term of a decade.

Blindly increasing equipment size to achieve more production without an understanding of the implications may not be prudent. It is both unknown and unclear what the effect of implementing the next generation of larger equipment will be. Consequently, there is a compelling need to investigate the details of how size affects the overall economics of the mining industry. Krause[14] mentions that the mining industry is unsure of the effects of proceeding to the next generation of large equipment as shown in Fig. 1. In this figure, scenario A shows the possibility of a larger



1 Cost per tonne of production versus the equipment size[14]

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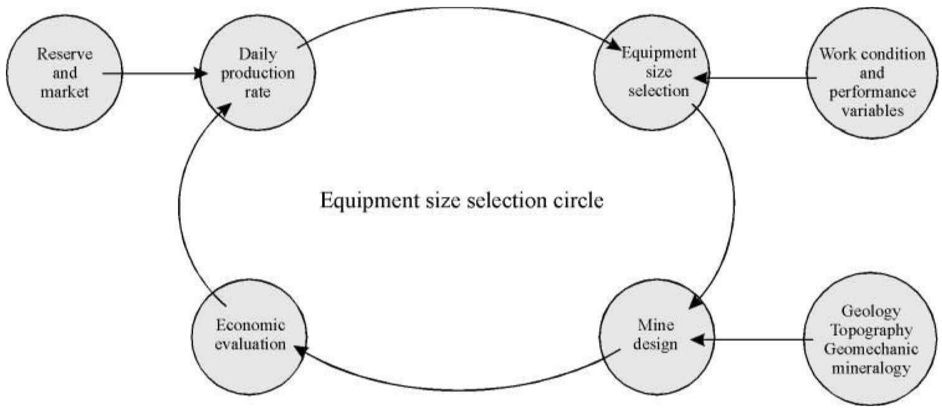


2 The equipment size selection environment

generation of haul trucks having higher operating cost per tonne, B shows no change in cost and C shows a decrease in operation costs per tonne.

EQUIPMENT SELECTION

Open pit mine optimisation is a key step in the viability of a surface mining project, and on which the next steps, detailed mine planning and economic evaluation, relies. The selection of equipment influences the optimisation process. For example, one of the inputs for the process is mining costs, which are strongly influenced by the kinds of equipment that are purchased. Consequently, equipment optimisation and pit optimisation are strongly linked. An optimum pit limit is assumed to be achieved whenever some economic criteria such as, for example, return on investment (ROI) are optimal. Improved equipment selection will lower mining costs and may change the optimised pit limits.

In mine equipment selection, the type, size and number of units are major considerations, and these three items are strongly interdependent. Regardless of the method used, the goal of the equipment selection process is to satisfy the production rate requirements while minimising the mining cost.

Fig. 2 shows the interaction between equipment size and other mining parameters. The first and the most important consideration in the size selection process is the required daily production rate. This is generally determined by looking at reserves, commodity markets, corporate production strategy and the expected pay-back period or ROI. Assuming a daily production rate combined with job efficiency of operators, utilisation, availability (of equipment) and the mine layout, the mining equipment sizes are determined. The selected equipment size then influences the mining cost, which eventually affect the optimised pit location and dimensions.

The dimensions of a machine and its production rate are important factors in equipment sizing. Larger dimensions and increased productivity do not necessarily go hand-in-hand. Speed of each component of a digging cycle and dimensions, such as dumping height, influence loading machine productivity and should also be taken in consideration.

The size selection criteria for loading machines and haulage machines are not the same. The size of the loading machine is an important factor in selective mining and prevention of dilution. In addition, the loading machine initially determines the productivity of a mining system. In an open pit mine, the number of loading machines is limited and their reliability and flexibility are very important. Thus, the mining selectivity, productivity, reliability and flexibility are essential factors for loading machine selection.

The size of haulage machines directly influences the mine layout and design, and loading and haulage should be adequately matched. Haulage costs are usually twice the cost of loading; consequently, greater attention must be paid to truck selection. Fig. 3 shows typical open pit mining costs.

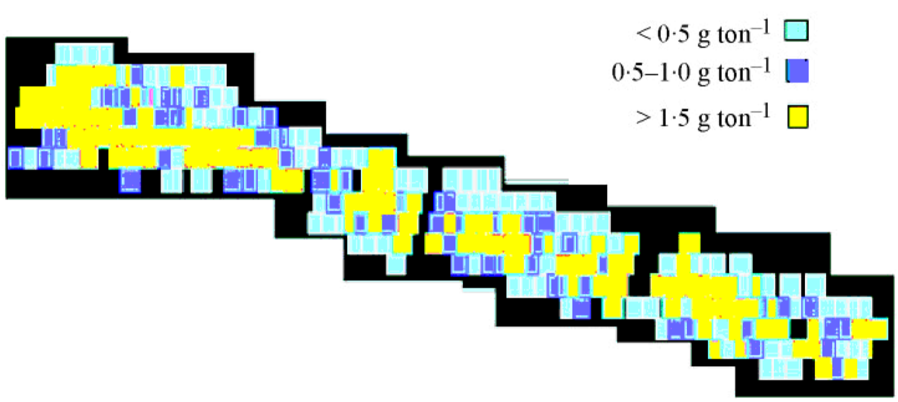
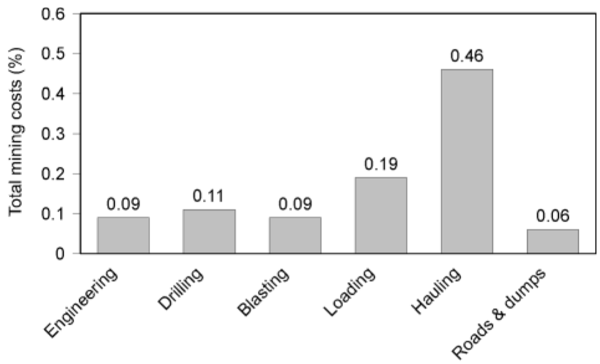


Plate I A plan view of a bench in a small gold mine (*see text on* **p.177)**



3 Typical open pit mining costs[6]

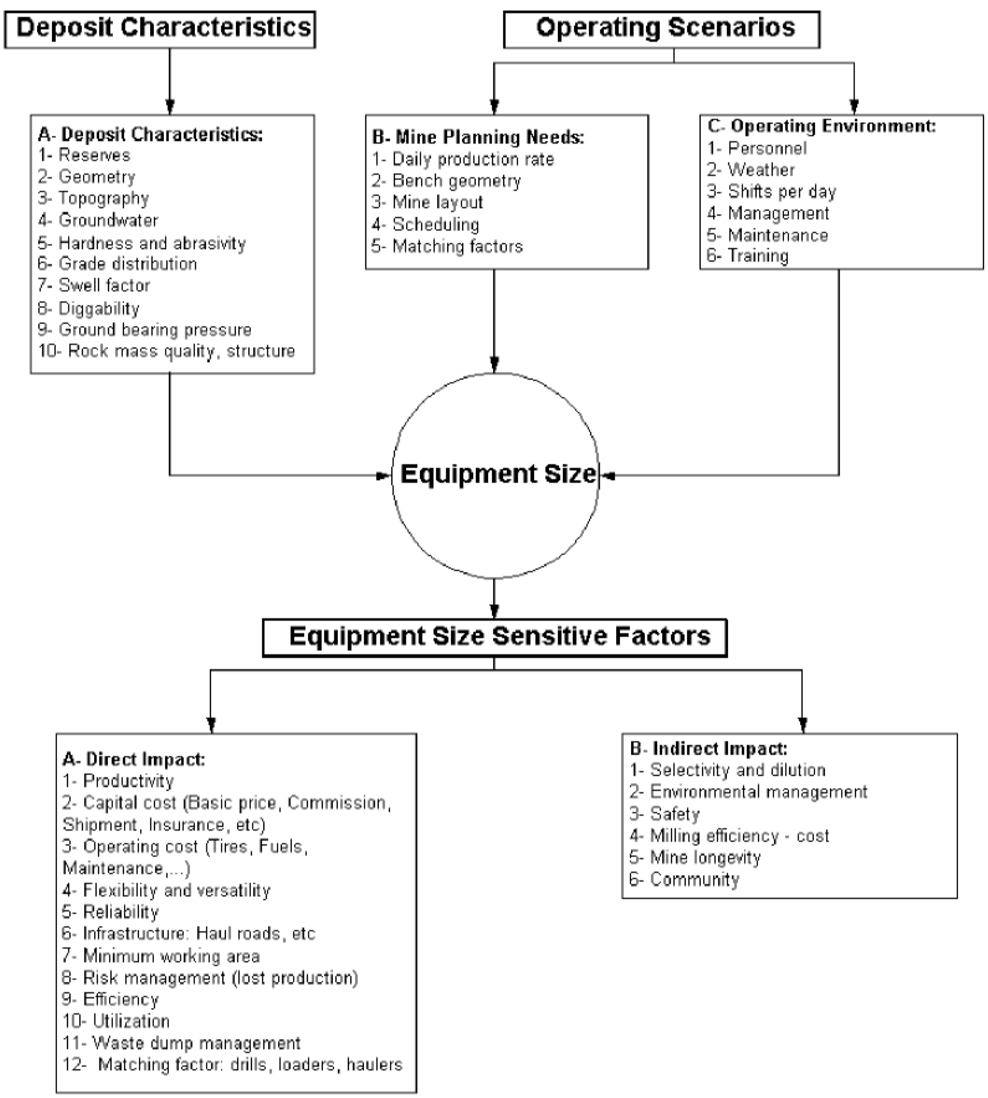
There are different methods available to size mining equipment. Eq. 1 computes the dipper capacity (volume) of the shovels:[1]

$$B = Q/[(60/tc) \times S \times A \times O \times (bucketfill\ factor)] \quad (1)$$

where B is the dipper capacity (t), Q is the production required (t/h), tc is the shovel cycle time (min), S is the swing factor, A is the mechanical availability, and O the job operational factor.

Eq. 1 provides a bucket (dipper) capacity for loaders by assuming some factors such as the job operational factors and availability. Since the availability and job operational factors are functions of management and equipment size, it is very important to have an overall economical evaluation before making any final decisions regarding size of equipment. Equipment size can also be considered as a function of the characteristics of the material (rock) being dug in terms of ore and waste.

The smallest (or selective) mining unit (SMU) is the smallest block inside which ore and waste cannot be separated, and grade estimates of SMUs are used to maximise the pit value. The run-of-mine grade, particularly in metal mines, is sensitive to the dimensions of mining blocks such as bench height and hence the equipment size. This matter will be discussed later in the section on dilution. In a mine with erratic spatial ore distribution, such as most gold deposits, the dimensions of the mining block size have immense impact on the final pit value and should be



4 Equipment size considerations and the equipment size sensitive factors

Table 1 Issues that need to be considered with the implementation of larger equipment in open pit mines

Equipment costs
Tyres
Complexity
Match factor
Loss of production
Maintenance
Infrastructures and haul roads
Dilution and selectivity
Flexibility and versatility
Environment
Milling cost

determined with precision.[5] In deposits with little variation in grade over distances less than say 30 m (*e.g.* large porphyry copper deposits), it is possible to increase the size of the dimensions of the mining block without influencing the selectivity. It is also implied that the size of the mining block can be increased in waste rock, hence the use of small equipment for ore mining, and large equipment for waste.

The number of constraints determining the type of equipment selected is greater for loading machines than for haulage machines. Selectivity and the amount of dilution are important factors for sizing loaders, whereas they are not important for sizing the haulage fleet. Loading machines are also more sensitive to flexibility and reliability than haulage machines.

EQUIPMENT SIZE-SENSITIVE FACTORS

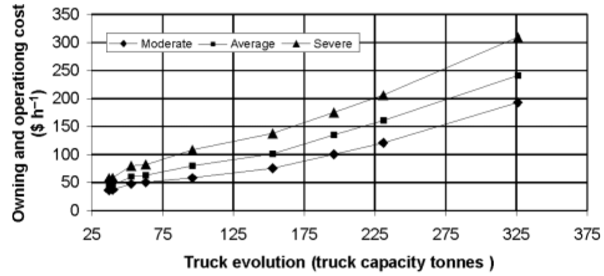
In mine operations, drills, loading machines and haul trucks comprise the major cost items. The operating cost of just haul trucks in most open pit mines is usually between one-third and one-half of the mining cost.[4] Parameters influencing equipment size selection may be deposit specific, affecting design criteria and mine economics, which in turn are strongly affected by equipment size. Any investigation to identify these parameters will assist in providing a more accurate and precise pit optimisation. Fig. 4 shows a list of the parameters that are basically considered in sizing mining equipment and the factors affected by equipment size.

A list of issues that need to be considered with the implementation of larger equipment in open pit mines is given in Table 1: these will be discussed below.

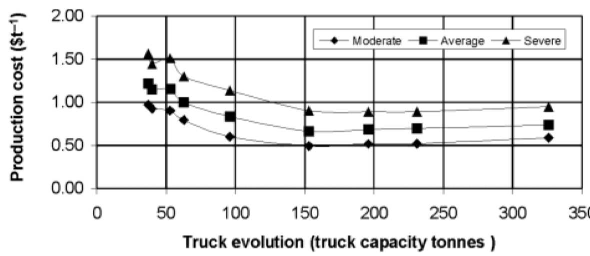
Equipment costs

The cost of equipment consists of two parts – ownership 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 two-thirds of total cost for trucks.[8] Fig. 5 shows the changes of ownership and operating cost versus the size evaluation based on the manufacturer's data for a single truck on an hourly basis. The total equipment cost depends on the operating conditions of which the following three different



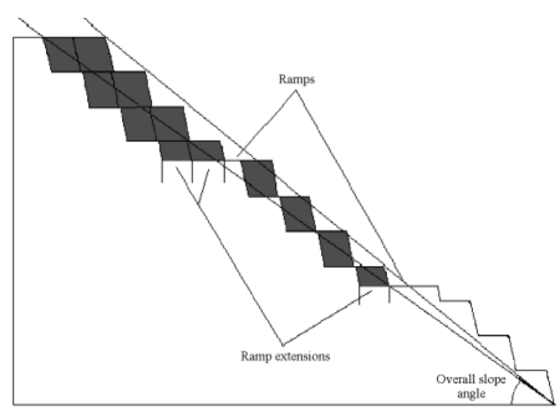
5 Total truck hourly costs ($/h) versus truck evolution. Data from Caterpillar[9]



6 Truck production costs ($/h/t) and hourly truck cost versus truck evolution. Data from Caterpillar[9]

categories were considered – moderate, average and severe. The trend in cost increases as equipment size increases, but this is balanced with greater production (Fig. 6). The unit cost decreases as shown in Fig. 7 which shows the unit cost in the form of $/t for a single truck for three different operating conditions (moderate, average and severe).

By varying the equipment size, factors such as SMU, the final pit limits, the mining cost, the milling cost and the environmental cost change. Unless all of these cost effects are taken into account, the equipment size will be sub-optional and, consequently, the unit cost may not be minimised. Reports from some mines indicate that a significant reduction in equipment costs is associated with the larger equipment. However, not all mines have been able to use larger equipment.[12] Some reasons that not all mines can use larger equipment are:



7 The effect of the larger equipment on the stripping ratio

(i) Equipment size can be considered as a function of the size of deposit. The size of the deposit in combination with productivity determines the final value of the project and the mine life. The deposit must be large enough to justify the purchase of larger equipment. The length of the project must also be matched with the equipment life. It is hard to justify the economic parameters of a project if the mine life is less than the equipment life, especially in remote areas.

(ii) The size of operation is limited by the available capital for investment. Sometimes, because of the shortage of investment or the existence of extraordinary risk of investment, it is not possible to extend the current operation or commence a large operation. In this case, companies may intend to apply sequential mining system even for a large deposit, so that by purchasing smaller equipment, they are able to overcome the lack of investment capital.

For these two reasons the application of large equipment is limited to big mines.

Tyres

Tyre consumption has a huge impact on overall truck operating cost. Tyre cost for a haulage truck is equal to its capital cost during its operating life.[2] Some related considerations are that the life of larger tyres is reduced due to the increased air pressure and high operating temperatures. To mitigate this, manufacturers have recommended speeds less than 32 km h^{-1}.[15] In some mines on long hauls, managing routes based on tyre temperature has resulted in a loss of flexibility and extra costs.[18]

Complexity

Large equipment may require more and complex components. For example, to deliver more power, some new trucks are equipped with two engines and new monitoring and control systems are required. Modern large equipment is equipped with diagnostic tools to overcome this complexity; nevertheless, training of mechanics (and electricians) is especially important. Maintenance, repair and operation of larger equipment demands skilled and educated personnel and special tools, which will increase total costs. According to Djan-Sampson and Daneshmend:[11] 'a comparison of the ratios for open pit mine and underground in Canada seems to indicate the fact that maintenance costs increase with increasing equipment size and complexity'.

Although these machines are equipped with the newest technology, their utilisation (hours working per year) may not be as good as older machinery where design flaws have been corrected over time. The reliability (hours available for working per year) for larger trucks is on average about 80%.[19]

The way employees adapt to new equipment is also a problem. An employee's career life is about 30 years, while the rate of technology change is currently less than 5 years. The time taken to become proficient with a new machine or technology has a cost attached, including the loss of efficiency in the learning process, however this is hard to quantify.

Equipment matching factor – system approach

Open pit mining equipment operates interdependently, and any change in operational performance of one part of the fleet will immediately affect the other parts. The 'match factor' sizes trucks and loaders appropriately; as the size of truck increases, the match factor issue begins to become problematic.[9] Matching problems for truck and shovel include:

(i) For an operating mine switching to a higher level of production, there are numerous restrictions such as equipment matching and the mine geometry/dimensions that equipment needs to be matched to. Among these restrictions, shovels play a key role in the decision-making process. This is simply because shovels are more expensive and have a much longer life than trucks.

(ii) Having a mixed fleet of trucks makes it difficult to load all the trucks optimally with identical shovels. Adding new, larger trucks to the haulage fleet may add problems such as inability to reach the truck box and improper load distribution in the box. Matching is not considered to be a big problem for projects in the planning stage when it is possible to match loading machines with the appropriate haulage machines, usually with an integer number (3–5) of loader buckets per truck load.

Loss of production

As the equipment size increases, the amount of lost production (tonnage) resulting from down-time increases. The following equation is a simple way to quantify this loss of production:

$$L_p = P_u \times T_d \quad (2)$$

where L_p is the lost production (t), P_u is the productivity (t/h), and T_d is the total down time of that unit (h).

Larger equipment has larger productivity (P_u). If increasing the productivity of a unit is not accompanied by an improvement in its availability, Eq. 2 shows that loss of production will increase. Wohlgemuth[19] explains with data that the availability of larger equipment is similar to smaller ones. Hence, according to Eq. 2, lost production is a more serious problem for larger equipment than it is for smaller equipment.

Maintenance

Maintenance accounts for a large portion of total operating cost in an open pit. The maintenance cost to operating cost ratio in open pit mines in Canada and Australia is about 45%.[7] The maintenance considerations associated with larger equipment are discussed below.

Increasing equipment size requires bigger bays and special tools. Due to the size and complexity of this equipment, 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 specialised tools and equipment are required to complete repairs.

Although increasing equipment size results in less operators and lower total wages, there may be a requirement for more staff to maintain more complex and larger equipment. The number of maintenance technicians required per truck (technician ratio) is raised from 1·5 persons per truck for 240-t trucks to 2 persons per truck for 360-t trucks.[19] Another issue is the miscellaneous equipment required for servicing larger primary equipment. These include washing bays, cranes, tire changers, *etc.*, resulting in higher maintenance costs as the equipment size increases.

Infrastructure and haul roads

Roads are one of the most important infrastructure in open pit mines. When increasing the unit size of trucks, road restrictions such as bridges, overpasses, power lines and pipelines can create serious problems because the road width for larger trucks is significantly greater. In comparison with other mining methods such as strip mining, the economics of open pit mines are more sensitive to the road width. Any changes in the road width will directly influence the overall pit wall slope (Fig. 7). For deep open pit mines, this dramatically changes the stripping ratio. Depending on the location of the road (internal or external) it causes the loss of some of the ore, or the addition of some waste, or a combination of both. Eq. 3 calculates the amount of the additional slope due to implementation of larger trucks. Where the ramp is switch-backed or circles the pit more than once, Eq. 4 should be used:

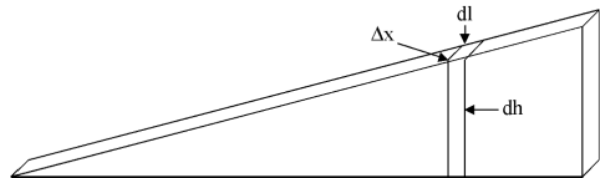
$$\Delta\alpha = \tan^{-1}\left(\Delta x \times \sin(\alpha) / y\right) \qquad (3)$$

$$\Delta\alpha = \tan^{-1}\left(\sum_{1}^{n}(\Delta x) \times \sin(\alpha) / y\right) \qquad (4)$$

where

$$n = INT\left[g^{-1} \times PD / LR\right] \qquad (5)$$

where PD is the pit depth, LR is the length of pit wall the ramp occupies, Δx is the road width increase required to use larger trucks (m), $\Delta\alpha$ is the overall pit slope decrease from implementing larger trucks in degrees, α is the overall pit slope before implementing larger trucks in degrees, n is the number of times that the ramp cuts (crosses) the mine wall (determined from Eq. 5), y is the pit depth (m), and g is the ramp grade (%).



8 Geometry for ramp widening

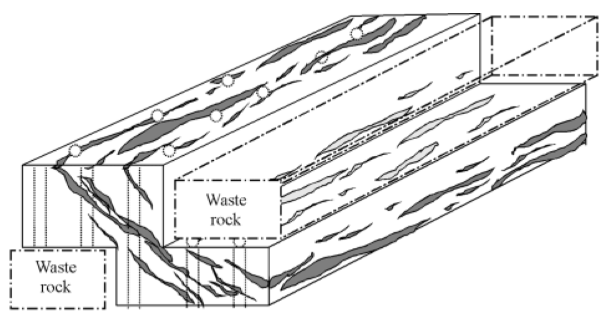
Fig. 8 shows the impact of ramp extension due to implementing the larger trucks on the overall pit slope and stripping ratio.

The general rule of thumb for 2-way traffic is that road width should be at least 3 times the truck width, and Couzens[10] recommends at least 4 times. Adding an additional lane for uphill traffic will speed up the traffic flow, and larger mines design 3-way traffic ramps rather than two lane. The general rule of thumb for 3-way traffic according to Couzens[10] is at least 5 times the truck width. Table 2 shows typical road widths based on this rule and using Caterpillar's truck widths.[12]

The amount of material mined due to ramp widening is independent of the overall pit slope (see Fig. 8) and is calculated from Eq. 6):

$$W = \int_0^{Y/g}\int_0^{Y}(0.5 \times \gamma \times \Delta x) \times dh \times dt \qquad (6)$$

where γ is the average specific weight of the materials to be mined, Δx is the amount of the ramp widening, dh is an element of pit depth, dl is an element of the length of the ramp, g is the ramp grade (%), and Y is



9 The effect of increasing bench height on dilution. Here the dip of the ore is about 45°

Table 2 Approximate road widths for various truck size

Truck payload (t)	Approximate width (m)	2-way road width (m)	Difference with previous truck size (m)	3-way road width (m)	Difference with previous truck size (m)
37	5·01	20·04	0	25·05	0
40	5·01	20·04	0	25·05	0
53	5·08	20·32	0·28	25·4	0·35
63	5·21	20·84	0·52	26·05	0·65
96	6·1	24·4	3·56	30·5	4·45
153	6·64	26·56	2·16	33·2	2·7
196	7·67	30·68	4·12	38·35	5·15
232	7·41	29·64	-1·04	37·05	–1·3
326	9·15	36·6	6·96	45·75	8·7

Table 3 Statistics for two options

	Pit 2 37-m wide ramp		Pit 1 45·75-m wide ramp		Difference
	Total production (t)	Grade (%)	Total production (t)	Grade (%)	Total production (t)
Waste	1 979 970 844	N/A	1 943 085 094	N/A	36 885 750
Ore	247 548 750	0.6027	247 178 906	0·6030	369 844
Waste/ore	8·00	N/A	7·86	N/A	0·14

the maximum depth of pit which the ramp is to reach. Solving Eq. 6 gives:

$$W = \left[(0.5 \times \gamma \times \Delta x) \times Y^2 / g \right] \quad (7)$$

According to Eq. 7 and Table 2, a 100-m deep pit switching from a 230-t to 320-t fleet will require a ramp 8·7 m wider, increasing the overall pit slope by 3·5°. Assuming a ramp gradient of 8% and rock specific gravity of 2·65, about 1·5 Mt of extra waste will have to be mined.

Haul road width design effect example

The effect of equipment size on the stripping ratio was investigated using SURPAC Vision™ for two identical open pits planned for an actual copper porphyry deposit. Two different scenarios were examined (Table 3): (i) a fleet of 230-t trucks using a 37·0-m width by-pass lane ramp; and (ii) a fleet of 320-t trucks with a by-pass lane ramp of width 46·0 m. As shown in Table 3, a significant increase in waste mining equal to 36·9 Mt is associated with the larger trucks. The cost of this amount of waste should be considered in any equipment selection and economic evaluation process.

Dilution and selectivity

One advantage of open pit mining is its ability to use selective mining techniques. Implementing larger equipment forces the mine layout to use larger mining blocks that will consequently result in a mixture of ore and waste or low grade to feed the mill. This will also result in transfer of a part of the mining cost to the processing plant by feeding the mill more waste, increasing milling cost. Whether the reduced mining costs offset the increased milling costs needs to be determined.

Dilution reduces the head grade of ore, and may result in re-classification as waste or low grade. For example, consider a drill hole consisting of two samples 0·1 g t^{-1} and 1·8 g t^{-1} gold. The average grade value of this drill hole is 0·95 g t^{-1}. Assuming a cut-off grade of 1 g t^{-1}, this material will be classified as waste and the better material lost. If the lower grade sample were 0·2 g t^{-1}, resources would be used to process the waste resulting in higher costs. The effect of dilution on the surface mine economy has not been well documented in the literature.

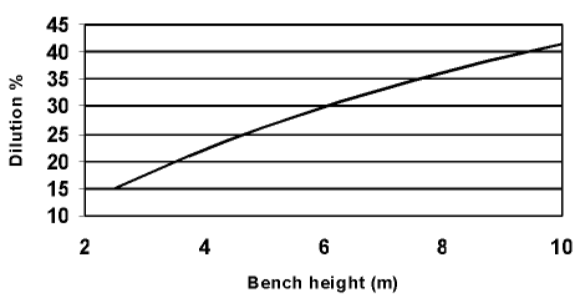
Fig. 9 shows how increasing the bench height in an open pit mine to allow larger equipment to operate productively causes the inclusion of waste in ore blocks and, consequently, reduces the mine grade.

Plate I (*see* p.172) shows the plan view of a bench in a small open pit gold mine. The holes are drilled on a 2·5 × 2·7 m pattern. The mineralisation occurs in the fractured zone of a fault. As shown, the grades are not evenly distributed and the low and high-grade blocks are immediately adjacent. Precise ore selection cannot be achieved with a loader bucket larger than 2·5 m in width. The authors are aware of the operational restriction for extraction of small blocks such as blast movement. However, this example illustrates that, for optimum grade control, small equipment is better than larger equipment in some cases.

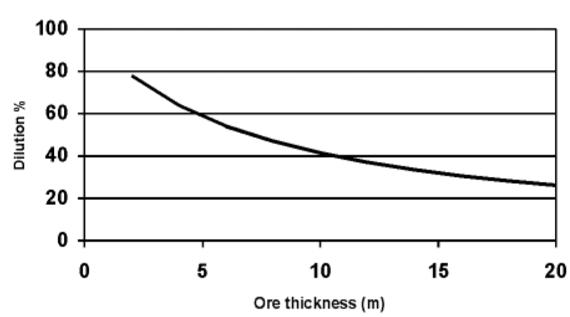
Figs. 10–12 show the effects of bench height, ore thickness and dip of the ore-body on the amount of dilution for a simple stratiform orebody. These three parameters are studied separately, but it should be noted that the bench height is strongly dependent on the other two parameters. Depending on the dip of the ore and the ore thickness, different bench heights represent different amounts of dilution. In a thick and steep ore body, the amount of dilution is not as sensitive to the bench height as in a thin and flat lying ore body.

Flexibility and versatility

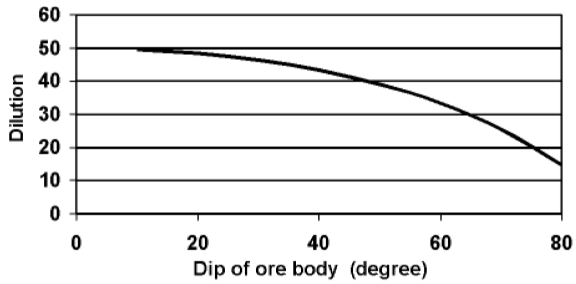
For a specific level of productivity, the required number of units of equipment (fleet size) decreases as



10 Dilution versus bench height



11 Dilution versus ore thickness



12 Dilution versus ore dip

the unit size increases. By increasing the number of shovels (operating, standby and maintenance), management can reduce the risk of possible shut down by having more faces ready to be mined, and keep production at a constant level. The ability to access several blocks of ore and waste simultaneously leads to better blending, and also to greater flexibility in mine and maintenance planning. As the size of equipment increases, the cost of ownership and maintenance may be prohibitive. Dunbar[17] states: 'the dependence on fewer but larger pieces of equipment in striving to exploit economies of scale for improved competitiveness also tends to reduce a mining system's inherent flexibility'. Krause[14] adds: 'is going from a fleet of eight small trucks to four large trucks, the same as going from a fleet of 120 trucks to 60 trucks?' Obviously the answer is no. The mine going from eight trucks to four is at more risk in terms of the lost production associated with a truck failure.

Environment

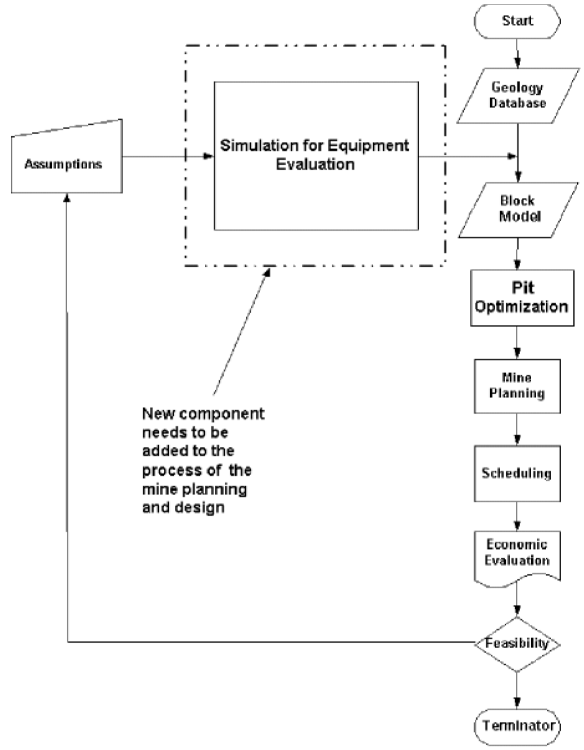
The most important environmental issue for larger equipment is that additional waste is processed in the mining of larger mining blocks. This makes waste management more costly and complicated. More land must be acquired to contain additional waste dumps and tailing dams, requiring more capital investment. If mill tailings are in any way toxic, this will require additional environmental protection. To date, little research has been carried out on the environmental impact of larger mining machines and economies of scale.

Milling cost

The equipment size effect on the processing plant is associated with two essential items:

(i) The unit cost of a ore processing is sensitive to the size of material feeding the mill. Although the size of rock mined in the pit is not directly related to the size of mining equipment, a higher production rate may tend to decrease fragmentation. The alternative is higher drilling and blasting costs, which must be taken into account.

(ii) Dilution resulting from the use of larger equipment will increase milling costs significantly due to lower head grade, but per tonne milling costs will decrease with the throughput of unwanted waste rock.



13 Mine planning and design sequence

Since the milling cost is usually 2–10 times the mining cost, it is very important to quantify the effect of mine equipment size on the mill capital and operating cost before making any decision.

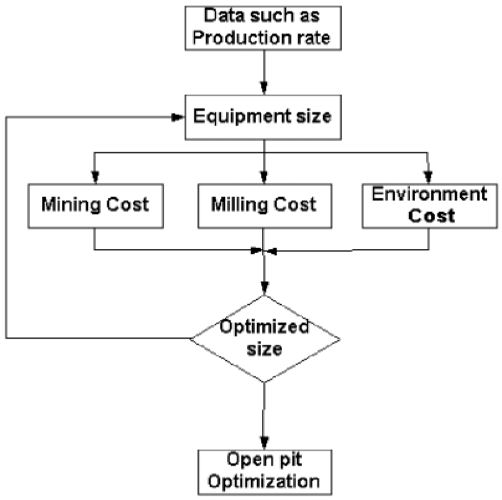
PROPOSED APPROACH TO MINE PLANNING AND EQUIPMENT SELECTION

Fig. 13 shows a sequence of mine optimisation and design. The mine planning and optimisation is based on some initial assumptions, especially regarding mining equipment. Since any change in equipment specification has a dramatic affect on mine design, layout and planning, it is prudent to pay attention to the equipment size selected. Simulation has proven itself to be quite acceptable at solving the mining related issues including various optimisation problems.[5]

A process that makes this possible is shown in Fig. 14. Using a simulation program, it is possible to model equipment functions in open pits. It is envisioned that such a program can be incorporated as a component of a mine design package to assist in equipment selection.

CONCLUSIONS

As a result of new technology, economy of scale will continue to be an extremely important factor in the competitiveness of the mining industry. This implies that both mine size (physical dimensions) and mining equipment will continue to grow. The effects of these changes have not yet been fully evaluated or clearly documented. The mining industry requires a reliable



14 Equipment size optimiser as a component of mine design packages

model to help size the mine and equipment, recognising that the two are interdependent. Understanding the size-sensitive factors of equipment and quantifying them will help to provide a more holistic and reliable technique for mine design and optimisation.

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