Distribution of the Main Operational Costs Due to the Size of the Loading and Haulage Fleet: Brazilian Reality

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Abstract. Throughout the history of mining, the increase in the size of trucks and excavators allowed the mining of materials located in areas farther away from the dumping points at a reduced cost. Therefore, in pre-feasibility studies, it is possible to carry out several simulations, considering a production target to be reached and the use of trucks with capacities from 30 to 500 tonnes for the operation phase of a mine. In this study, a production target was set and for each of the fleet size considered, the main operational costs of loading and haulage materials were estimated, such as machine operators cost, diesel consumption and tire replacement. The results showed that the increase in the volumetric capacity of excavation or haulage fleet does not necessarily imply reduction of operational costs. Moreover, it can be concluded that labour costs are more significant for small fleets (up to 100 tonnes) than for large ones (more than 100 tonnes) in Brazil, showing that the automation of these small fleets may be an economical alternative in the future.

Keywords: Operational costs · Trucks · Excavators

1 Introduction

Most mining companies commercialize commodities, products with strict standards of physical-chemical homogeneity, whose prices are controlled by external agents, such as stock exchanges. Therefore, methods to add value to final products are very limited, as they require large investments in processing plants or metallurgy. Reducing operational costs is the most immediate way to increase profitability in mines. In this sense, loading and transport operations are strong candidates for minimizing operational costs, since they consist of 60% of mining costs [1, 2]. The greatness in the mining industry is that the use of large equipment results in lower cost per tonne transported.

For many decades, technologies of loading and transportation have been directed at increasing the size of the machines. Before the end of the 19th century, wheelbarrows, pickaxes, small rail-drawn or animal-drawn vehicles were the main means of excavation

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and transportation in mining. With the invention of steam powered engines, the first large excavators, built by Bucyrus-Erie Shovel Company (1882) and Marion Steam Shovel Company (1884) began to appear. These types of equipment were in high demand for many large projects, including road construction, railroads and also stood out in the construction of the canal of Panama (1908) and in the iron and cooper mining of the United States. At that time, the capacity of buckets varied between 2 and 6 m^3 [3].

Around the 1940s, the development of diesel and electric excavators with bucket capacities of up to 25 m^3 stand out, enhanced by the progress of the coal industry in the United States. In the late 1960s, the company Marion produced the largest excavator in history, the Marion 6360, with a capacity of 140 m^3 [3].

The trucks tried to replicate the magnitude of the excavators, but they were limited initially by tire technology. Over decades, this technology has advanced, enabling the payload capacity to be extended to more modern standards. Around the 1920s, trucks were built to transport between 1.5 and 7 tonnes. Currently, the world's largest truck, the Belorussian Belaz 75710, has a load capacity of approximately 500 short tonnes or 450 metric tonnes. A larger number of models for excavators can also be considered, since they have sizes proportional to the modules they are loading [4, 5].

However, does a larger proportion of equipment necessarily mean that the operation cost is lower? When considering geometries or track conditions, it is easy to realize that the above sentence is untrue. The choice of truck-excavator set which results in a lower cost of loading and transportation, local costs of labor, fuel and tires are preponderant in the decision process.

The objective of this article is to propose an applicable methodology for economic pre-feasibility projects to determine the proportions that result in the lowest operational costs. This may demonstrate that, when local economic factors are considered, the larger proportion is not always the most economical.

2 Methodology

Fundamentally, the bias of the economic analysis to be discussed in this article is comparative. The development of the study consisted of the accomplishment of a simplified dimensioning of trucks and hydraulic excavators of different capacities. In addition, an economic analysis at the level of pre-feasibility studies, aiming to raise relevant operational costs, practiced in Brazil, and to compare them to different sized fleets. The goal is to verify if the largest fleet of equipment represents the lowest operational costs of loading and transportation.

Therefore, the maximum excavation and transport capacity of the excavators and trucks was considered, to determine the minimum theoretical amount of equipment that would result in the desired annual movement. For this, global variables such as operational efficiency, average transport speed, average transport distance and hours effectively worked had to be established to make the sizing possible [6]. The Caterpillar Performance Manual [7] was also embraced to determine the different proportions of trucks and excavators, as well as other operational parameters.

The assumptions adopted in this article were based on the typical iron ore production of large companies in Brazil, especially those operating in the Iron Quadrangle region in the State of Minas Gerais, and are presented in Table 1. The companies considered as large are those that produce more than 1 million tonnes of ore per year [8].

Table 1. Global assumptions adopted for fleet sizing.

Parameters	Numbers
Annual movement (waste + ore)	42 millions of t
Operational efficiency (Physical Availability × Use)	0.87 × 0.89 = 0.77
Average transport speed (*Vm*)	22.6 km/h
Average transport distance (*DMT*)	1.55 km
Working hours per year	6,745 h

Assuming the parameters of Table 1 for fleet sizing and compatibility between the excavation modules and transportation, the minimum number of trucks and excavators required to meet the hourly moving target was determined (6,227 t/h).

2.1 Considered Trucks and Excavators

The loading and transport vehicles used for the sizing study were trucks with payloads ranging from 40 to 400 t and hydraulic excavators with bucket volume between 7 and 52 m^3.

The truck cycle time (Tc) is the amount of time required to complete 1 cycle. It considers the time that the module spends to transport the material from the extraction zone, the time it takes to return empty to the place of loading and fixed times (Tf) spent in queues, maneuvers, positioning, loading, and tipping. The Tf considered for all fleets was 12 min. The Eq. 1 was adopted for the average cycle time of the trucks.

$$Tc = \frac{DMT}{Vm} \times 2 + Tf \tag{1}$$

For the excavator, the cycle time consists of the sum of loading times, loaded hopper rotation, tipping time and hopper rotated time. The total cycle time of the excavator, also called the pass time, will depend on the size of the machine, the operating conditions and the operator's ability. For this work, it was considered the pass time for hydraulic excavators in moderate condition of excavation, as shown in Fig. 1.

The definition of possible combinations between the loading and transport vehicles was determined by the number of passes required to fill the dumpster of a truck. It was considered that an excavator would be compatible with a truck model if it could fill it with 3 to 5 passes, a quantity that also reflects the physical compatibility between the machines.

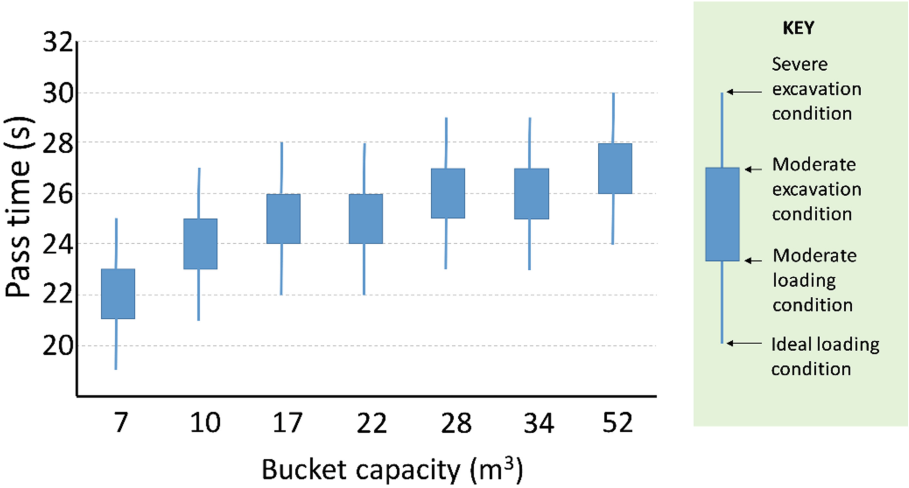


Fig. 1. Table for estimating the cycle time of hydraulic excavators [7].

Table 2 shows the number of passes required to fill the dumpster of the 15 pairs of equipment considered compatible for the actual work. The trucks are identified by their maximum carrying capacities and the excavators by a letter followed by the volume of the bucket. The last lines of Table 2 show the number of trucks and excavators required to meet the productivity of 6,227 t/h.

Table 2. Number of passes between excavators (column) and trucks (row) compatible, and the quantity of equipment to meet production.

Truck (t) Shovel (m^3)	40	50	70	100	150	200	250	345	400
A-7	4	4							
B-10		3	4						
C-17				4	5				
D-22					4	5			
E-28					3	4			
F-34						3	5		
G-52							3	4	5
Numbers of trucks	53	42	30	21	14	11	9	7	6
Numbers of shovels	A: 6	A: 5 B: 4	B: 4	C: 3	C: 3 D: 2 E: 2	D: 2 E: 2 F: 2	F: 2 G: 1	G: 1	G: 1

It is important to note that, as it was done for the trucks, the theoretical minimum number of excavators required to meet the production goal was calculated, i.e. to reach a productivity of 6 227 t/h. Due to the fact that excavators are generally the bottleneck of mine production, a design factor of 1.3 was considered for the quantity of this equipment over the calculated number.

2.2 Determination of the Main Operational Costs

By determining the number and sets of compatible trucks and excavators, it was possible to make an economic analysis involving the 3 largest mining costs: the Fuel Costs (*FC*), Operator Costs (*OC*) and Tire Costs (*TC*), according to the selected truck-excavator pair, based on economic values in Brazil.

Fuel Cost. Fuel consumption, in litres per hour (l/h), truck or excavator, is a function of the model and the consumption classification (low, medium or high) [7]. For the calculation of the diesel consumption of each truck and excavator model, the average consumption factor and the average of the values presented for this factor were considered. The *FC* is given by Eq. 2 for the fleet of trucks and excavators, in R$/h. The price considered for the litre of diesel was R$ 3.55.

$$FC = N^{\underline{o}}\ vehicles \times consumption \times diesel\ price\ \left(\frac{R\$}{l}\right) \tag{2}$$

Cost of Operators. In the determination of *OC*, for the salary (*S*) of an operator a monthly amount of R$ 3,000.00 was considered and a factor (f) on the salary of 2.5 to account for common indirect expenses in Brazil, such as food, insurance life, funeral plan, health plan, vacations, among others. It was also considered that, on average, each operator works 22 days (*D*) a month and, on each day of 8 h worked, 6.16 h (*h*) are effective for the operation. The determination of the cost of fleet operators per hour worked can then be estimated by Eq. 3. The unit of measurement of *OC* is R$/h.

$$OC = N^{\underline{o}}\ operators \times \frac{S \times f}{D \times h} \tag{3}$$

Cost of Tires. The *TC* of the trucks is another extremely important factor to be considered in transport costs in open pit mines. It was considered that each tire would have 3 life expectancies, with the first life expectancy being 3,000 h, the second of 2,000 h and the third of 1,745 h. In order to determine the cost of repair (*RC*) of the tires after each life expectancy, it was considered as the value of 30% on the cost of swap (*SC*) for new tires.

As a result of the calculation of the number of hours worked per year for each truck, it was estimated that the tires of each vehicle undergoes 3 annual repairs and are changed once at the end of the year. The unit of measure of *TC* is R $/h given by Eq. 4.

$$TC = N^{\underline{o}}\ Trucks \times \frac{RC + SC}{h} \tag{4}$$

3 Results and Discussion

From the results obtained, it was possible to create a series of graphs that compare the 3 operational costs (labor, fuel and tires) of the 15 pairs of excavator-trucks. The total cost per tonne moved (R$/t) is shown in Fig. 2. It demonstrates that the lowest cost is R $ 1.20/t (fleet of 200 t trucks with 22 m^3 excavators).

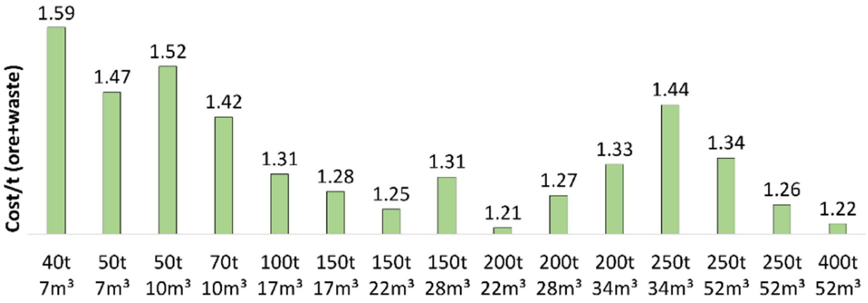


Fig. 2. Cost (R$/t) in function of the fleet.

Figure 2 also shows that there is a tendency to decrease the cost of the tonne moved with the increase in the proportion, however, the costs increase again when considering the application of larger excavators, such as 28 m^3. The fuel consumption of these big machines is mainly responsible for the cost increase: excavators of this magnitude consume more than 250 l/h.

In Brazil, the diesel cost is the most significant operational cost. In this economic analysis, it varied between 59 and 74% of the total costs, with a trend of growth from the lowest to the highest equipment, as can be seen in Fig. 3. In all cases, the consumption of the fleet of trucks is higher than the fleet of excavators. Figure 4 shows, in

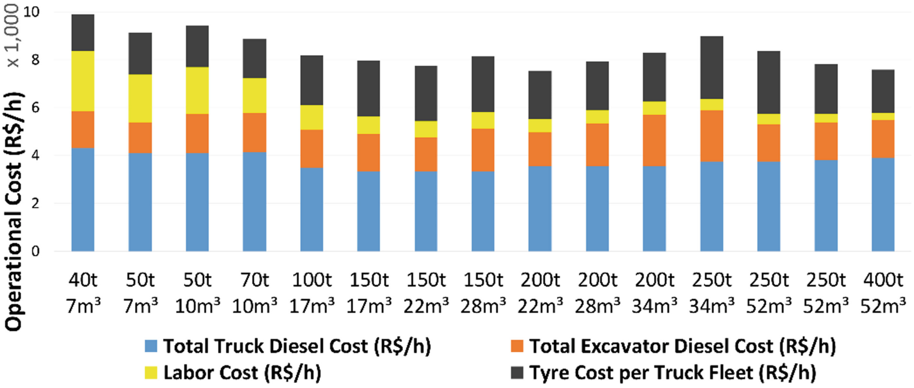
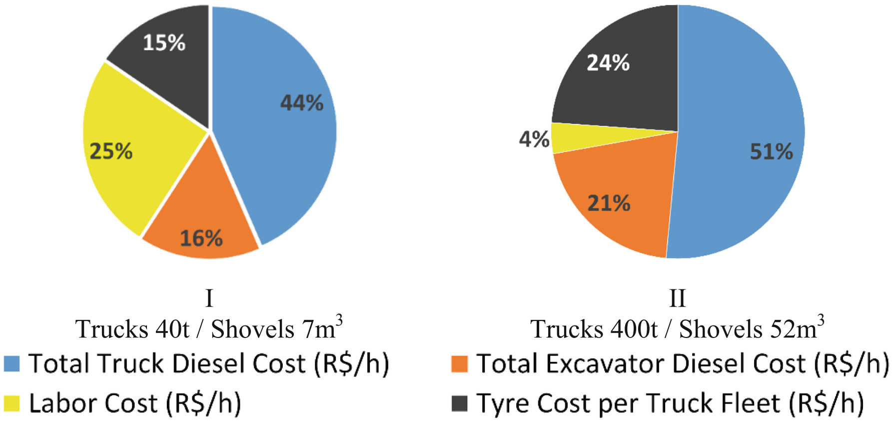


Fig. 3. Composition of total diesel costs per truck, total diesel by excavator, manpower and tires, according to the fleet.

detail, the consumption partition of the smallest fleet and the largest fleet in question: the percentage increase in fuel costs is noticed (from 60 to 72% of the total), while the labor costs decrease dramatically (from 25 to 4% of the total). In fact, the salaries of Brazilian operators are not influenced by the size of the machines, and it is reasonable to assume a constant value independent of the proportion.

The diesel costs are always significant, while the cost of labor is more considerable for small fleets. Figure 5 shows the trend of reducing labor costs with the growth of the fleet. While for the smaller fleets an operational team of almost 60 people is needed, in the larger fleets this number is theoretically less than 10.

The tire costs increase with the growth in the fleet size, and represent up to 31% of total costs. These costs increased moderately with the size, even considering that the number of tires decreases with the growth of the fleet. It was noticed that although the number of trucks is reduced in the larger fleets, the tire cost is higher. The cost of repairing and swapping tires for large trucks can be the double, compared to the costs of small trucks.



I
Trucks 40t / Shovels 7m^3

II
Trucks 400t / Shovels 52m^3

Fig. 4. Detail of the cost partition for the smallest fleet (I) and for the largest fleet (II).

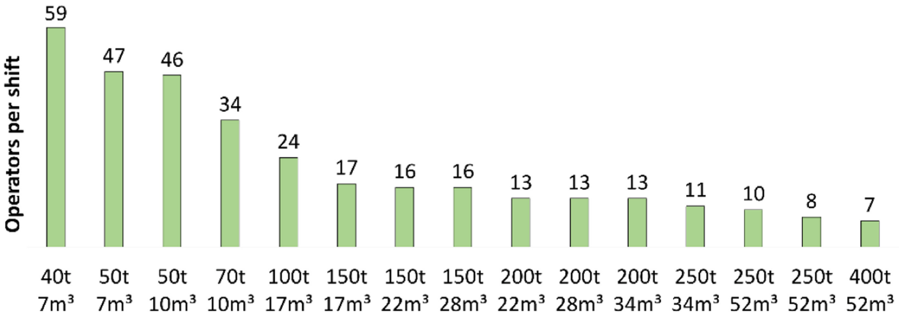


Fig. 5. Number of operators per shift according to equipment size.

4 Conclusion

There is a tendency of reducing costs, as the size increases; however, it is necessary to consider the compatibility between truck and excavator and, mainly, the estimated fuel consumptions that always represented more than 50% of the total cost. In the analysis performed by this article, the most economic model is the one represented by the 200 t truck with the 22 m^3 bucket excavator.

The graphs show that the diesel consumption of trucks represents, in general, the highest percentage of the total operating cost of the loading and transport operation, ranging from 41% to 51%. For the smaller truck fleets, the operator cost represented a large share of the total costs. For the combination of smaller sizes, this cost represented 25% of the total operating cost, while for the larger fleet; this cost represented only 4%.

An interesting point is observed when analyzing the tire cost among the studied fleets. It was noticed that although the number of trucks is reduced in the larger fleets, the tire cost is higher. This shows that despite the smaller number of tires to be restored and replaced, the cost of repairing and replacing large truck tires may be double compared to the cost of small trucks.

Smaller fleets, such as those with 40, 50 and 70 tonne trucks, had higher operational costs than larger fleets. However, it was found that these had an interesting economic range between 150 and 200 t, demonstrating lower operating costs than larger equipment fleets.

In order to apply the conclusions in this article and complete the feasibility studies, the authors suggest that the investment costs, equipment life expectancy, economic life of the equipment, resale value, capacity and deadlines to deliver the machines, spare parts availability and specialized manpower for the maintenance and operation of the equipment, as well as the technical characteristics of the mine may limit the applicability of any of these combinations.

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