

Quality Criterion of the Loading and Transport System Operation at Open-Pit Mines

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Abstract. Loading and transport operations at open-pit mines are performed mainly by heavy loading & transport systems (LTS). One of the main problems of the LTS is a rather low level of its operation quality, mainly due to the imbalanced influence of various factors on the efficiency of the joint operation of shovels and trucks as parts of the LTS. In this article we formulate, derive and analyze a functional criterion for assessing the LTS operation quality at open-pit mines. The rationale, general principles of the functional criterion formation, its general form for mixed (heterogeneous) truck and shovel fleets, which are typical for modern mining LTSs, are presented. For this purpose, modern methods of data collection and processing, mathematical modeling, analysis and synthesis are used. The possibility of assessing the LTS operation quality is very important for identifying the main directions of improving its operational performance and operation quality, for reaching an optimization of the key performance indicators by the quality criterion, and, as a result, for a possible saving of resources during the open-pit mining of minerals.

1 Introduction

It is known that the LTS operation quality can show itself only during performing its task in accordance with its purpose – the timely excavation, loading and transport of the mined material under certain conditions. The LTS operation as a unified system in the mine should be considered as the result of the interaction between its component loading and transport machines with the limitations imposed by the external environment.

The main purpose of assessing the quality of the interaction between mining shovels and trucks in the LTS is to determine how effectively each of them performs its task in specific conditions. For such an assessment, it is necessary to have a functional criterion for the joint operation of shovels and trucks as parts of the LTS.

2 Materials and methods

A functional criterion is the basis to develop a methodology for the non-expert assessment of the open-pit LTS operation quality. This approach has already been implemented in a number of methodologies for assessing the technical level and quality of mining machines.

The problem of determining the rational LTS structure is the subject of a large number of researches, for example [1–6]. There is noted that, from the point of the joint operation

of mining shovels and trucks, the main purpose of shovels, which are the leading machines in the system, is to ensure high performance of the LTS; the main purpose of trucks is to be able to achieve this performance, that is, the shovel and truck fleets operation should be as balanced as possible. It is possible to balance the total performance of N_s shovels available using the required number of N_t trucks by comparing the actual performance of the shovel fleet with the potential (theoretical) performance of the truck fleet.

The total shift (day) operational performance (output) of the LTS shovel fleet can be determined by the following formula [m^3/shift (day)]:

$$P_{\Sigma}^s = \frac{E_b^s}{t_c^s} \cdot N_s \cdot T_{sh} \cdot k_{LTS} \quad (1)$$

where E_b^s – shovel bucket capacity, m^3 ; t_c^s – duration of one shovel cycle (time to load one bucket), min; N_s – number of shovels in the LTS; T_{sh} – working shift (day) duration, h; k_{LTS} – coefficient of the LTS operational performance.

The coefficient of operational performance k_{LTS} is the ratio of the time of pure operation of mining shovels and trucks to the shift duration, taking into account all regulated and unplanned downtimes. After transformation, it can be represented as:

$$k_{LTS} = 1 - \frac{\sum_1^{N_s} t_D^s + \sum_1^{N_t} t_D^t}{T_{sh}(N_s + N_t)} \quad (2)$$

where $\sum_1^{N_s} t_D^s$, $\sum_1^{N_t} t_D^t$ – total downtimes of N_s shovels and N_t trucks per shift (day), h.

$\sum_1^{N_t} t_D^t$ doesn't include the downtime of trucks waiting for loading. It is included in the truck haul duration.

The total theoretical performance of the truck fleet (N_t units) is [m^3/shift (day)]:

$$P_{\Sigma}^t = \frac{E_b^t}{t_h} \cdot N_t \cdot T_{sh} \quad (3)$$

where E_b^t – truck body capacity, m^3 ; t_h – truck haul time from the end of the previous load to the beginning of the next one, h; N_t – number of trucks in the LTS.

The ratio of these performances (P_{Σ}^t and P_{Σ}^s) most characterizes the balance of the joint operation of mining truck and shovel fleets, and, therefore, can serve as a functional criterion for assessing the LTS operation quality. Then we have:

$$\lambda = \frac{P_{\Sigma}^t}{P_{\Sigma}^s} = \frac{E_b^t \cdot N_t \cdot T_{sh} \cdot t_c^s}{E_b^s \cdot N_s \cdot T_{sh} \cdot t_h \cdot k_{LTS}} \quad (4)$$

Considering that $\frac{E_b^t}{E_b^s} = n_b$ is the number of buckets loaded into the truck body, and $t_c^s \cdot n_b = t_L^s$ is the time to load the body by certain shovel, after transformations we get:

$$\lambda = \frac{N_t}{\frac{N_s}{t_L^s} \cdot t_h \cdot k_{LTS}} \quad (5)$$

If we don't take into account the downtime of shovels and trucks, the dependence (4) dwindles into $\frac{N_t \cdot t_c^s}{N_s \cdot t_h}$, which was studied in [7–10] and named “match factor”.

In fact, the functional criterion λ (4) is the ratio of the intensity of truck arrival for loading (λ_t) and the intensity of servicing them by shovels (λ_s). If $\lambda = 1$, then there is an equilibrium point when trucks arrive to shovels with the same intensity with which they are serviced. If $\lambda > 1$, then trucks arrive faster than they are serviced, so we should expect the

truck queues. $\lambda < 1$ indicates that shovels operate faster than trucks arrive, and then shovel downtime waiting for the truck arrival is possible.

Criterion (4) assumes that the truck arrival for loading is even, that is, each subsequent truck arrives for loading at exactly that moment when the previous one is released. However, it's almost impossible to achieve absolutely even movement of trucks in an open-pit mine due to the large number of unforeseen factors. As a result, even if the number of trucks in the LTS is sufficient to transport the entire material loaded by available shovels during the shift (day), downtime of both shovels and trucks will still occur due to the uneven truck arrival for loading. There are many other aspects inherent in the particular mine, such as: possibility of unforeseen truck interactions at the road intersections, impossibility of overtaking (can lead to bunching), different quality of different road sections, poor rock crushing during drilling and blasting (can lead to the loading cycle lengthening), varying degrees of machine wear and driver qualification (affects the speed of trucks).

Criterion (4) also assumes that the fleets of loading and transport equipment are homogeneous, that is, only one size of both trucks and shovels is used. An attempt to consider various options for the fleet structure in determining the functional criterion was made in [11]. However, in practice, most often there are mixed (heterogeneous) fleets. Therefore, we can consider only mixed fleets, for which in formula (4) it is advisable to use the weighted average values of the corresponding indicators. They are defined as follows.

First we need to determine the time required for each shovel to service the trucks working with it. The time to load the trucks (t_{Lj}^s) for each shovel j is determined as:

$$t_{Lj}^s = \sum_1^{N_t} t_{Lij}^s \cdot N_{t_i} \quad (6)$$

where t_{Lij}^s – time to load the truck i by the shovel j .

Then the intensity of service of all trucks by all shovels will be equal to

$$\lambda_s = \sum_1^{N_s} \left(\frac{N_{s_j}}{t_{Lj}^s} \right) \cdot N_t \cdot k_{LTS} \quad (7)$$

The intensity of truck arrival for loading will be defined as (auto/min):

$$\lambda_t = \frac{N_t}{\bar{t}_h} \quad (8)$$

where \bar{t}_h – average haul time (including waiting time) for all trucks per shift (day), min.

Since the truck fleet is mixed, it is advisable to use individual values of truck cycle times, that is, in the formula (7), instead of the average time, weighted average values of individual truck cycles should be used. We have a dependency:

$$\bar{t}_h = \frac{\sum_1^{N_t} (t_{h_i} \cdot N_{t_i})}{N_t} \quad (9)$$

where t_{h_i} – haul time for the truck i , min.

Since the functional criterion λ is the ratio of the intensity of truck arrival for loading to the intensity of servicing by shovels, then, dividing expression (7) by expression (6), and substituting the corresponding expressions (5) and (8), we obtain:

$$\lambda = \frac{N_t}{\sum_1^{N_s} \left[\frac{N_{s_j}}{\sum_1^{N_t} (t_{Lij}^s \cdot N_{t_i})} \right] \sum_1^{N_t} (t_{h_i} \cdot N_{t_i}) \cdot k_{LTS}} \quad (10)$$

It's easy to see that the expression for determining the functional criterion λ (9) is an extended (individualized) version of the original dependence (4).

In the dependence (9), four unknowns are fundamental: t_{Lij}^s – time to load the truck i by shovel j ; t_{hi} – haul time of the truck i (including waiting for loading); $\sum_1^{N_t} t_D^t$, $\sum_1^{N_s} t_D^s$ – downtimes of trucks and shovels during the shift (day), respectively.

The t_{Lij}^s and t_{hi} values can be determined analytically or taken from the actual data of the mine. And if t_{Lij}^s can be determined analytically quite accurately, then the truck haul time t_{hi} is difficult. Therefore, in order to avoid obtaining incorrect results, it is desirable to use actual values. At some mines (at Kuzbassrazrezugol, these are Kedrovsky and Taldinsky coal cuts), there have been installed a system for managing and recording the operation of open-pit vehicles, which allows to record the time of all operations to a second. Analytical calculations or timing should be resorted to if such a system is not installed.

Total downtimes of trucks ($\sum_1^{N_t} t_D^t$) and shovels ($\sum_1^{N_s} t_D^s$) are purely stochastic, therefore its analytical determination is impossible. They should be taken from the mine data.

3 Results and discussion

The summary report on the LTS operation at Kedrovsky mine in the summer period is given in the table.

Table 1. Summary report on the LTS operation at Kedrovsky mine.

Objects, Indicators	Downtime of trucks, t_D^t , min	Downtime of shovels, t_D^s , min	Loading time, t_L^s , min	Truck haul time, t_h , min	Haul time including downtime, $(t_h+t_D^t)$, min
BelAZ-75131 (2 units)	1	2	3	4	5
Work with ES-10/70 (1 unit. 101 hauls)	30.6	426.0	754.9	1481.1	1937.7
Total sum for a group of machines	30.6	426.0	754.9	1481.1	1937.7
In total for a haul (101 hauls)	0.303	4.217	7.474	14.665	19.185
BelAZ-75306 (29 units)	1	2	3	4	5
Work with R-9200 (1 unit. 145 hauls)	315.5	192.0	529.3	4222.3	4879.3
Work with EKG-10 (1 unit. 111 hauls)	241.5	0	624.4	3451.4	3954.3
Work with EKG-12 (1 unit. 119 hauls)	258.9	258.0	496.9	3527.7	4066.9
Work with EKG-15 (2 units. 200 hauls)	435.1	888.0	807.6	5901.4	6807.6
Work with P&H-2800 (2 units. 388 hauls)	844.2	930.0	790.7	10672.7	12430.6
Total sum for a group of machines	2095.2	2268.0	3248.9	27775.5	32138.7
In total for a haul (963 hauls)	2.176	2.355	3.374	28.843	33.374
In total for the mine. including:	2125.8	2694.0	4003.7	29256.8	34076.6
– for 1 shovel (8 units)		336.8	500.5		
– for 1 truck (31 units)	68.6	86.9	129.2	943.8	1099.2
– for 1 haul (1064 hauls)	1.998	2.532	3.763	27.497	(18.32 h)

The value of the functional criterion λ , calculated according to the table, is 0,597, that is, it is far enough from the ideal ($\lambda = 1$). Optimization of the LTS operation will reduce this gap.

4 Conclusion

A distinctive feature of the functional criterion for the system of machines (LTS) is to ensure the rational interaction of the constituent mining shovels and trucks. Shovels as the leading machines of the system should ensure the highest possible performance of the LTS; the task of trucks is to ensure that this performance is achieved, that is, the operation of shovel and truck fleets should be as balanced as possible.

The degree of balance in the total performance of the shovel fleet at a particular mine using the necessary truck fleet can be assessed by comparing the intensity of truck arrival for loading and the intensity of servicing them by shovels.

In the case of homogeneous shovel and truck fleets, the definition of the functional criterion is not difficult. In practice, however, mixed equipment fleets are commonly used, making it difficult to determine the functional criterion due to the need to collect a large amount of statistics, process the available data, conduct time-keeping observations and computing procedures to obtain reliable results.

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