Comparative assessment of the operation quality of shovel-truck systems at open-pit coal mines in the summer and transitional seasons

Anton Voronov[1], *Valery* Nesterov[2], *Yuri* Voronov[2*], and *Artyom* Voronov[2]

[1]Kuzbassrazrezugol Coal Company JSC, 650054 Kemerovo, 4a Pionersky blvd., Russian Federation
[2]T.F. Gorbachev Kuzbass State Technical University, Department of Road Transport, 650000 Kemerovo, 28 Vesennyaya st., Russian Federation

Abstract. The operation quality of shovel-truck systems (STSs) at open-pit coal mines in the summer and transitional autumn-spring periods differs markedly. This is due to a decrease in the speed of haul trucks during the transitional season compared to the summer season. This leads to an increase in the travel time of trucks. Shovels and trucks must work longer to ensure the planned volumes of loading and transportation and the required number of hauls. Consequently, the duration of the working shift (or day) increases. This leads to deterioration in the STS performance in the autumn-spring period. A quantitative assessment of changes in the STS operation quality will reveal the directions of its improvement.

Introduction

Currently, there are quite a large number of models that investigate the STSs at open-pit mines [1–5]. However, there are not enough methodological and normative materials regulating such an important direction of improving the quality of objects as their optimization. To date, several works have been devoted to the optimization of the rotary drilling rigs, single-bucket hydraulic excavators, motor transport equipment for open-pit coal mines, and also STS operation in the summer period [6–11, 16-20].

Materials and methods

Mathematical model of optimization (MMO) of the STS operation indicators at open-pit coal mines in Kuzbass in the summer period has the following form [11]:

$$k = -0{,}268 + 0{,}209 k_N + 0{,}397 t_l^s - 0{,}0415 t_h \to max;$$
$$0{,}130 k_N + 0{,}230 t_l^s - 0{,}0250 t_h \geq 0{,}917;$$
$$0{,}130 k_N + 0{,}230 t_l^s - 0{,}0250 t_h \leq 1{,}083;$$
$$t_l^s + 0{,}0619 t_h \geq 4{,}822;$$
$$t_l^s + 0{,}0619 t_h \leq 5{,}134; \qquad (1)$$
$$k_N \geq 5{,}124;$$

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* Corresponding author: vyue.ap@kuzstu.ru

$$k_N \leq 6{,}653;$$
$$k_N \geq 0; \; t_l^s \geq 0; \; t_h \geq 0,$$

where k is the generalized indicator of the STS operation quality (optimization criterion); k_N (coefficient of effective composition of the STS), t_l^s (time to load a mining truck with a shovel), t_h (duration of a truck haul) are the parameters to be optimized.

It was found in [12] that the speed of trucks in the transitional (autumn-spring) period decreases by 15–20% compared with the summer period. This leads to an increase in the travel time of trucks in the loaded (t_{lt}) and unloaded (t_{et}) directions and in the haul time (t_h). Shovels and trucks must operate longer to meet the scheduled volumes of loading and transportation and the required number of hauls. Consequently, the duration of the work shift (day) T_o will increase, but should not exceed $T_o^{max} = 24$ hours. To assess the influence of only the conditions of the autumn-spring period on the STS operation, all other indicators of this operation are left unchanged. The initial data for the calculations are given in Table 1.

Table 1. Summary report on the STS operation at open-pit coal mines of Kuzbassrazrezugol Company.

Indicators	Mines					
	Kedrovsky	**Mokhovsky**	**Bachatsky**	**Krasnobrodsky**	**Taldinsky**	**Kaltansky**
Number of shovels in the fleet, N_s, units	8	10	9	12	14	10
Number of trucks in the fleet, N_t, units	31	28	67	93	91	31
Number of hauls performed, n_h	1064	1632	1833	3518	3372	1241
Total in-shift downtime of equipment, t_{dt}^e, min	4820	4874	7114	4209	6376	1741
Downtime of trucks, t_{dt}^t, min	2126	1022	5620	1947	2818	457
Downtime of shovels, t_{dt}^s, min	2694	3852	1494	2262	3558	1470
Loading time, t_l^s, min	4004	6041	4528	9567	9750	4448
Truck mileage per day, L, km	3714	3361	10611	16182	13072	4722
Loaded travel time, t_{lt}, min	13505 / 15531	11639 / 13385	36687 / 42190	55997 / 64396	45022 / 51775	16282 / 18724
Dumping time, t_d, min	874	1530	1689	2880	2760	1091
Empty travel time, t_{et}, min	10013 / 11515	9395 / 10804	27965 / 32160	42573 / 48959	34307 / 39453	12500 / 14375
Haul time, t_h, including:	29257 / 32784	28960 / 32115	73142 / 82840	112348 / 127133	95126 / 107025	34909 / 39225
− downtime waiting for loading, t_{wt}^t, min	861	355	2273	1331	3287	587
Haul time with downtime, $(t_h + t_{wt}^t)$, min	34076 / 37604	33835 / 36990	80256 / 89954	116557 / 131343	101502 / 113401	36649 / 40967
Equipment operation time per day, T_o, hr	18,32 / 20,22	20,14 / 22,02	19,96 / 22,38	20,89 / 23,54	18,59 / 20,77	19,70 / 22,03

The STS operation indicators for the summer period are indicated in the numerator and for the autumn-spring period in the denominator.

To obtain comparative characteristics, the basic values of the specific quality indicators according to the methodology given in [13] should be taken over the summer period.

By analogy with the study for the summer period [14], a mathematical 2^3 full factorial experiment was carried out, as a result of the statistical analysis of which the MMO was obtained for the transitional (autumn-spring) period:

$$
\begin{aligned}
k = -0{,}244 + 0{,}177 k_N + 0{,}395 t_l^s - 0{,}0308 t_h &\rightarrow max; \\
0{,}116 k_N + 0{,}206 t_l^s - 0{,}0199 t_h &\geq 0{,}925; \\
0{,}116 k_N + 0{,}206 t_l^s - 0{,}0199 t_h &\leq 1{,}075; \\
t_l^s + 0{,}0539 t_h &\geq 4{,}787; \\
t_l^s + 0{,}0539 t_h &\leq 5{,}097; \\
k_N &\geq 5{,}079; \\
k_N &\leq 6{,}600; \\
k_N \geq 0; \; t_l^s \geq 0; \; t_h &\geq 0,
\end{aligned}
\tag{2}
$$

the study of which gives the comparative optimal simplex Table 2.

The optimal solution, therefore, is as follows:

$$k_N^* = 5{,}079; \; t_l^{s^*} = 4{,}116 \text{ min}; \; t_h^* = 18{,}19 \text{ min}; \; \lambda^* = 1{,}149; \; k^* = 1{,}330.$$

If, by analogy with the summer period [11], we consider not the minimum but the maximum value $k_N = 6{,}600$ to be optimal, then the optimal solution is the following one:

$$k_N^* = 6{,}600; \; t_l^{s^*} = 3{,}809 \text{ min}; \; t_h^* = 23{,}88 \text{ min}; \; \lambda^* = 1{,}053; \; k^* = 1{,}321. \tag{3}$$

The solution for the summer period [11] is similar:

$$k_N^* = 6{,}653; \; t_l^{s^*} = 3{,}616 \text{ min}; \; t_h^* = 24{,}53 \text{ min}; \; \lambda^* = 0{,}981; \; k^* = 1{,}370. \tag{4}$$

Table 2. Comparative simplex table of the optimal solution for the summer and autumn-spring periods.

Value	Absolute term	Free variables		
		y_2	y_4	y_5
k	1,385	1,684	0,00980	0,00990
	1,330	1,576	0,01040	0,00590
Basic variables				
k_N	5,124	0	0	−1
	5,079	0	0	−1
t_l^s	3,929	1,578	0,637	0,205
	4,116	1,739	0,642	0,202
t_h	19,467	−25,489	5,860	−3,313
	18,193	−32,254	6,644	−3,742
y_1	0,166	1	0	0
	0,150	1	0	0
y_3	0,312	0	1	0
	0,310	0	1	0
y_6	1,529	0	0	1
	1,519	0	0	1

The values for the summer period are indicated in the numerator, and for the autumn-spring period in the denominator.

From the optimal solutions for the summer (4) and autumn-spring (3) periods, it can be seen that the values of k_N^* do not coincide. This means that in the summer, the number of trucks servicing the same number of shovels should be more than in the autumn-spring pe-

riod. The reason for this is the long duration of a haul (t_h) in the autumn-spring period due to the lower speed of movement, which means that the turnover of trucks is lower.

However, such a seasonal revision of the STS fleet structure is inappropriate. It makes sense to leave one value of the indicator k_N. Obviously, this will be the smaller value $k_N^* = 6{,}60$, since for the autumn-spring period this is the maximum possible value. But the value of k_N^* for the summer period (6,653) can be reduced. A decrease in the value of k_N^* from 6,653 to 6,60 means that, in accordance with the margin for the limitation of the STS efficiency [11], its decrease will not be 1,529 (maximum), but 1,474. In proportion to this coefficient, the values of t_l^s and t_h will also change. The value of t_l^s will be 3,627 minutes and t_h will be 24,35 minutes.

The value of the functional criterion will be $\lambda = 0{,}983$, and the value of the generalized quality indicator will be $k = 1{,}355$.

Then the optimal solutions for the summer and autumn-spring periods, respectively, will be as follows:

$$k_N^* = 6{,}60; \; t_l^{s^*} = 3{,}627 \text{ min}; \; t_h^* = 24{,}35 \text{ min}; \; \lambda^* = 0{,}983; \; k^* = 1{,}355;$$
$$k_N^* = 6{,}60; \; t_l^{s^*} = 3{,}809 \text{ min}; \; t_h^* = 23{,}88 \text{ min}; \; \lambda^* = 1{,}053; \; k^* = 1{,}321. \qquad (5)$$

The next difficulty lies in the fact that the actual values of the haul time in the autumn-spring period are noticeably higher than the optimal value $t_h^* = 23{,}88$ minutes (5). To establish the relationship between the haul time in the summer and autumn-spring periods, we will carry out statistical processing of the corresponding data given in Table 1.

The communication equation has the following form: $t_h^{trans} = 1{,}154 t_h^{summer} - 0{,}815 \pm 0{,}097$, where t_h^{summer} and t_h^{trans} are truck haul times in the summer and transition periods, respectively.

A change in the value of the indicator t_h entails changes in the values of t_l^s, λ and k in comparison with the optimal solution (5). We have from Table 2 that the reduction coefficient is 0,105, then $t_l^s = 3{,}627$ minutes; $\lambda = 0{,}877$; $k = 1{,}155$.

The results of t_h^{trans} calculations for the given values of the haul duration t_h^{summer} are shown in Table 3. Minimum, maximum and recommended values are shown in bold.

To obtain complete data on the ratios of the indicators being optimized, the functional criterion and the generalized indicator of the STS operation quality for the given values of the haul time (t_h^{summer}), the corresponding calculations are carried out in a similar way. The results are also presented in Table 3.

Table 3. The results of calculating the ratios of the optimized indicators, the functional criterion and the generalized indicator of the STS operation quality in the summer and autumn-spring periods ($k_N^* = 6{,}60$)

t_h, min	**24,35**	25,0	25,5	**26,0**	26,5	27,0	27,5	28,0	**28,58**
	27,28	28,04	28,61	**29,19**	29,77	30,34	30,92	31,50	**32,17**
t_l^s, min	**3,627**	3,587	3,556	**3,525**	3,494	3,463	3,432	3,401	**3,365**
	3,626	3,585	3,554	**3,523**	3,491	3,461	3,429	3,398	**3,363**
λ	**0,983**	0,947	0,920	**0,895**	0,870	0,847	0,824	0,802	**0,777**
	0,877	0,844	0,820	**0,797**	0,774	0,753	0,732	0,712	**0,690**
k	**1,355**	1,312	1,279	**1,246**	1,213	1,180	1,147	1,114	**1,076**
	1,155	1,118	1,090	**1,062**	1,033	1,005	0,977	0,949	**0,916**

The actual values of the STS operation indicators for the summer period are indicated in the numerator, and for the autumn-spring period in the denominator.

A comparative analysis of the STS operation in the summer and autumn-spring periods shows (see Table 3) that the truck haul time (t_h) in the autumn-spring period is on average 11% longer than in the summer period; the truck loading time (t_l^s) does not change; the

functional criterion λ decreases by 11%, so does the generalized factor of the STS operation quality k – by 14,8%.

In [12, 15] it is indicated that in the mining industry, the rational values of the match factor (in this case, the functional criterion λ) are less than 1,0 (optimal value), which corresponds to smaller fleets of mining trucks. At the same time, although the downtime of shovels is increasing, operating costs are significantly reduced, most of which falls on motor transport exactly.

All values $\lambda \geq 0,9$ are acceptable (for the summer period of the STS operation it means: t_h^{max} = 26,0 minutes; $t_l^{s\,min}$ = 3,525 minutes; λ^* = 0,895; k^* = 1,246). The value of the generalized STS operation quality indicator k = 1,246, in this case, exceeds the best value for the Company's mines k = 0,879 (Krasnobrodsky mine) by 29,5%; and 50,7% higher than in the whole Company (k = 0,614). In addition to the optimal and the above options, it is advisable to consider also the option with the maximum possible value of the haul time t_h^{max} = 28,58 minutes (the worst option). Despite the fact that the value of the functional criterion in this case is only λ = 0,777, this is still 9,4% higher than that achieved at the Taldinsky mine, which is the best by this criterion (λ = 0,704), and the value of the generalized indicator (k = 1,062) is 17,2% higher than that achieved at the best Krasnobrodsky mine (k = 0,879).

Conclusion

Comparative analysis of the STS operation in the summer and autumn-spring periods shows that the duration of truck hauls in the autumn-spring period is on average 11,0% longer than in the summer period; truck loading time does not change; the functional criterion decreases by 11,0%, and the generalized quality factor of the STS operation decreases by 14,8%. The functional criterion values acceptable for the mining industry are 0,9 and higher. The value of the generalized indicator of the STS operation quality in this case exceeds the best one achieved by the Company at the optimal values of the truck haul duration by 29,5% and the average one in the Company by 50,7%. The use of even the worst option at the maximum possible value of the haul duration gives an increase in the functional criterion by 9,4%, and in the value of the generalized indicator of the STS operation quality – by 17,2%.

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