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IMPROVING THE ORGANIZATION OF THE SHOVEL-TRUCK SYSTEMS IN OPEN-PIT COAL MINES

Summary. The aim of the study is to reduce idle times of mining trucks and shovels in an open-pit coal mine. A heuristic algorithm for making dispatching decisions in conditions of dynamic allocation of trucks is developed. Priority parameters for choosing the shovel after the end-of-truck unloading are introduced. Also, an algorithm for searching for the optimal priority parameters to satisfy the required efficiency criterion is developed. This algorithm is based on a simulation model of a shovel-truck system. The proposed approach is applicable in terms of the group of shovels with a common dump point in various open-pit coal mines. The importance of this work lies in the fact that the proposed model takes into account the random factors related with the duration of loading and dumping, truck movement, repair of shovels and haul trucks, as well as the duration of periods between repairs.

1. INTRODUCTION

Most of the world's solid minerals are mined in open-pit mines, particularly in Russia and the CIS. The proportion of open-pit mining in recent decades in the CIS reached a high level (an average of about 75%) and, according to forecasts, will remain at this level for long. A large proportion of open-pit mining is explained by its advantages over underground mining such as higher labor productivity (10-11 times in coal mines), lower production costs (3-4 times) and shorter terms of mine construction (2-3 times) [1].

In Russia, the proportion of open-pit mining in the total coal production currently stands at about 70% (Fig. 1), and it has tendency to increase [2]. Most of the Russian coal is mined in the Kuznetsk Basin (Kuzbass). The leading companies of Kuzbass engaged in open-pit mining of coal are "Kuzbassrazrezugol" and "SDS-Ugol", the share of which accounts for about 20% of Russian coal production.

The materials in open-pit coal mines can be moved in various ways, such as road transport, rail transport, combined transport (by trucks in conjunction with conveyors), hydraulic transport, as well as non-transport handling of overburden. The haul trucks are the main means of transport in open-pit coal mines of Kuzbass. According to official data, they now carry from 85 to 100% of over-burden and all of the coal [3].

With the development of automated methods for the planning of open-pit mining operations and mining truck dispatching, there is a need to create mathematical models and algorithms by which the problem of operational management would be solved. At present, there are two main ways to organize the work of mining trucks.

While working under the strategy of fixed assignment each truck at the beginning of the shift is assigned to a particular shovel and a dump point, and it works with that shovel for the entire shift. Trucks are reassigned only in case of changes in operating conditions (for example, the breakdown of the shovel).

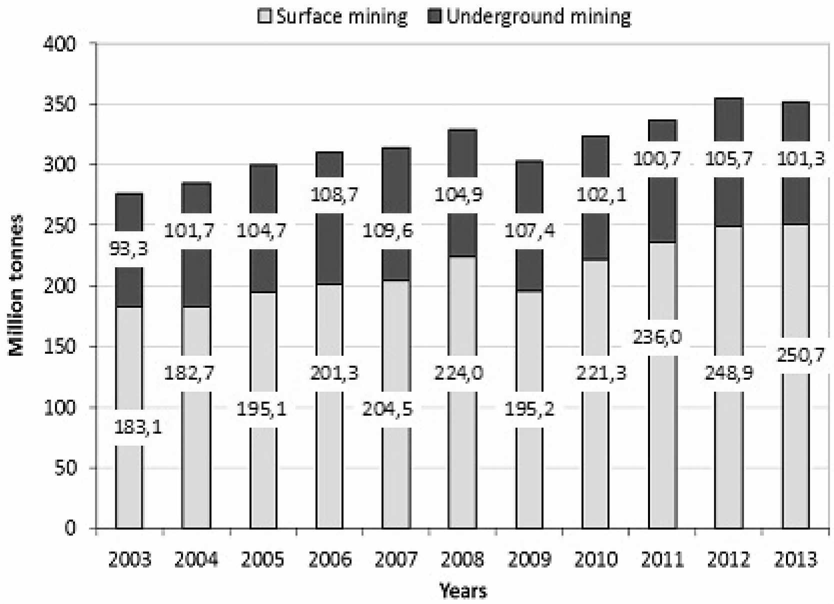

Fig. 1. Coal production in Russia in 2003-2013

This strategy is the most inefficient as the probabilistic nature of transport processes and idle times of mining equipment cause queues to form near particular shovels, whereas other shovels may idle due to the lack of trucks. Such a system achieves the highest productivity when all shovels operate continuously, and trucks arrive to the shovels at equal time intervals. However, it is quite difficult to ensure the timely arrival of trucks to the shovels due to the impact of uncontrollable factors.

Currently, all Russian coal cuts organize the work of their shovel-truck systems under the strategy of fixed assignment, which leads to significant idle times of trucks and, sometimes, shovels.

Fig. 2 shows the distribution of haul-truck idle times at one of the "Kuzbassrazrezugol" affiliates ("Kedrovsky" cut) – according to the results of 2013. Data were obtained by the automated dispatching system, which is currently operating in the mine. The figure shows that the largest proportion among the possible idle times of trucks is taken by waiting for loading. These idle times appear mainly due to poor organization of the work of the shovel-truck system, and it can be significantly reduced by effective organization. This will increase the utilization of equipment and, consequently, increase the productivity.

The method of dynamic allocation can be used, in which the truck, after dumping, is assigned to a free (or a less busy) shovel, based on the selected dispatching criterion. This will significantly reduce the idle time of the cargo-handling equipment and improve its performance. However, there are some problems: first, the difficulty of such management, and, second, the possible mismatch between the sizes of trucks and shovels, which can lead to increased truck idle time and decreased productivity of the shovel-truck system.

Therefore, a modified method of dynamic allocation is considered to be more rational. In this method, a dispatching system (or a human dispatcher) forms the so-called "dispatching groups" consisting of the specific shovels and dump points that will work together. Each of these groups is attached to a certain number of trucks, which are assigned to the loading points according to the method of dynamic allocation.

Dynamic allocation of mining trucks between the shovels (or dispatching) is traditionally used to improve the utilization of equipment for open-pit mining. The primary objective of existing automated dispatching systems is to reduce the capital and operating costs through more efficient use of available trucks and shovels as a part of the shovel-truck systems. Dispatching is a dynamic process that requires continuous monitoring of routes and locations of trucks and shovels. Applying dispatching can either increase productivity of the shovel-truck system with the available equipment, or provide a desired performance with less equipment.

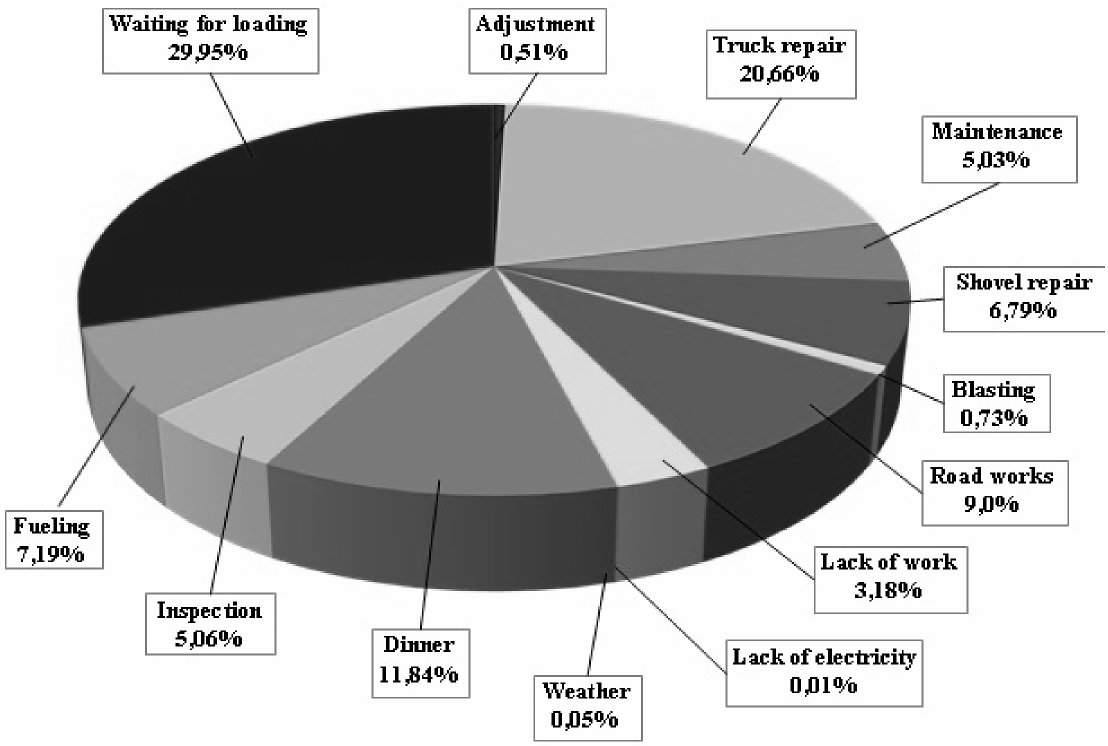

Fig. 2. Distribution of haul-truck idle times in the "Kedrovsky" cut in 2013

This can be achieved by making optimal dispatching decisions, which reduce idle times and improves the utilization of mining equipment. Trucks are productive only when they are carrying cargo (minerals or overburden), and loaders only when they are loading cargo. Therefore, idle times show the unproductive use of equipment and should be minimized.

2. PROPOSED METHODS

There are two main approaches to mining truck dispatching – the single-stage and the multi-stage [4]. When the single-stage approach is used, trucks are allocated between shovels guided only by available experience, without taking into account any specific needs or operation conditions. In fact, it is a heuristic approach, which has a purely empirical nature. In multi-stage systems, the dispatching problem is usually subdivided into two stages: on the upper stage there is the setting of production targets for shovels, on the lower stage – allocation of trucks between shovels so as to minimize the deviation from the target, which was set at the upper stage.

A linear or non-linear programming model is generally used at the upper stage, and there is a heuristic method at the lower stage since the dispatching decisions must be made in real time. Approximate methods of quick solutions, in many cases, may be preferable to the accurate solutions by optimal methods since the accurate solutions require a large amount of time [5].

Heuristic methods are relatively simple, and in most cases are able to solve the problem, but do not guarantee an optimal solution. Dispatching systems based on heuristic principles are more easy to implement and do not require large computing power to make decisions in real time. They provide the assignment of "one truck at one time". Every decision is made regardless of further action [5].

The problem of mining truck dispatching is that for each truck, leaving the unloading zone, a dispatcher needs to choose the most suitable loading point. Usually this point is the one that best satisfies any "dispatching criterion" [6]. Different criteria are used for the allocation of mining trucks between loading points, and a common goal is to maximize the productivity of the shovel-truck system or minimize the inefficient use of equipment (i.e. idle times) under specified conditions. A detailed description of these criteria and existing methods of dispatching were made in [4, 6-10]. In addition to aforementioned single-stage and multi-stage approaches, Alarie and Gamache [4] also distinguish three main strategies of dispatching: "1-truck-for-N-shovels", "M-trucks-for-1-shovel", "M-trucks-for-N-shovels".

It is no doubt that the open-pit mining operations have a probabilistic nature. Different operation durations can vary significantly from time to time, and the use of average time values can lead to incorrect decisions. It means that the mining truck dispatching problem can be solved correctly only with the help of simulation modeling.

Variation patterns of duration of technological operations and maintenance of various types of equipment are best described by a gamma distribution [11]. In addition, a gamma distribution for these time components is recommended in a classical work on simulation [12]. The process of material transporting is described by a closed queuing network (with the same number of truck requests), for which analytical formulas are derived only for the exponential distribution of technological operation duration [13]. It proves the need for simulation of a solution to the dispatching problem.

There are quite a large number of simulation models, which explore the shovel-truck systems in open-pit mines. Detailed reviews of existing models were made in [5, 9, 14-20]. Some of them only visualize processes in the shovel-truck systems or simply evaluate the effectiveness of the proposed methods [14, 15]. The others do not consider the uncertainties of mining operations [18-20]. Genetic algorithms [9] need a lot of time to make dispatching decisions. An effective dispatching algorithm should be accurate and fast enough.

A dispatching model that consists of two stages is proposed in the current paper. At the upper stage a production target for each shovel is defined and a rational allocation of cargo flows between the available routes is made. These production targets are then used as system optimization constraints; this optimization occurs at the upper stage.

"Dispatching groups" are also formed at the upper stage; dynamic allocation is used in these groups. They include shovels working with the same type of material, located at the same mining site and able to be serviced by the same type of haul trucks. It is recommended to use the same type of trucks in the groups, as this will minimize their idle time while waiting for loading; in addition, the effect of truck-bunching on routes will also be reduced [1, 21]. The policy of forming the haul-truck fleets at Russian mines usually makes it possible. The ratio between the capacities of a truck body and a shovel bucket should also be taken into account.

At the lower stage we propose an algorithm for dynamic allocation of trucks between shovels in real time. To reduce the total idle times of trucks and shovels, the expected idle time of the considered truck should aspire to the minimum while making a dispatching decision; i.e., it is necessary to find a shovel upon arrival to which the truck will be loaded in the shortest time. This will reduce both the queue of trucks waiting for loading, and the risk of shovel idle times. This MTWT (minimizing truck waiting time) criterion is reported to be the best for most of the real situations [8].

Therefore, the following criterion for making dispatching decisions is proposed:

$$j^* = \arg\min_j \frac{T_j + \delta}{x_j}$$

or, in more detail,

$$j^* = \arg\min_j \frac{\left(T_j^e - t_c - T_j^m\right)_+ + \delta}{x_j}, \tag{1}$$

where j^* – number of the shovel, to which the truck will be assigned; T_j – expected "idle time" of a truck after assignment to shovel j; T_j^e – expected "emptying time" (the end of the last loading) for shovel j, including trucks already in queue near this shovel, as well as on the way to it; t_c – "current time" elapsed from the start of the shift; T_j^m – expected "movement time" for the truck being assigned to reach the shovel j; x_j – priority parameter of the shovel j and the corresponding transportation route; δ – small value, allowing the choice of the highest-priority destination in the absence of idle times and in the possibility of assigning the truck to several destinations.

In order to speed calculations for the simulation model, the expected "emptying time" and "movement time" are deterministic here (but only here) and also do not consider the possibility of equipment breakdowns.

This dispatching system assigns one truck at one time. So, we can say that our system is closer to the "1-truck-for-N-shovels" one. The approximate scheme of making a dispatching decision is shown in Fig. 3.

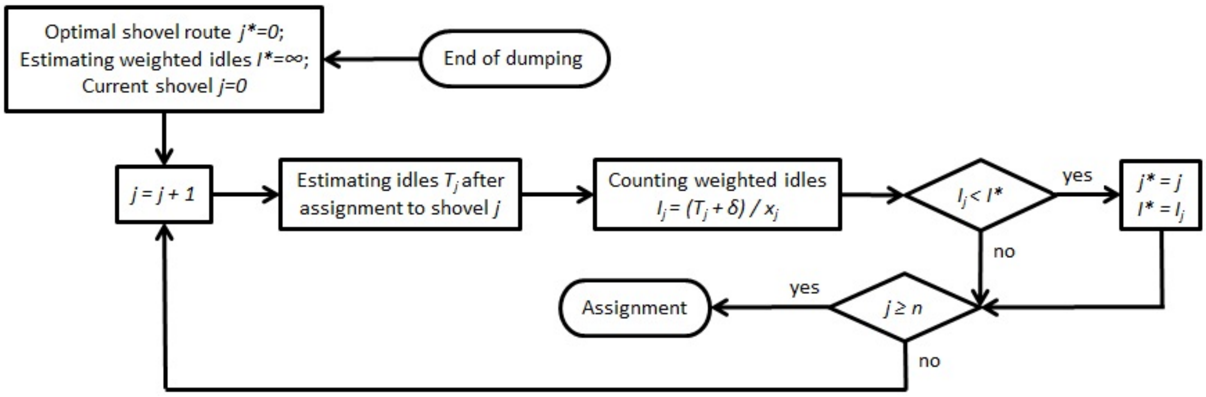

Fig. 3. A flowchart of dispatching decision

The selection of priority parameters takes place at the upper stage. Let n be the number of shovels in a certain dispatching group, then $X = (x_1, x_2, ..., x_n)$ is the priority parameter vector. Simulation allows estimating the characteristics of the system – C(X) – by statistical methods. It is necessary to simulate a sufficiently large number of shifts to obtain an accurate estimation, so the central limit theorem of the probability theory can be used to determine the stopping rule.

Let $\hat{C}_k(X)$ be the average value of a characteristic for k tests (or simulation program runs), S_k^2 be the value of a characteristic with the selection variance, ΔC be the allowable error. Then the calculation error will be equal to

$$P\left(\left|C(X) - \hat{C}_k(X)\right| < \Delta C\right) = F\left(\frac{\Delta C}{S_k^2}\right) - F\left(\frac{-\Delta C}{S_k^2}\right), \quad (2)$$

where F is the function of the standard normal distribution.

Under these conditions, the number of program runs – k – increases as long as the probability of appearing in a confidence interval (2) reaches the required value.

The next problem to be solved is the search for optimal priority parameters:

$$X^* = \arg\min_X \hat{C}_k(X). \quad (3)$$

The solution to this problem requires significant computing resources since the estimation of $\hat{C}_k$ for each set of X is obtained by simulation. To reduce the time spent, the following method is used. For making dispatching decisions (1) it is important to know the ratio between the priority parameters, i.e., by how many times is one parameter greater than the other. Let the first parameter be $x_1 = 1$, and parameter step be q > 1. The priority parameter of shovel j ranges between $q^{-m} < x_j < q^m$, where m is a non-negative integer. Thus, each parameter can take (2m + 1) values. That is, there will be $(2m+1)^{n-1}$ calculations of $\hat{C}_k$ required to solve problem (3) using full sorting. Thus, we have an uneven scale that allows us to consider symmetrical proportions, as well as to describe various parameter ratios for a smaller number of variations (in comparison with an even scale).

C(X) is presented as money losses because of idle times of all shovels and all trucks in the considered dispatching group per shift. It is measured in Russian rubles (RUR). Since the cost of idle times for different shovels and trucks is not the same, the criterion of priority parameter selection may be presented as follows:

$$C(X) = \sum_{j=1}^{n} c_j^s \cdot I_j^s + \sum_{j=1}^{n} c^t \cdot I_j^t \to min, \tag{4}$$

where c_j^s – cost of idle time of shovel j, RUR/h; I_j^s – expected idle time of shovel j per shift, h; c^t – cost of idle time of same-type trucks in a group, RUR/h; I_j^t – expected idle of trucks near the shovel j per shift, h.

The cost of the idle time for each type of equipment is defined as the lost financial benefit from coal that was not produced and was not sold as a result of idle time. It can be approximately determined by the following formula:

$$c = \frac{W_h}{r_s} \cdot c_c, \tag{5}$$

where W_h – operating performance of the piece of equipment for overburden, m3/h; r_s – stripping ratio, m3/t; c_c – average market cost of coal, RUR/t.

If the idle times of equipment are reduced, the overall production is increased, and as a result, the mine’s revenue is increased too. However, we believe that maximizing production should not be an end in itself. For example, the continuous use of a high-productive shovel (located close to the dump) will undoubtedly increase the overall production, but will lead to inadequate use of other shovels. At a coal mine, the use of all loading points should be as even as possible. For this, each shovel simply has to fulfill its production plan with minimal costs (or with maximum profit). The increase in production is advisable only to reduce the number of working haul trucks.

As a result of calculations on the simulation model, for the different number of trucks working in a group, the set of priority parameters, which best satisfies condition (4), is selected. Condition (4) is also the estimation of dispatching algorithm efficiency at the lower stage of the dispatching system.

Priority parameters, defined at the upper stage, are entered to the database and will then be used for making dispatching decisions at the lower stage. There is a link between the two stages: if any significant change takes place in the operating environment (for example, change of travel distances, replacement of a shovel, equipment breakdowns, etc.), the parameters are revalued.

3. RESULTS AND DISCUSSION

Under the conditions of the "Kedrovsky" cut (the data is for July 5, 2013) one dispatching group was selected. Only the transportation of overburden was considered, since the overburden is the main cargo in open-pit coal mines. The group included two shovels – EKG-12us with a bucket of 12,5 m3 and P&H-2800 with a bucket of 33 m3, which worked with one dump. The average transportation distances, according to an automated dispatching system, were 4,2 km for EKG-12us and 3,95 km for P&H-2800. The group used the same type of trucks – BelAZ-75306 – with a carrying capacity of 220 tons. The whole 10-hour shift was simulated; confidence was 90%.

The calculations were carried out for the working modes of fixed assignment and dynamic allocation. The calculation results are shown in Figs. 4 and 5.

Fig. 4 shows that the organization of the work of a shovel-truck system under the strategy of dynamic allocation provides significant cost savings compared with a fixed assignment – mainly due to the reduction of truck idle times. At the optimum number of trucks for the dynamic allocation – 18 – reduction of losses from idle time equals 12,6%, or almost 139 thousand rubles per shift. On average, for various numbers of trucks, the reduction of losses from idle time will be 7,3%.

Working on the principle of dynamic allocation gives performance gain too. With 14 trucks in a group, fixed assignment allows carrying only 50800 tons of overburden, while dynamic allocation allows carrying around 52900 tons, that is, 4% more. Therefore, if the production target is set at no less than 52500 tons per shift (which nearly corresponds to the actual production of shovels in a group), the fixed assignment will require one truck more. This suggests that the organization of the work of a shovel-truck system on the principle of dynamic allocation can provide cost savings not only by reducing the idle time of mining equipment, but also by reducing the number of operating trucks.

It should be noted that the optimum number of trucks on the criterion of a minimum of losses from idle time is not always possible in practice, since the expected production of shovel-truck system can be more (or less) than the production target. In this case, we have to be restricted by the production target, which corresponds to the actual operating performance of shovels. This restriction is implemented in the proposed simulation model, that is, the program allows choosing only those options that ensure desired production.

Fig. 5 shows that for any number of trucks the more productive P&H-2800 shovel has higher priority than the EKG-12us shovel $(x_2 > x_1)$. It is quite obvious that fast loading of the shovel leads to a greater probability of its being idle. Therefore, it is necessary to assign more trucks to this shovel. But the most interesting is the ratio of the priority parameters to each other. The smooth sector of the graph (from 1 to 10 trucks) indicates that, at a relatively small number of haul trucks, both shovels are usually available while making dispatching decisions. The leap (from 11 to 13 trucks) indicates instability of the shovel-truck system; the probability of controversial situations while making dispatching decisions increases rapidly. Next, starting from 14 trucks, the situation is stabilized again. Both shovels are busy; there is an overage of trucks.

Based on these calculations, we can conclude about the rational number of trucks in a group. This feature can be used to estimate the rational number of haul trucks in the absence of the production target in the mine (or lack of data on it).

The adequacy of the simulation model was checked for the route with EKG-12us shovel and 4 BelAZ-75306 trucks (under fixed assignment). The average deviation for truck cycles was 1,65%, and for idle time of trucks – 5,2%. So, we can say that our model is adequate for a real scenario.

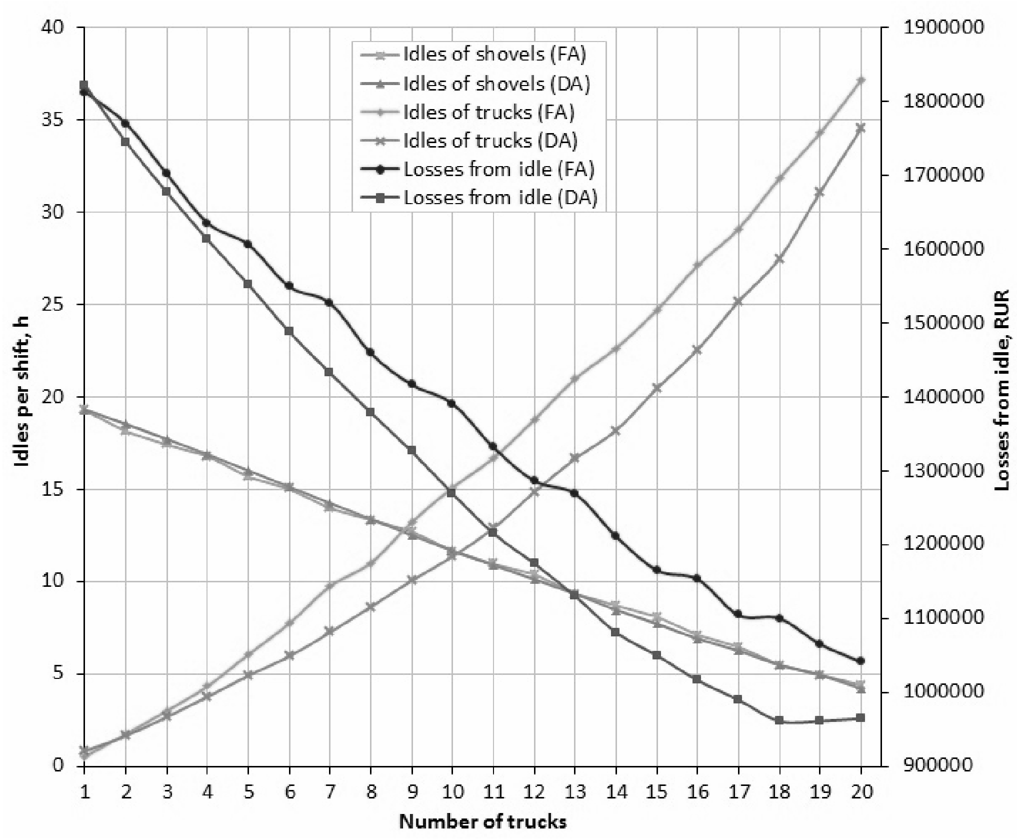

Fig. 4. Idle times of mining equipment and losses from idle time for various numbers of trucks for the modes of fixed assignment (FA) and dynamic allocation (DA)

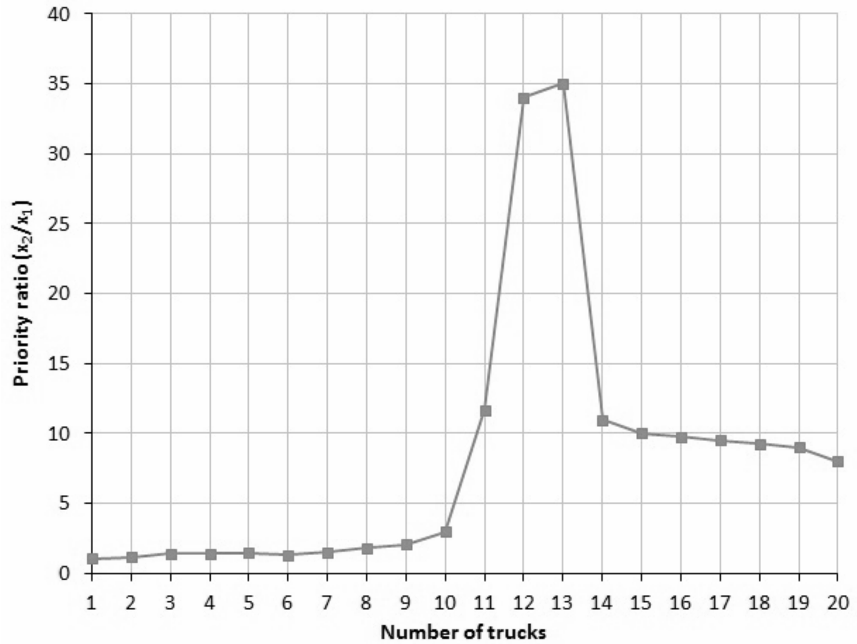

Fig. 5. Priority parameters of shovels for various numbers of trucks for the mode of dynamic allocation

4. CONCLUSION

In the paper, the lower stage of the mining truck dispatching system is considered, on which the dynamic allocation of haul trucks between the loading points (shovels) is performed. The concept of "priority parameter" of the shovel and the corresponding route of material transportation is introduced. Also it is shown that the work of mining shovel-truck systems without fixed assignment of trucks to shovels and after taking into account the priority parameters of various routes allows getting significant cost savings by reducing the idle time of mining equipment and the number of operating trucks.

In the future it is planned to introduce a developed simulation program, which calculates the priority parameters in the dispatching systems currently operating in the open-pit coal mines of Kuzbass. It also makes sense to extend the functionality of the model, so that it could be used in ore mines.

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