Designing optimal structure of road construction machines kits

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Abstract. The article presents modernized mathematical model for optimizing the structure of road sets of machines, taking into account the technical and organizational downtimes of mechanization facilities employed in technological construction processes. In the process of operation, technical downtimes are caused by the wear of parts, assemblies and units of transport and technological machines, the removal of which takes more time each year. This circumstance causes an adequate decrease in the annual output of the mechanization facilities. The organizational kind of downtimes is caused by internal and external factors. The internal factors lead to the under-exploitation of the potential capabilities of individual pieces of the equipment of the kit. External factors are characterized by late supply of construction materials, caused by the irregularity of their production and delivery. Dependencies between productivity and the operating period of transport-technological machines, obtained using this mathematical model, will allow determining the real time of work, the output of machines, taking into account their age.

1. Introduction

At the design stage of the organization of construction, it is important to consider the possible impact of technical and organizational downtimes. Automation of designing options for the mechanization of road construction can significantly reduce the labor intensiveness; improve the efficiency of machinery use.

The potential capabilities of each machine during the life cycle of its operation are reduced, as the processes of parts, assemblies and units wear develop. To eliminate them, the machines are removed from production processes and set to maintenance or repair. The duration of machine downtimes depends on the amount of work, availability of high-performance technological equipment and maintenance personnel qualification.

The duration of these downtimes increases every year, and the annual output of machines decreases.

To keep records of technical downtimes, it is necessary to rely on the results of complex technical diagnostics. Based on the diagnostic information, the residual resources are determined and the moment of decommissioning of the machines is defined. On the basis of the information received, a schedule of repair and maintenance (R and M) is calculated. Given the schedule of R and M, you can determine the real time of employment of the machine in production processes.

Taking into account the intensity of production decrease due to wear of parts, assemblies, units and an increase in technical downtimes of equipment over time, one can predict the performance of specialized kits of machines (SKM), the timing of implementation of the planned volumes of construction works.

Organizational downtimes of machines kits during a shift can be caused by untimely completion of previous technological operations, supply of construction materials, lack of fuel, nonconformance of the potential capabilities of machines to each other inside the kit, etc. Organizational downtime must also be taken into account when forming sets of machines. For this purpose, the mathematical expectation of the execution time of technologically interconnected construction works performed by
road-building machines is investigated and used at the design stage of the organization of construction [1].

There are mathematical models aimed at optimizing the structure of SKM [1–6, 9]. The structure of a kit of machines is understood as the number of units of equipment of various functional purposes, dimension-type, and the order of their technological location in SKM.

A mathematical model for the optimization of the SKM structure is presented in the paper [1]. The mathematical model optimizes the SKM structure and determines the number of transport and technological machines. However, it does not take into account downtimes because of various reasons, including downtimes during maintenance and repair, due to poor organization of work. The calculation of the mathematical model allows us to determine the optimal composition of the SKM from the alternative ones, being formed from the existing fleet. The mathematical model also takes into account the possibility of renting cars from third-party organizations and allows adequate assessing resource-saving construction technologies, by using such an indicator in the efficiency criterion as the cost of the consumed material.

In the paper [2], the issue related to the influence of factors on the increase in the duration of maintenance and repair is insufficiently covered. The rate of decrease in machines productivity and increase in the duration of maintenance and repair were assumed to be conditionally constant within certain time intervals. In reality, depending on the change in the technical condition of various parts, assemblies and units over time, the rate of decrease in machine performance, the increase in duration of maintenance and repair will have different values after carrying out recovery operations.

2. Statement of the problem
The structure optimization of road kits of machines, taking into account the duration of repair and maintenance (R and M), organizational downtimes of road construction machinery is one of the most important tasks in road construction, since this relationship has a significant impact on productivity of transport and technological machines operating at construction sites.

The authors propose to improve the existing mathematical model by applying the adjusted performance values, the duration of maintenance and repair from operating time, internal production downtimes.

3. Methodology
In the modernized mathematical model, the cost of mechanized works spent for manufacture of production unit was taken as a criterion when building highway elements. The statement of the problem is as follows: to determine the effective structure of the kit of machines for work, taking into account the calendar schedule of the organization of construction and the plan for maintenance and repair, based on diagnostic information.

Approbation of a mathematical model for the optimization of the SKM structure is planned for one of the stages of a highway construction, namely, the construction of a road bed. The object of construction is characterized by geometrical parameters (width, height, angle of slope), individual terms and construction pace. A bulldozer, an excavator and a scraper are used as leading SKM machines for construction of the road bed. The choice of type, quantity and sequence of machines in SKM will depend on the technological requirements of construction objects (physical-mechanical properties of the soil, transportation distance, slope of the terrain, etc.), time of maintenance and repair, performance of equipment, extent of organizational downtimes.

Each kit includes machines of various functionalities \( a = \bar{I} A \). In turn, a group of machines of one functional purpose is divided by the numbers \( j = \bar{I} J \), since each of them may have an individual performance value, which depends on the dimension-type, technical condition of parts, assemblies and units, design features.

We formalize the pace of the kit work at the object, which is expressed by the following formula:
\[ t_{w_i} = \min \left\{ \sum_{j=1}^{J} P_{ij}^a(t) \cdot n_{ij}^a \cdot (t_{sh}^a - t_{org}^a - t_{rm}^a(t)) \right\} \]  
\[ i = 1, I; \ j = 1, J; \ a = 1, A. \]

where \( i \) is an index (number) of machines kit, \( i = 1, I \);
\( j \) is an individual number of a machine of definite functionality, \( j = 1, J \);
\( a \) is an index of SKM machines of various functionality, \( a = 1, A \);
\( P_{ij}^a(t) \) is hourly operational productivity of machines of various (namely, \( a \) functionality from an operating time from the beginning of operation;
\( n_{ij}^a \) is the number of machines of the \( a \) functionality, of the \( j \)-th number in the \( i \)-th SKM.

On the basis of the car park, possible options for SKM with a different construction rate (\( t_{w_1}, t_{w_2} \ldots t_{w_i} \)) are compiled.

\[
\begin{array}{c|c|c}
\text{SKM} & \text{SKM} & \text{SKM} - i \text{- th} \\
1 & 2 & \\
\hline
P_{sh1} & P_{sh2} & P_{sh1} \\
1 \cdot n_{i1} & 2 \cdot n_{i2} & 1 \cdot n_{i1} \\
\hline
P_{sh1} & P_{sh2} & P_{sh1} \\
1 \cdot n_{i1} & 2 \cdot n_{i2} & 1 \cdot n_{i1} \\
\hline
P_{sh1} & P_{sh2} & P_{sh1} \\
1 \cdot n_{i1} & 2 \cdot n_{i2} & 1 \cdot n_{i1} \\
\hline
P_{sh1} & P_{sh2} & P_{sh1} \\
1 \cdot n_{i1} & 2 \cdot n_{i2} & 1 \cdot n_{i1} \\
\hline
P_{sh1} & P_{sh2} & P_{sh1} \\
1 \cdot n_{i1} & 2 \cdot n_{i2} & 1 \cdot n_{i1} \\
\hline
P_{sh1} & P_{sh2} & P_{sh1} \\
1 \cdot n_{i1} & 2 \cdot n_{i2} & 1 \cdot n_{i1} \\
\end{array}
\]

\[ t_{w_1} = \min \] \[ t_{w_2} = \min \] \[ t_{w_i} = \min \]  

At that \( P_{sh ij}^a(n_{ij}^a \geq t_{w_i}) \),

where \( P_{sh ij}^a(t) \) is replaceable operational productivity of machines of various (namely, \( a \) functionality from an operating time from the beginning of operation;
\( t_{w_1}, t_{w_2} \ldots t_{w_i} \) are working rates of construction of different structures of SKM.

Formula (1) shows that the minimum total performance of machines of the \( j \)-th numbers, \( a \)-th functional purpose, will be the real rate of the entire kit. For a kit of machines, the cost of mechanized work spent on a unit production can be determined by the following formula:

\[ C_{ei} = \sum_{a=1}^{A} \left\{ \sum_{j=1}^{J} \frac{C_{mh ij}^a}{P_{ij}^a(t)} \cdot n_{ij}^a \right\} \rightarrow \min \]

\[ i = 1, I; \ j = 1, J; \ a = 1, A. \]

Here \( C_{mh ij}^a \) is a cost of machine-hour of the \( j \)-th machine of \( a \)-th functionality;
\( E \) is overhead expenses; \( t_{sh ij}^a, t_{org ij}^a, t_{rm ij}^a(t) \) are duration of a shift, organizational downtimes and repair and maintenance downtimes respectively.

It is necessary to take into account some restrictions regarding which the search for the optimal SKM for the construction of road elements will be carried out. First, the minimum total productivity of machines of the \( j \)-th number, \( a \)-th functional purpose, must be greater than or equal to the given shift work rate that needs to be performed.

\[ \min \left\{ \sum_{j=1}^{J} P_{ij}^a(t) \cdot n_{ij}^a \cdot (t_{sh}^a - t_{org}^a - t_{rm}^a(t)) \right\} \geq t_{w_i} \]

\[ i = 1, I; \ j = 1, J; \ a = 1, A. \]

In the model being created, each machine of the \( j \)-th number, \( a \)-th functional purpose, is considered individually, i.e. it works or does not work.

\[ n_{ij}^a \leq 1 \]
The number of machines that will be obtained as a result of the calculation must be an integer and a positive number and can take the values of either 0 or 1, $n_{ij}$ is an integer number.

$$n_{ij}^a \geq 0 \quad i=1,I; \quad j=1,J; \quad a=1,A.$$  \tag{6}

The total duration of repair and maintenance of machines of $j$-th numbers, $a$-th functional purpose per shift must not exceed the duration assigned in accordance with the capacity of the repair base. In case of overloading the repair base, the duration of equipment downtime increases due to the postponement of repair work to the next days.

$$T \geq \sum_{a=1}^{A} \sum_{j=1}^{J} t_{rm}^a \delta(t) \quad i=1,I; \quad j=1,J; \quad a=1,A.$$  \tag{7}

The duration of organizational downtimes associated with conducting repair and maintenance of a $j$-th number machine, $a$-th functional purpose per shift must be less than or equal to the shift fund of working time.

$$T_{org}^a + t_{rm}^a \delta(t) \leq t_{sh}^a \quad i=1,I; \quad j=1,J; \quad a=1,A.$$  \tag{8}

The total maintenance and repair duration of a $j$-th number machine of $a$-th functional purpose may have different value depending on the dynamics of changes in diagnostic parameters, which regulate the conducting of repair operations to various components and assemblies of machines during the operation period under consideration. Postponement of the time of conducting repair operations to the corresponding units and assemblies is carried out under the condition that their residual life exceeds the construction completion date or not less than periodicity until the next maintenance. Such approach reduces downtime for troubleshooting. The value of productivity between maintenance and repairs will be determined by the minimum cost of unit production.

4. Results and discussion
For conducting the calculating experiment, SKMs for construction of a road bed with a bulldozer as a leading machine were considered. The construction conditions were as follows: road bed length was 7 km, height was 1.4 m, width of the upper part of the road bed was 10.8 m, width of the base was 15 m, construction period was from 20.06 to 05.09, the soil was of the second category, soil transportation distance were 15, 25, 35, 50 m, the required construction rate per shift was 1180 m$^3$.

Considering the fact that each of the kinds, brands, and dimension-types of machines has a certain productivity value, the duration of the implementation of a shift workload is performed at a different speed. The ratio of the shift rate of work and the shift operational performance of machines is characterized by the number of machine shifts, which are given for each technological operation during the construction of the road bed (see table 1).

| Table 1. Number of machine shifts for performing the technological operations at road bed construction. |
|---|---|---|---|---|---|---|---|---|---|
| Number of the operation | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| SKM-1 | 1.1 | 1.16 | 1.36/1.97/2.58/3.19 | 1.07 | 0.87 | 1.36 | 1.19 | 1.25 | 1.1 |
| SKM-2 | 1.12 | 0.96 | 1.25/1.81/2.36/2.91 | 0.98 | 0.87 | 1.36 | 1.19 | 1.25 | 1.1 |
Initially, SKM-1 was tentatively selected based on the given pace of construction. Further, on the basis of the proposed mathematical model for determining the optimal structure of the SKM, an algorithm was developed for solving systems of equations (see formulae 1–8) in MS Excel using the “Search for solutions” option by the conjugate gradients method. As a result of substitution of data using regulatory sources, cost of equipment, fuel, lubricants, the optimal composition of SKM-2 was obtained for the construction of a road bed with a leading machine bulldozer while minimizing the cost of mechanized work expended on unit production (see table 2).

Table 2. Results of calculation of SKM structure for road bed construction with a bulldozer as a leading machine

| Sequence number | The name of operation                                          | SKM-1 Mechanization facilities | Number of machines | SKM-2 Mechanization facilities | Number of machines |
|-----------------|----------------------------------------------------------------|-------------------------------|--------------------|-------------------------------|--------------------|
| 1               | Removal of the plant layer of soil and moving it beyond the limits of reserves | Bulldozer Caterpillar D5N       | 1                  | Bulldozer Komatsu D39EX-22    | 2                  |
| 2               | Compacting the base of the earthfill with medium rollers $G = 15-17$ tons | Medium roller Hamm grw18       | 2                  | Medium roller Hamm grw18      | 1                  |
| 3               | Earthwork and moving soil with a bulldozer                      | Bulldozer Chetra 11P           | 2; 2; 3; 4         | Bulldozer ChTZ B10M           | 2; 2; 3; 3         |
| 4               | Levelling the soil with a layer of given thickness              | Bulldozer Chtz TM10            | 1                  | Bulldozer Chetra T9           | 1                  |
| 5               | Bringing the soil to optimum moisture                          | Street washer MD-43118         | 1                  | Street washer MD-43118        | 1                  |
| 6               | Compacting the soil with medium rollers $G = 15-17$ tons        | Medium roller Hamm grw18       | 2                  | Medium roller Hamm grw18      | 2                  |
| 7               | Compacting the soil with heavy rollers $G = 25-30$ tons         | Heavy roller XP262             | 2                  | Heavy roller XP262            | 2                  |
| 8               | Profiling the subgrade top and slopes                           | Motor grader DZ-98-ChSDM       | 2                  | Motor grader DZ-98-ChSDM      | 2                  |
| 9               | Compacting the soil with medium rollers $G = 15-17$ tons        | Medium roller Hamm grw18       | 1                  | Medium roller Hamm grw18      | 1                  |

We also obtained a graph of the change in the cost of mechanized work expended on the production of the roadbed depending on the distance of earthwork and transportation of soil by bulldozers at different SKM structures (see figure 1).
The graph in figure 1 shows that in construction of the roadbed the cost of production unit for distances of 15, 20, 35 and 50 m at SKM-1 is 8-10% higher compared to SKM-2.

The results obtained indicate that in the practice of machines kitting it is really necessary to take into account the design features of the applied machines, which affect their performance. The reason for the lower cost of unit production at SKM-2 is not only the cost of equipment, its service, presence of a larger amount of equipment during certain technological operations, but also the intershift use of equipment. Given the number of machine shifts necessary to perform a certain technological operation (see table 2), it can be seen that some machines perform their work much earlier than others. For example, a street washer machine performs its shift work for 0.87 machine shifts, and in the earthworks and moving soil operations at a transportation distance of 50 m a bulldozer implements its work for 3.19 machine shifts, i.e. between the SKM machines there is a waste of time associated with waiting for the execution of technological operations. Comparing the loss of time due to the expectation of the conducting earthmoving works by equipment, we can see that at SKM-1 the average value is 2.05 machine shifts, while at SKM-2 it is 1.83 machine shifts. At SKM-2 organizational loss of time is 10% less than at SKM-1.

When selecting equipment for construction it is also important to consider the drop in productivity, the rise in the number of failures and duration of their elimination with an increase in the operating time of machines from the beginning of operation. These factors were considered in the previous papers for bulldozers, excavators and scraper [2, 7-9].

5. Conclusion
The proposed approach for calculating the effective structure of kits of machines in comparison with previous models of the authors additionally takes into account the varying duration of downtimes associated with maintaining and restoring the operational state of various parts, assemblies and units of machines, as well as organizational downtimes inside production.

The application of the proposed approach will significantly reduce the damage from technical and organizational machine downtimes, increase productivity, and thus ensure the construction of facilities in a given time frame.
References

[1] Permyakov V B and Ivanov V N 2002 The effectiveness of the use of mechanization facilities in the construction industry (Omsk: SibADI)

[2] Ivanov V N, Salikhov RF and Grusnev MG 2013 Optimal planning of the functioning of systems of production, technical operation and development of road-building machineryparks (Omsk: SibADI)

[3] Sabha F N 2012 Modeling reclamation earthwork operations using special purpose simulation tool (Edmonton, Alberta) Available from: https://era.library.ualberta.ca/items/6c99462c-629a-451d-bdda-660041d58728 [Accessed 11th February 2019]

[4] AbouRizk S M and Mohamed Y 2002 Proc. Winter Simulation Conf. vol 2 (Piscataway, New Jersey: IEEE) pp 1704-1708

[5] AbouRizk S M, Halpin D, Mohamed Y and Hermann U October 2011 Journal of Construction Engineering and Management 137 (10) pp 843-852

[6] Obergrießer M 2016 Digital tools to integrated infrastructure, building, planning: The example of Rails-and road construction doctoral thesis (Tehnical universuty of Munich)

[7] Salikhov R F 2017 Improved methods of forecasting changes in the operational performance of construction machines from operating time Mechanization of construction 78 (4) pp 46-50

[8] Salikhov R F and Popkov V I 2018 Methodology for calculating of change of productivity of a single-bucket excavator in the course of operating time Mechanization of construction 79 (3) pp 26-31

[9] Ivanov V N, Trofimova L S and Linev F V 2013 A model of formation and development of technological complexes of machines for highway construction Construction and road building machinery 6 pp 22-25