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Assessment of operational reliability of quarry excavator-dump truck complexes

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The method proposed in the article is based on the mathematical apparatus for quantitative assessment of the reliability of majority schemes of structural redundancy of transport processes, which provide the availability and usage of several backup delivery channels in the transport process in case of any malfunction. The principle of multi-channel haulage is commonly used in quarries for transportation of overburden and minerals from benches by dump trucks, when excavators and dump trucks performing cyclic operations function as a single excavator-dump truck complex. This pattern of work significantly increases the likelihood of fulfilling the daily plan for transporting rock mass due to the redistribution of dump trucks between mining and overburden excavators in the event of failure of one or more units of mining and handling equipment.

The reliability of excavator-dump truck complexes is assessed in three stages: initial data collection for mathematical modeling of excavator-dump truck complex performance; solving the problem of optimizing the distribution of dump trucks between excavators, ensuring maximum productivity of the excavator-dump truck complex; assessment of the reliability of its work depending on the probability of fulfilling the daily plan for the transportation of rock mass.

The proposed method is implemented as part of a computer program and makes it possible to automate the operational management of the process of transporting rock mass in a quarry using a mobile application. The developed guidelines can be used for any quarries with automobile transport, regardless of the type of mineral extracted, the mining method, the loading pattern, the capacity of the excavation and loading equipment fleet, and the capacity of operated dump trucks.

Key words: excavator and dump truck complex; reliability of the transport process; majority schemes of structural redundancy; rock mass; optimal transportation plan; excavation and loading operations

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Introduction. The volume of rock mass haulage per day (shift) is determined by a combination of factors, including the number of fully operational excavators and dump trucks, the distance of transportation of overburden and minerals, respectively, to a dump or warehouse, weather conditions affecting the state of benches and haul roads, and others. The transportation plans are often disrupted by the failures of mining, handling, and transport equipment. Unscheduled repair of equipment significantly complicates the planning of the mining operations, therefore, the only way to fulfill the transportation plan for overburden and mineral resources is to redistribute working dump trucks between available excavators to have the most efficient performance of the excavator-dump trucks complex.

The scientific literature offers various methods for determining the performance of excavator-automobile complexes in continuous and deep mining systems. This paper presents guidelines for selecting patterns for distributing dump trucks between excavators based on the following: the influence of mining and technical parameters of the scope of work on the productivity of the excavator-automobile complex [1, 4, 6]; the quantitative composition of excavator-automobile complexes [11] and their usage domain in the quarry [12]; ensuring the operating capacity of loading, extracting and haulage equipment with modern means of diagnosing the technical condition and monitoring the performance of mining machines [3, 8, 9].

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Equality of volumes of excavation and transportation of rock mass requires finding the best option for the distribution of dump trucks between excavators. To solve this problem, we used a set of methods for optimizing transport processes, particularly algorithms for determining the shortest distances and optimizing the transportation plan [10].

The mathematical apparatus of the proposed methodology was based on using the principles of calculating the reliability of technical processes and systems described in [7, 13, 14]. The formulation of the definitions of reliability and failure of the transport process, as well as the systematization of reservation methods to increase the reliability of transport due to failure-free operation, was based on these papers. The results of the studies are presented in the publications of the authors, for example, in [5]. A method for calculating the reliability of the transport process when using major patterns of structural redundancy is described in [2].

The degree of study of the issue considered in this article in relation to its specific tasks is quite high. There are methods for calculating the productivity of mining and transport equipment in quarries, considering a wide variety of performance factors. Known methods for optimizing transport processes are used to increase the efficiency of technological processes in open cast mining.

However, existing methods do not fully cover the possibility of using the features of the transportation process management in quarries with road transport due to multiple channels and majority issues to improve the reliability of loading, excavating and transport vehicles. This determined the task of the current research: to develop the methodology for assessing the reliability of excavator-dump track complexes based on major structural redundancy patterns. The solution to this problem will automate the operational management of haulage in a quarry with road transport, regardless of the open-pit mining method, the loading schemes, the capacity of the excavation and loading equipment and the load capacity of operating dump trucks.

Methodology. The development of the proposed assessment method was carried out using the following research methods: analysis of scientific and normative documentation, system analysis, linear programming of transport processes, and computer simulation. At the implementation stage we used the following research methods: field observations, time and motion study, statistical, technical and economic analysis.

Description of research methods:

1. Development of the proposed method:

• Analysis of scientific and normative documentation – the study of existing solutions to the problem and the technical characteristics of modern mining and loading equipment and dump trucks.

• System analysis – establishing the boundaries of process steps of the mining and transport system of a quarry: extraction, excavation, loading, transportation, unloading, and storage of rock mass.

• Linear programming of transport processes – writing a computer program algorithm.

• Simulation computer modeling – program debugging, formalization and assessment of calculation results.

2. Implementation of the proposed method:

• Field observations – the identification and assessment of the degree of influence of organizational and technological factors on the productivity of the excavator-dump track complex.

• Time and motion study – determining the time needed to perform certain technological steps of the transport process, management working hours of dump truck and excavator drivers.

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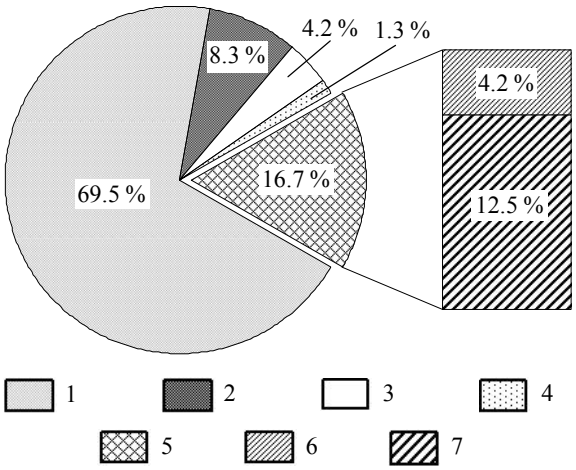


Fig.1. Workday of dump truck drivers of OJSC "Loga" hauling the overburden rock

1 – work; 2 – lunch; 3 – shift turn over; 4 – zero haulage; 5 – loss of work time; 6 – operational downtime; 7 – uncontrolled downtime

• Statistical analysis – statistical processing of the time and motion results to build the input database.

• Technical and economic analysis – analysis of the results and assessment of the economic effect.

The assessment of the calculation results and the effectiveness of the implementation of the proposed method are mainly determined by the accuracy of identifying and assessing the degree of influence of various organizational and technological factors on the performance of the excavator-dump truck complex. For example, in [2] based on field observations and time and motion study it was found that on certain shifts the downtime of the excavator-dump tuck complex (EDTC) due to process delay (preparation of bench, cleaning of access roads to a bench, intra shift maintenance of vehicles) were insignificant (about 4 %) (Fig.1). As can be seen from the figure, the main performance losses are associated with uncontrolled downtime caused by a low level of production management, as was confirmed by long lunch break of drivers, the distraction of dump trucks to fill the quarry ramps, and the ending of shift before the scheduled time.

The list of organizational and technological factors and their influence on the performance of the excavator-dump truck complex vary for each quarry.

Discussion. *Mathematical model.* The solution to the problem of the optimal distribution of dump trucks between excavators uses a mathematical model with the objective function of maximizing the total volume of transported rock mass in a quarry per shift:

$$Q_{\text{tr}}^{\text{EDTC}} = \sum_{i=1}^{A_{\text{i}}} (n_{\text{trn}} q_{\text{vol}})_i \rightarrow \max, \tag{1}$$

where n_{trn} – turnover of the ith truck per shift; q_{vol} – volume of rock mass carried by truck per a turnover, m^3; A_{i} – number of trucks on the line, items.

The system of limitations of the optimization mathematical model is determined by the operation of dump trucks on the shuttle routes with unchanging haulage distance. The model works when the number of dump trucks exceeds the number of excavators. In addition, the mandatory value is the ratio of the dump truck capacity to the excavator bucket in the range from 1:3 to 1:7:

$$\begin{cases} l_{\text{h.l}} = \text{const}; \\ \beta = 0.5; \\ A_{\text{i}} > A_{\text{e}}; \\ 3 \le \dfrac{Q_{\text{tr}}}{Q_{\text{buck}}} \le 7, \end{cases} \tag{2}$$

where $l_{h.l}$ – haulage distance with a load, km; β – loaded truck mileage proportion per one ride; A_{i}, A_{e} – number of trucks and excavators involved in haulage and loading, items; Q_{tr}, Q_{buck} – capacity of truck body and excavator bucket, m^3.

For the proposed mathematical model, the use of mining, loading and transport equipment with the same technical and operational characteristics is not a limitation. The model will be applicable for excavators of various capacities of a bucket and dump truck bodies.

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According to the results of calculating the shift capacity of each dump truck from the vehicle pool of the quarry, its total productivity is determined for any of the possible combinations of available excavators. These calculations are easily automated on a computer, as well as the options of their distribution. The variant providing the maximum total performance will be optimal.

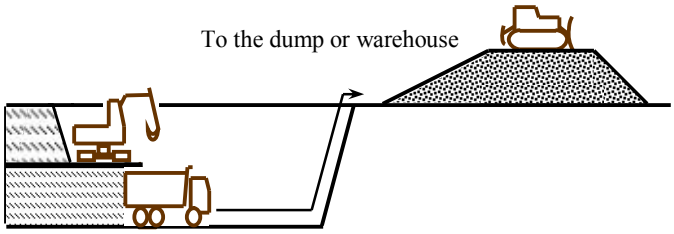


Fig.2. Scheme of bottom loading with haulage of overburden or rock mass with dump trucks in case of absence of processing plant

At the next stage, it is necessary to conduct a quantitative assessment of the reliability of the optimal option. In reliability theory, the method for assessing the reliability of any object depends on the type of connection scheme of its structural elements. The connection diagram of the elements of the excavator-dump truck complex is created based on the following considerations.

In the quarry, the overburden and mining excavators are the sources of material flow. The endpoints of the flow are the dumps of waste rock or the warehouse of mined minerals. The waste is dumped with bulldozers. In the absence of a processing plant, mined minerals are stored in the same way (Fig. 2). The presence of a processing plant limits the flow of ore, coal or other extracted raw materials from the quarry, which are sent to the receiving hopper of the crushing line. Dump trucks move the material flow from the starting point to the end.

The joint operation of several excavators, dump trucks and bulldozers ensures the continuous parallel channels for delivering rock mass from the quarry. This operation scheme significantly improves the reliability of the transport system, since the failure-free operation does not require the simultaneous operation of all delivery channels. The performance is provided with the minimum required number, which ensures the implementation of a shift plan for the transportation of overburden and mineral resources.

Thus, the excavator-dump truck complex includes excavator, haulage and bulldozer units. The formulas for assessing the reliability of each unit are different, which is explained by the differences in the applied distribution methods. For example, the principle of a “roving” redundancy is used in the operation of the excavator unit – one of the E_r excavators is spare and used during the scheduled maintenance or unscheduled repairs of the main n units of the excavator fleet. In reliability theory, such schemes are called majority schemes of general redundancy by substitution. In the absence of a “roving” redundancy, the reliability of the excavator unit will be assessed in the same way as the reliability of the transport unit.

The transport unit uses the majority permanent redundancy scheme with fractional multiplicity and spare rock delivery channels constantly included in the operation, the number of which exceeds 1.0. This redundancy scheme determines the maximum possible l and necessary h number of channels, required for the uninterrupted delivery of overburden from the quarry to the dump or mineral to the warehouse or processing plant. The value of h is determined by the total productivity of the delivery channels, which ensures the implementation of the daily plan for the transportation of rock mass. The maximum possible number of channels l is equal to the number of delivering dump trucks. The difference $(l - h)$ represents the number of redundant delivery channels.

The bulldozer unit uses the principle of “active” redundancy when, for example, two bulldozers work in the dump, although one bulldozer out of fully operational m is enough to form this type of reserve without violating the current mining technology. It doesn’t matter which of the two bulldozers is the backup and which is the main. In this case, there is a constant backup scheme with integer multiplicity (Fig.3).

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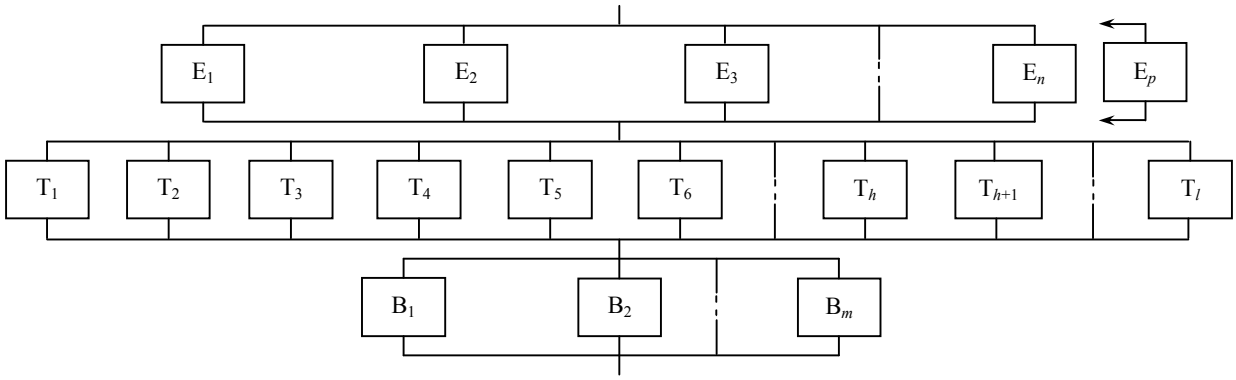


Fig.3. The scheme of excavator-dump truck complex of the quarry for performance reliability assessment
E – excavator; T – dump truck; B – bulldozer

A quantitative assessment of the reliability of excavator and automobile units is calculated taking into account the probability of their failure-free operation over time t:

• excavator unit

$$P_{\text{e}} = P_{l-h} + P_{\text{s}} \sum_{i=1}^{\frac{t}{t-t_i}} [P_{t,t_i} Q_{t,t_i}] Q_{l-h}, \tag{3}$$

where P_{l-h}, Q_{l-h} – accordingly, the probability of failure-free operation and failure of the main and backup $(l-h)$ delivery channels over time t; P_{t,t_i}, Q_{t,t_i} – the probability of failure-free operation and the failure of one redundancy channel within the time $(t-t_i)$; P_{s} – the probability of failure-free operation of a switcher;

• transport unit

$$P_{\text{tr}} = 1 - [P^l + lP^{l-1}Q + \frac{l(l-1)}{2!}P^{l-2}Q^2 + \frac{l(l-1)(l-2)}{3!}P^{l-3}Q^3 + \\ + \frac{l(l-1)(l-2)(l-3)}{4!}P^{l-4}Q^4 + \ldots + Q^l], \tag{4}$$

where P,Q – the probability of failure-free operation and the failure of a dump truck when h main channels are working out of l possible;

• bulldozer unit

$$P_{\text{b}} = 1 - \prod_{i=1}^{m} (1-P)_i. \tag{5}$$

The proposed mathematical apparatus is implemented on the example of overburden transportation during the construction of the Mikheevsky mine (Varna district, Chelyabinsk region) by one of the contractors of OJSC "Loga" (Magnitogorsk).

Calculations. The transported overburden is a clay-sand mixture with a density of 1.6 t/m^3. Loosening of the overburden rock mass is carried out simultaneously with extraction by an excavator. In difficult areas, loosening is performed mechanically using a bulldozer equipped with a ripper. Excavation and loading operations are carried out by three hydraulic backhoe loaders with a bucket capacity of 1.44-2.0 m^3. The fourth excavator is a backup.

In winter groundwater leads to the formation of large pieces of frozen rock that can fit in the bucket of an excavator. Separate storage and subsequent crushing of frozen pieces are not required. However, high moisture content contributes to the sticking and freezing of the transported overburden to the excavator buckets, bulldozer dumps, dump bottoms and sides, which negatively affects the operational performance of the mining and transport equipment of the quarry.

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Loading areas are organized as dead ends and passageways, with top or bottom loading. The platforms for maneuvering dump trucks are formed at the working bench. The overburden loading is carried out in three- and four-axle dump trucks with a carrying capacity of 20-30 tons: HOWO – 1 unit; SAMS – 2 units; DONG-FANG – 4 units.; MAN – 1 unit; KAMAZ-6520 – 4 units.

Overburden is delivered by shuttles from the quarry to the dump. The length of a route, depending on the movement, varies between 0.5-2.0 km. The maximum longitudinal slope of the highway is 10 ‰. Roads in the quarry are temporary, the surface is periodically bladed by a grader. Overburden is unloaded from the dump truck to the ground at a distance of 5-7 m to the edge of the protection embankment. After dumping the unloaded rock mass is moved by two B-130 bulldozers.

The most time-consuming is the calculation of the reliability of the transport unit since in order to determine the minimum required number of delivery channels that ensure the failure-free operation of the excavator-dump truck complex, it is necessary to calculate the time of the return route of dump trucks and their shift capacity. The turnover time depends on the duration of the technological operations performed by the dump truck during the turnover: loading, haulage, maneuvering before unloading, unloading, moving without material, waiting for loading, and maneuvering before loading. The duration of technological operations of the transport process is determined by time and movement study. The calculation of the turnover time is made for options for loading dump trucks with excavators with different bucket capacities. An example of the calculation results for the HITACHI excavator loading option with a bucket capacity of 2.0 m^3 is given in Table 1.

Table 1

Calculation of turnover time for dump trucks when loading with HITACHI excavator (2.0 m^3)

Brand of dump truck	Standard route distance, km	Turnover time	
		min:s	h
KAMAZ-6520	0.5	12:08	0.202
	1.0	16:55	0.282
	1.5	21:43	0.362
	2.0	26:32	0.442
DONG-FANG	0.5	12:54	0.215
	1.0	17:41	0.295
	1.5	22:29	0.375
	2.0	27:18	0.455
MAN	0.5	15:37	0.260
	1.0	20:24	0.340
	1.5	25:12	0.420
	2.0	30:01	0.500
HOWO	0.5	11:56	0.199
	1.0	16:43	0.279
	1.5	21:31	0.359
	2.0	26:20	0.439
SAMS (3 axles)	0.5	12:29	0.208
	1.0	17:16	0.288
SAMS (3 axles)	1.5	22:04	0.368
	2.0	26:53	0.448
SAMS (4 axles)	0.5	12:29	0.208
	1.0	17:16	0.288
	1.5	22:04	0.368
	2.0	26:53	0.448

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The shift performance of the dump truck, in addition to the time of the return trip, is determined by the time it worked on the route and performing the work order, the duration of the zero run and lunch break, and other elements of the working day of dump truck drivers (see Fig.1). The results of calculating the shift performance of the considered dump trucks for the boundary values of the accepted range of changes in the length of the ride with the load (0.5-2.0 km) are given in Table 2.

Table 2

Shift performance of dump trucks involved in overburden haulage

Brand of dump truck	Turnover per shift		Shift performance, m^3			
			Bulk volume		Solid volume	
	0.5 km	2.0 km	0.5 km	2.0 km	0.5 km	2.0 km
Day shift						
Loading with HITACHI excavator						
KAMAZ-6520	48	22	283.8	619.2	187.0	408.0
DONG-FANG	45	21	338.1	724.5	231.0	495.0
MAN	37	19	366.7	714.1	228.0	444.0
HOWO	49	22	354.2	788.9	242.0	539.0
SAMS	47	21	338.1	756.7	231.0	517.0
Loading with HYUNDAI excavator						
KAMAZ-6520	45	21	270.9	580.5	178.5	382.5
DONG-FANG	41	20	322.0	660.1	220.0	451.0
MAN	34	18	347.4	656.2	216.0	408.0
HOWO	45	21	338.1	724.5	231.0	495.0
SAMS	43	21	338.1	692.3	231.0	473.0
Night shift						
Loading with HITACHI excavator						
KAMAZ-6520	41	18	232.2	528.9	153.0	348.5
DONG-FANG	38	18	289.8	611.8	198.0	418.5
MAN	32	16	308.8	617.6	192.0	384.0
HOWO	41	18	289.8	660.1	198.0	451.0
SAMS	40	18	289.8	644.0	198.0	440.0
Loading with HYUNDAI excavator						
KAMAZ-6520	38	18	232.2	490.2	153.0	323.0
DONG-FANG	35	17	273.7	490.2	187.0	385.0
MAN	29	15	289.5	563.5	180.0	348.0
HOWO	38	18	289.8	559.7	198.0	418.0
SAMS	36	17	273.7	611.8	187.0	396.0

Note: 1. For SAMS excavators irrespective of a number of axles the shift performance stays the same. 2. The performance indicators for HITACHI excavators are the same irrespective of bucket capacity.

Table 2 determines the total performance of the excavator-dump truck complex for any of the possible combinations of distribution of dump trucks between excavators. To automate these calculations, a computer program has been developed that is based on the objective function and the system of restrictions [see formulas (1), (2)] optimizes the option of distributing dump trucks for excavators by maximizing the total performance of the excavator-dump truck quarry complex per shift. The list and sequence of input of the source data into the program are shown in Fig.4.

The best option of distribution of dump trucks between excavators offered by a computer program is shown in Fig.5. The failure-free operation of the excavator-dump truck complex is determined by the feasibility of the monthly plan for the transportation of overburden for OJSC “Loga”,

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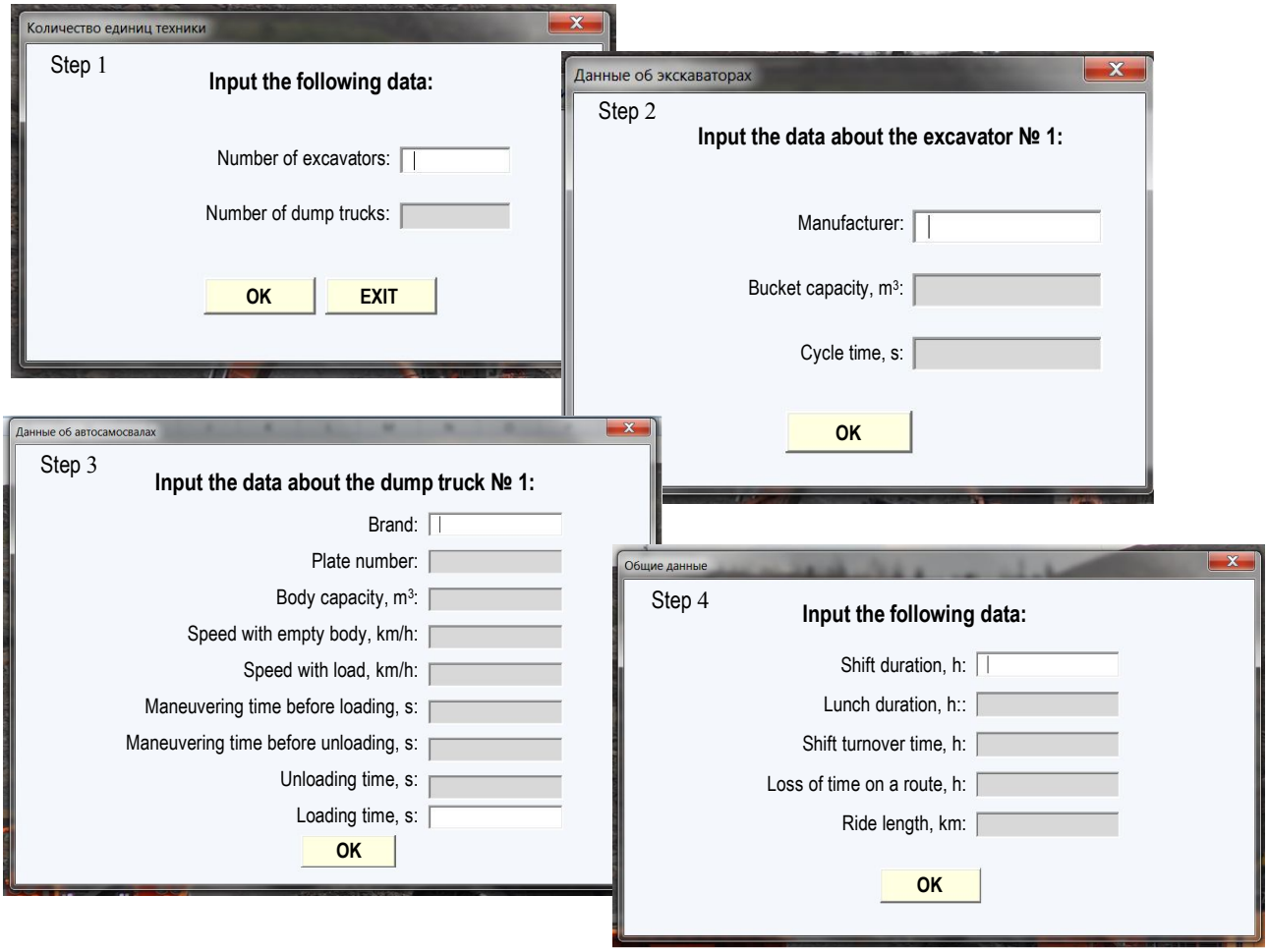


Fig.4. List and sequence of source data input

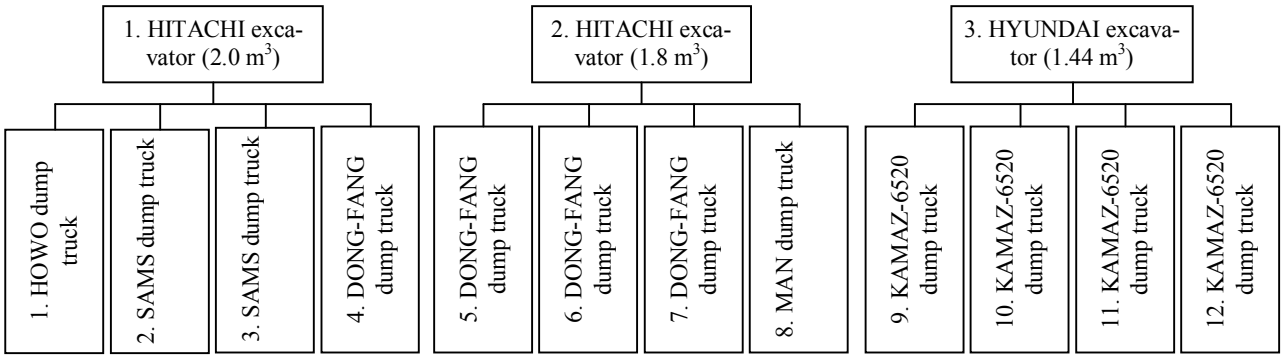


Fig.5. The optimal distribution of trucks between excavators in the given example

which is 150 thousand m^3. Transportation is carried out according to the 4-crew schedule in two shifts of 12 hours each. The number of work shifts per month is 60. The corresponding shift plan for overburden delivery is 2.5 thousand m^3.

The proposed software enables to simulate the feasibility of a shift plan for overburden transportation in case of failure of one or more dump trucks or excavators. Based on the data in Table 2, the program redistributes the remaining fully operational dump trucks between the remaining serviceable excavators and calculates the total productivity of the excavator-dump truck complex for

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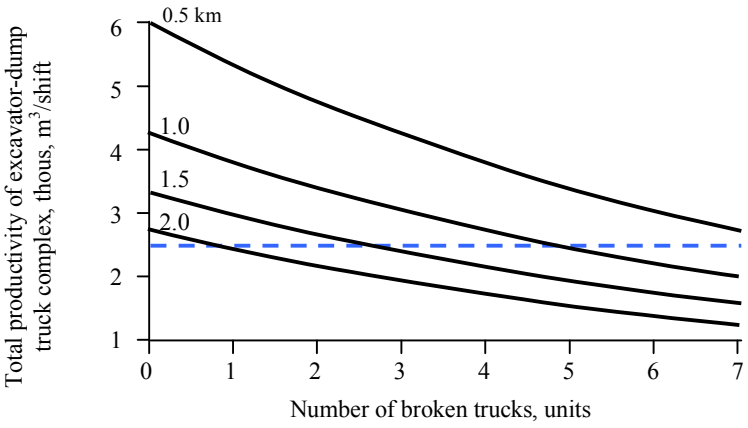


Fig.6. Modeling results for overburden haulage production plan implementation (dotted line)

all combinations of the new distribution patterns, choosing the best option. The distribution pattern with a total shift performance of lower than 2.5 thousand m^3 is not considered by the program. The results of simulation modeling of the feasibility of a shit overburden transportation plan for the conditions under consideration are shown in Fig.6.

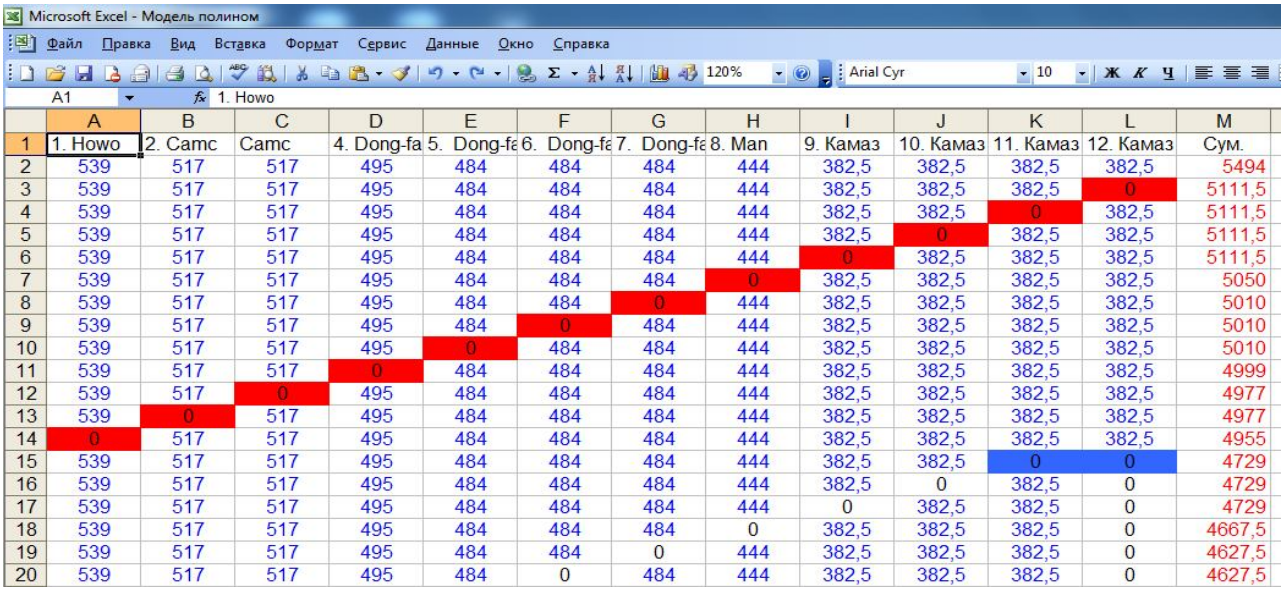
When calculating the reliability of the excavator-dump truck complex, we assume the equal reliability of its elements within each of the units: excavators – regardless of the brand and capacity of the bucket; dump trucks – regardless of brand, load capacity and a number of axles. The one brand of bulldozers also determines their equal reliability. The reliability of excavators, dump trucks and bulldozers is taken equal to the coefficient of their technical readiness – the ratio of the number of shifts during the month for excavation and loading, for overburden delivery and the formation of a dump to the number of work shifts in a month. The value of the sought indicator is: for excavators – 0.9; for dump trucks – 0.93; for bulldozers – 0.95. The reliability of the excavator unit (E_1-E_4) is determined by the formula (3) and is 0.9997. The reliability of the bulldozer unit (B_1-B_2) is calculated according to formula (5) and is 0.998.

The reliability of the transport unit (T_1-T_{12}) is calculated by the formula (4). The calculation consists of expanding the polynomial of combinations of possible states of the full and partial operability of the transport unit. The condition of the full operability is observed during the proper operation of 12 dump trucks, and partial, in the case of serviceability of less than 12 dump trucks. The first considered combination is when all dump trucks engaged in transportation are fully operational. At the same time, the total productivity of the excavator-dump truck complex is maximum and is determined by the inverse relationship with the length of a loaded ride. So, with a length of a loaded ride of 0.5 km, the productivity is 6.0 thousand m^3 of overburden per shift. With a length of a loaded ride of 2.0 km, the total productivity of the excavator-dump truck complex is reduced to 2.65 thousand m^3.

Then, combinations of possible states of loss of operability of one of the 12 dump trucks are considered, which will require a computer program to carry out 12 calculations of the total productivity of the excavator-dump truck complex. It should be noted that the total productivity of the complex will depend on the brand of the failed dump truck. With the loss of operability of the least productive KAMAZ-6520 dump truck, the total shift capacity of the excavator-automobile complex in all possible states of 11 serviceable dump trucks out of 12 will be maximum. The total smallest productivity of the excavator-dump truck complex will be observed in case of the failure of the HOWO high-performance dump truck. The curves in Fig.6 correspond to the minimum values of the total productivity of the complex. It can be seen from the figure that the overburden transportation plan will be feasible when the average ride length does not exceed 2.0 km. The fragment of the macros for calculating the total productivity of the excavator-dump truck complex is shown in Fig.7.

With the simultaneous failure of two dump trucks, the computer program recounts 66 combinations of transport unit operation states. Then, these combinations are successively considered in

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	A	B	C	D	E	F	G	H	I	J	K	L	M
1	1. Howo	2. Camc	Camc	4. Dong-fa	5. Dong-fa	6. Dong-fa	7. Dong-fa	8. Man	9. Камаз	10. Камаз	11. Камаз	12. Камаз	Сум.
2	539	517	517	495	484	484	484	444	382,5	382,5	382,5	382,5	5494
3	539	517	517	495	484	484	484	444	382,5	382,5	382,5	0	5111,5
4	539	517	517	495	484	484	484	444	382,5	382,5	0	382,5	5111,5
5	539	517	517	495	484	484	484	444	382,5	0	382,5	382,5	5111,5
6	539	517	517	495	484	484	484	444	0	382,5	382,5	382,5	5111,5
7	539	517	517	495	484	484	484	0	382,5	382,5	382,5	382,5	5050
8	539	517	517	495	484	484	0	444	382,5	382,5	382,5	382,5	5010
9	539	517	517	495	484	0	484	444	382,5	382,5	382,5	382,5	5010
10	539	517	517	495	0	484	484	444	382,5	382,5	382,5	382,5	5010
11	539	517	517	0	484	484	484	444	382,5	382,5	382,5	382,5	4999
12	539	517	0	495	484	484	484	444	382,5	382,5	382,5	382,5	4977
13	539	0	517	495	484	484	484	444	382,5	382,5	382,5	382,5	4977
14	0	517	517	495	484	484	484	444	382,5	382,5	382,5	382,5	4955
15	539	517	517	495	484	484	484	444	382,5	382,5	0	0	4729
16	539	517	517	495	484	484	484	444	382,5	0	382,5	0	4729
17	539	517	517	495	484	484	484	444	0	382,5	382,5	0	4729
18	539	517	517	495	484	484	484	0	382,5	382,5	382,5	0	4667,5
19	539	517	517	495	484	484	0	444	382,5	382,5	382,5	0	4627,5
20	539	517	517	495	484	0	484	444	382,5	382,5	382,5	0	4627,5

Fig.7. The fragment of the macros for calculating total productivity of excavator-dump truck complex

case of failure of three, four, five or more dump trucks. The number of combinations calculated by the program is directly proportional to the number of failed dump trucks, however, the relationship between these parameters is non-linear. For example, in case of failure of three dump trucks, the number of combinations is 220, in case of failure of four, it increases to 470.

According to formula (4), by factorization of a polynomial combination of possible states of full and partial operability of the transport unit, its reliability is quantified as the sum of the probabilities of overburden transportation plan failure in case of failure of 1, 2, 3, ..., 7 dump trucks, respectively. For example, the criterion of reliability of a transport unit during a day shift with an average length of a loaded ride of 1.0 km will be determined as follows:

$$P_{T_1\text{-}A_{12}} = (R^T)^{12} + 12(R^T)^{11}(1-R^T) + 66(R^T)^{10}(1-R^T)^2 + 220(R^T)^9(1-R^T)^3 + \\ + 470(R^T)^8(1-R^T)^4 + 14(R^T)^7(1-R^T)^5.$$

With $R^T = 0.93$, the reliability criterion of the transport unit with an average length of a loaded ride of 1.0 km will be 0.9988. According to the previously calculated values of the reliability criterion for excavator and bulldozer units, as well as their sequential distribution (see Fig.3), a criterion for the reliability of the excavator-dump truck complex with an average length of a loaded ride of 1.0 km is determined as the following:

$$R_{1\,\text{km}}^{\text{EDTC}} = 0{,}9997 \cdot 0.9988 \cdot 0.998 = 0.9965.$$

As can be seen from Fig.8, the reliability of the excavator-dump truck complex is inversely proportional to the length of the loaded ride. The probability of fulfilling the transportation plan with a loaded ride of more than 1.5 km is significantly reduced.

The methodological tools for automating the planning process proposed in this article will allow the transportation company to increase the reliability of operations, thereby minimizing losses in the form of penalties due to the non-fulfillment of contract obligations.

Conclusion. The results of the studies showed the following:

1. The relevance of the problem of ensuring the reliability of excavator-dump truck complexes in quarries determines the probabilistic nature of the actual volume of rock mass transported per day

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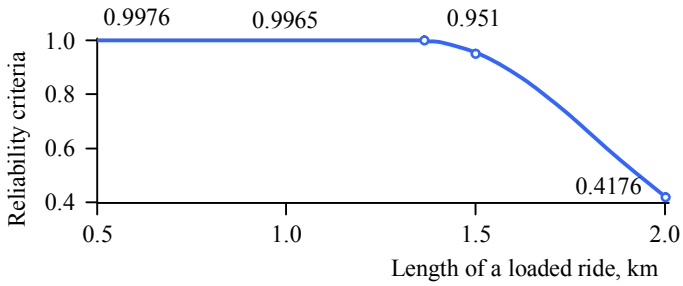


Fig.8. Calculation results for reliability of excavator-dump truck complex operation

(shift). This indicator is determined by a number of random factors, including the number of serviceable excavators and dump trucks, the distance of transportation of overburden and mineral, respectively, to a dump or warehouse, weather conditions that determine the condition of benches and quarries, and other factors.

2. Existing methods for calculating the productivity of mining and transport equipment in open pits do not fully provide the possibility of using the features of the organization of the transport process in open pits with road transport, which consists in its multi-channel system and majority factor to increase the reliability of loading and extraction and transport vehicles. This determines the choice of the research task – the development of a methodology for assessing the reliability of excavator-dump truck complexes based on major distribution patterns.

3. The proposed methodology for evaluating the reliability of excavator-dump truck complexes consists of three stages: collecting initial data for mathematical modeling of the performance of a complex; solving the problem of optimizing the distribution of dump trucks between excavators, ensuring maximum productivity of the excavator-dump truck complex; assessment of the reliability of its work on the basis of calculating the probability of fulfilling the daily plan for the transportation of rock mass.

4. The solution to the problem of the optimal distribution of dump trucks between excavators is based on a mathematical model with the following structure:

• an objective function of maximizing the quarry total volume of transported rock mass per shift;

• a system of limitations providing the conditions of operation of dump trucks on shuttle routes of an unchanged haulage distance, the excess of the number of dump trucks over the number of excavators, the ratio of the capacities of the body of a dump truck and excavator bucket in the range from 1:3 to 1:7.

5. The assessment of the reliability of the excavator-dump truck complex is based on a schematic representation of the series-parallel connection of its elements with a subsequent detailed description of excavator, transport and bulldozer units. The reliability of the excavator unit is based on determining the full probability of the failure-free options and the failure of the main delivery channel. The reliability assessment of the transport unit is carried out by expanding the binomial of state h of the main channels from possible l. The reliability of the bulldozer unit is defined as the probability of a joint event – the failure-free operation of one of the bulldozers.

6. The proposed method is implemented as part of a computer program and makes it possible to automate the operational management of the process of haulage in a quarry using a mobile application. Using the initial data for mathematical modeling, the program calculates the interchangeable performance of dump trucks involved in the transportation of rock mass, optimizes the distribution of dump trucks between excavators taking into account the failure of one or more units of mining, loading or haulage equipment, determines the value of a quantitative criterion for the reliability of the excavator-dump truck complex, and also gives the numerical and graphical representation of calculation results.

7. The feasibility of practical implementation of the proposed guidelines was verified by the example of transportation of overburden during the construction of the Mikheevsky mine (Varnensky district, Chelyabinsk region) by one of the contractors – OJSC “Loga” (Magnitogorsk).

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