On the Issue of Forming Construction Machinery Sets When Performing Construction and Installation Work

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Abstract. A large scope of work, tight deadlines, and the need to use various construction equipment suppose its widespread use. This will allow improving construction efficiency. Machinery sets and complexes support various process flows. Machinery sets serve individual lines (simple workflows). Machinery complexes support specialized flows being complex processes (work) and object flows – work packages. The performance of the leading machine in the complex (set) should ensure the fulfillment of the scope of work within the deadlines and with the pace specified. When choosing and integrating machines, the main process parameter is the performance of the leading machine or machinery complex. Also, when choosing machines, their design parameters should be considered. The study proposes tools to form the construction machinery sets. They are illustrated with specific examples.

1. Introduction

Forming machinery sets and complexes involves determining a certain set of machines and mechanisms to perform a given type of work. Machinery set is a group of main and auxiliary machines operating in coordination and mutually fit by their performance and other parameters, which are required to carry out labor-intensive processes. Machinery complex is a system of main and auxiliary machines or machinery set operating in coordination and mutually fit by their performance and other parameters, which are required to fulfill specific work (task).

Machinery sets are arranged to perform simple labor-intensive processes, i.e. excavating pits, leveling the ground, etc. Machinery complex is arranged to perform complex processes and consists of several machinery sets designed to mechanize individual work processes.

Combining machines into sets and complexes increases their efficiency due to implementing the buildup principle and improving control, maintenance, repair, and operation.

The buildup principle means creating a certain redundancy in the system, which allows maneuvering resources and means in the course of fulfilling the task (e.g., completing work started by a faulty machine by serviceable ones).

Machines structurally integrated into complexes and sets are already the higher complexity systems than each of them individually.
Machines integrated into systems affect each other that is manifested in a certain change in the system properties: therefore, individual machines combined into a complex should be interconnected. This interconnection occurring during their operation is called the interaction of machines as part of a complex, and the work process is called complex mechanization.

A system of machines is a time-varying set of machines, vehicles, labor-saving tools, and auxiliary equipment, formed based on the process requirements and ensuring the performance of complex mechanized work.

The way of mechanization is determined by the work technology, therefore, upon choosing it, detailed work method statements are developed.

The mechanized method of work is characterized by a leading machine used to perform the main process in the chain of this type of work. Coordinating the work of machines in the process chain is performed by the main operating parameter - output, as well as the main design parameters, i.e. the excavator bucket capacity, the load-carrying capacity of the crane and vehicles, etc. [1, 2, 3, 4, 5, 6, 7, 8, 9, 10].

Choosing machinery sets and complexes for complex mechanization includes the below stages:

- the necessary operating parameters of the main machines, their types and brands, a list of technically required auxiliary machines and their types are determined based on the forecasted scope of work, as well as the work technology adopted and the process or specialized flow structure,
- the optimal complex mechanization option is chosen based on a comparison of the main and additional indicators.

The main indicator here is the work duration.

Machines are chosen based on the compliance of their main operating parameters with the requirements for mechanical machines and work performance technology [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11].

2. Materials and techniques

2.1. Application of machines

The main technical means will be bulldozers, tracklayers, single-bucket excavators, mobile cranes, tools powered by mobile compressor and power stations, and torch cutters. Also, bucket loaders, dump trucks, and other machines can be used. The high efficiency of the machines listed above has been proven by repeated tests and experience of their use by installation and construction organizations.

In the temporary road construction, cohesionless road-building materials (crushed stone, gravel, slag, etc.) and precast slab pavements are used.

When arranging temporary passages in the rubble, crawler and wheel tractor bulldozers, loaders, cranes, and other machines are used.

To mechanize work, various types and brands of construction machines and mechanisms can be used. All mechanical means used in construction can be divided into four groups:

1. Machines and mechanisms used to perform the main types of work. They include equipment to lay temporary tracks, perform clearing-up operations, and arrange temporary passages, as well as hoisting machines and mechanisms. These are bulldozers, scrapers, motor graders, motor and trailed rollers, truck and tractor cranes, loaders, conveyors and elevators, drilling rigs and units, vibratory soil compaction machines, concrete pavers, concrete mixers, power plants, compressors, electric welding units, special machines and mechanisms, including those for municipal gas facilities.

2. Power tools and the simplest mechanical means used in the performance of work, i.e. pneumatic and electric tools, gasoline blow torches and gas cutters, hoists, jacks, hand winches, etc.

3. Means ensuring the transportation of loads, mechanical means, and materials to the construction site, i.e. trucks, dump trucks, concrete trucks, cement trucks, concrete mixers, support semi-trailers, panel trucks, wall trucks, frame-carrier trucks, block trucks, expanded clay and brick trucks, and heavy truck trailers.
4. Repair and maintenance facilities, i.e. repair workshops, service stations, refuellers and water loaders, and lighting stations and devices.

The need for main construction machines, mechanisms, and vehicles is determined in general based on the physical scope of work and the operational performance of machines and vehicles. Machinery sets and complexes should be chosen for the complex mechanization of work.

In general, the task is to perform the scope of work \( \{H | m\} \) within the time \( T \) not exceeding the value \( \bar{T} \) at the minimum allowable cost \( V \):

\[
\begin{align*}
V(\{H | m\}) & \rightarrow \min \\
T(\{H | m\}) & \leq \bar{T}
\end{align*}
\]

Each pair of indicators \( H \) and \( m \) refers to a certain structure (e.g.) if several identical structures should be raised to the same height; in the matrix \( \{H | m\} \), these structures will be represented by separate rows. The scope of lifting work can be specified by a table, in which each specific height corresponds to the load to be lifted to this height. In the mathematical model, the scope of work is set using the matrix \( \{H | m\} \).

It is important to consider each detail separately, primarily, to understand which crane models can and cannot lift a given load to a given height. Let us suppose that there are many permissible lifting equipment models, each of which has a set of technical and technical-and-economic characteristics.

Thus, e.g., the below list of equipment compared can be used to perform earthwork: truck crane, excavator, bulldozer, and dump truck.

The basic schemes of functioning the machinery complexes when arranging passages are shown below (Fig. 1).

![Figure 1. Basic Schemes of Machinery Complexes when Arranging Passages.](image-url)

a) leading machine with a set of replaceable attached implements and several auxiliary machines operating in parallel; behind a single leading machine, several auxiliary ones work in parallel; b) auxiliary machines operating in series also participate in the process; c) the leading machine and several parallel chains of auxiliary machines operating in series; the leading machine operates after the auxiliary one; d) several auxiliary machines operate behind the leading one; e) several leading machines and several parallel chains of auxiliary machines operating in series.
The machinery complexes, e.g., for the construction of roads, passages, driveways, and tracks should include engineer vehicles, tracklayers, bulldozers, and bucket loaders. When arranging tracks, a tracklayer is used. Along with the tracklayer, the complex should include a bulldozer with a capacity of over 130 hp. To arrange the driveway, it is advisable to use a machinery complex consisting of a truck crane or an excavator and a bulldozer; in this case, the latter’s power should exceed 160 hp.

Single-bucket excavators can be used when working in confined spaces; an attached ripper can be used as replaceable work equipment at hydraulic excavators.

To transport soil, it is advisable to use machinery sets composed of single-bucket excavators and dump trucks (haulers). When choosing a transport scheme, it should be considered that the optimal dump truck bucket and body capacity ratio is 1:4 or 1:5.

The approximate load-carrying capacity of vehicles depending on the excavator bucket capacity should be taken according to Table 1.

| Excavator Bucket Capacity, m\(^2\) | Dump Truck Load-Carrying Capacity, t | Tractor Trailer Load-Carrying Capacity, t |
|-------------------------------------|--------------------------------------|------------------------------------------|
| 0.3-0.4                             | 3.5-5                                |                                          |
| 0.5-1                               | 7-10                                 | 5-10                                     |
| 1.25-2                              | 10-25                                | 10-15                                    |
| 3-4                                 | 25-40                                | 15-25                                    |

Vehicles to transport materials are chosen depending on specific conditions. In this case, it should be considered that for a bulldozer, the rational material transportation distance is 0.01-0.1 km, for dump trucks and heavy-duty truck semitrailers operating in conjunction with an excavator - 0.5-5 km, and for tractor trailers - 0.1-1 km.

The single bulldozer output is relatively low. For this type of work, it is advisable to use machinery complexes comprising a high-power bulldozer (25 p.f.) as a leading machine and 2-3 bulldozers of lower power.

### 3. Results

The experiment has shown that when using machinery complex to arrange driveways, the operating time is reduced by 2-3 times compared to that for single machines.

Arrangement of access roads.

Calculating workload for loading [13]:

\[ T_p = \frac{V \cdot H_r \cdot s}{8}, \text{machine-shifts} \]

where \( V \) is the scope of work,
\( H_r \) is the time rate (machine-hour);
\( s \) is the shift duration, hours.

For the Hitachi ZAXIS 240 excavator with a bucket capacity of 1.25 m\(^3\), the time rate: \( H_r = 1.3 \) machine-hours.

\[ T_p = \frac{6.17^{1.3} \cdot 0.01}{8} = 10.03 \text{ machine-shifts} \]

\[ K_{ef} = M(T_o)/T = M(14/11) = 1.27 \]

For Doosan DX 300LCA with a bucket capacity of 1.50 m\(^3\), the time rate: \( H_r = 1.1 \) machine-hours.

\[ T_p = \frac{6.17^{1.1} \cdot 0.01}{8} = 8.49 \text{ machine-shifts} \]

\[ K_{ef} = M(T_o)/T = M(14/9) = 1.56 \text{ (The most optimal set)} \]

For Doosan DX 520LC with a bucket capacity of 3.20 m\(^3\), the time rate: \( H_r = 0.59 \) machine-hours.

\[ T_p = \frac{6.17^{0.59} \cdot 0.01}{8} = 4.55 \text{ machine-shifts} \]

\[ K_{ef} = M(T_o)/T = M(14/5) = 2.8 \]
Table 2. Demand for Dump Trucks when Using the Hitachi ZAXIS 240 Excavator, 1.25 m³

| Machine      | Brand, Capacity | Type, H_t | Number of Machines at Transportation |
|--------------|----------------|-----------|---------------------------------------|
| Excavator    | Hitachi ZAXIS 240, 1.25 m³ | -         | 1 1 1 1 1 1                           |
| Dump truck   | MAZ 551605 2130-024, 18.5 t | 0.68      | 2 3 6 8 11                            |
|              | KAMAZ 6520, 20 t | 0.62      | 2 3 6 8 11                            |
|              | MAN TGA 40.390, 27 t | 0.55      | 2 3 5 7 9                            |

Table 3. Demand for Dump Trucks when Using the Doosan DX300LC Excavator, 1.5 m³

| Machine      | Brand, Capacity | Type, H_t | Number of Machines at Transportation |
|--------------|----------------|-----------|---------------------------------------|
| Excavator    | Doosan DX300LC, 1.5 m³ | -         | 1 1 1 1 1 1                          |
| Dump truck   | MAZ 551605 2130-024, 18.5 t | 0.52      | 2 3 4 8 10 14                        |
|              | KAMAZ 6520, 20 t | 0.43      | 2 3 4 8 11 15                        |
|              | MAN TGA 40.390, 27 t | 0.40      | 2 3 4 7 9 13                        |

Table 4. Demand for Dump Trucks when Using the Doosan DX520LC Excavator, 3.2 m³

| Machine      | Brand, Capacity | Type, H_t | Number of Machines at Transportation |
|--------------|----------------|-----------|---------------------------------------|
| Excavator    | Doosan DX520LC, 3.2 m³ | -         | 1 1 1 1 1 1                          |
| Dump truck   | MAZ 551605 2130-024, 18.5 t | 0.41      | 2 3 5 9 12 17                        |
|              | KAMAZ 6520, 20 t | 0.35      | 2 3 5 10 13 19                       |
|              | MAN TGA 40.390, 27 t | 0.33      | 2 3 4 8 11 15                       |

Figure 2. Dependence of the Demand for Dump Trucks on the Transportation Distance when Loading with a Hitachi ZAXIS 240 Excavator with a Bucket Capacity of 1.25 m³
Figure 3. Dependence of the Demand for Dump Trucks on the Transportation Distance when Loading with a Doosan DX300LC Excavator with a Bucket Capacity of 1.5 m³

Figure 4. Dependence of the Demand for Dump Trucks on the Transportation Distance when Loading with a Doosan DX520LC Excavator with a Bucket Capacity of 3.2 m³.

When using a Hitachi ZAXIS 240 excavator with a MAZ-551605 2130-024 dump truck (the load-carrying capacity is 18.5 t, the volume is 11 m³), 10.3 m³ of construction waste weighing 18.5 t (the density is 1800 kg/m³) can fit in the dump truck. The dump truck loading downtime is 9.62 min (Hₐ = 0.52 [12]). At a transportation distance of 50 km, 14 vehicles will be required. The cycle time is 129.6 min. For 1 cycle, 14 vehicles will remove 144.2 m³, therefore, removing 6,174 m³ will require 43 cycles = 92.8 hours = 12 days (at an 8-hour shift).

When using a Doosan DX 300LCA excavator with a KAMAZ 6520 dump truck (the load-carrying capacity is 20 t, the volume is 12 m³), 11.1 m³ of construction waste weighing 20 t can fit in the dump truck. The dump truck loading downtime is 10.4 min. At a transportation distance of 50 km, 13
vehicles will be required. The cycle time is 130.4 min. For 1 cycle, 13 cars will remove 144.3 m$^3$, therefore, removing 6,174 m$^3$ will require 43 cycles $\approx 93.5$ h = 12 days (at an 8-hour shift).

When using a Doosan DX 520LC excavator with a MAN TGA 40.390 dump truck (the load-carrying capacity is 27 t, the volume is 19 m$^3$), 15 m$^3$ of construction waste weighing 27 t can fit in the dump truck; therefore, to remove 6,174 m$^3$, 412 loadings will be required. The dump truck loading downtime is 8.91 min. At a transportation distance of 50 km, 15 vehicles will be required. The cycle time is 128.9 min. For 1 cycle, 15 vehicles will remove 225 m$^3$, therefore, removing 6,174 m$^3$ will require 28 cycles $\approx 4.15$ hours, which is less than 1 day. This option is not suitable since the workload for removal of waste is 4.55 machine-shifts, i.e. 5 days.

To calculate the technical-and-economic indicators, the software package Excavator developed by Ph.D. in Engineering S.M. Kuznetsov has been used [11].

The main organizational and process parameters of the package are as follows: the distance of transportation by dump trucks is within 1 to 50 km; the excavator type is face shovel. The bucket capacity is 1.25, 1.5, and 3.2 m$^3$; Excavators: Hitachi ZAXIS 240 with a bucket capacity of 1.25 m$^3$, Doosan DX 300LCA with a bucket capacity of 1.50 m$^3$, and Doosan DX 520LC with a bucket capacity of 3.20 m$^3$; Dump trucks with a load-carrying capacity of 18.5, 20, and 27 tons; Dump trucks: MAZ 551605 2130-024 18.5 t, KAMA Z 6520 20 t, and MAN TGA 40.390 27 t.

### Table 5. Excavator Set Indicators

| Indicators                          | Dump truck with a load-carrying capacity of 18.5 t. | Dump truck with a load-carrying capacity of 20 t. | Dump truck with a load-carrying capacity of 27 t. |
|------------------------------------|---------------------------------------------------|---------------------------------------------------|---------------------------------------------------|
| Excavator with a bucket capacity, m$^3$ | 914. 1231 2268.                                  | 914. 1231 2268.                                  | 914.6 1231 2268.                                  |
| The production and process indicator value | 69 .4 7                                       | 69 .4 .7                                       | 9 4                                               |
| The excavator set output, m$^3$/shift | 8.75 6.50 3.53                                  | 8.75 6.50 3.53                                  | 8.75 6.50 3.53                                   |
| The excavator set time rate per 1,000 m$^3$, machine-hours | 114. 153. 283.6                                  | 114. 153. 283.                                  | 114.3 153.9 283.6                                 |
| Hourly excavator set output, m$^3$/h | 34 93 0                                        | 34 93 60                                       | 4 3                                               |
| Output, m$^3$/shift                | 233. 211. 208.5                                 | 264. 271. 270.                                 | 312.6 409.6 465.41                               |
| Soil volume in the bucket, m$^3$   | 0.91 1.19 2.55                                  | 0.91 1.19 2.55                                  | 0.91 1.19 2.55                                   |
| Buckets in a dump truck, pcs       | 12 9 4                                         | 13 10 5                                        | 15 11 6                                          |

At full provision with dump trucks, the excavator set performance is determined by the output of the leading machine - an excavator, therefore, the output values are the same for any transportation distance.

The estimated hourly output of the excavator set varies from 114.34 m$^3$ for an excavator with a bucket capacity $q = 1.25$ m$^3$ to 283.60 m$^3$ for an excavator with a bucket capacity $q = 3.2$ m$^3$.

For excavators with a bucket capacity $q = 1.5$ and $3.2$ m$^3$, the hourly output increases 1.35 and 2.48 times, respectively, as compared with an excavator with a bucket capacity $q = 1.25$ m$^3$.

The excavator set output per shift is 114.34, 153.93, and 283.60 m$^3$ at $q = 1.25$, 1.5, and 3.2 m$^3$, respectively.
Choosing and estimating possible results for the complex chosen can be made using the machinery complex efficiency indicators.

The work performance efficiency of the entire process machinery complex will depend on the efficiency of each (main and auxiliary) machine included in it. The efficiency criterion $K_{ef}$ of machinery complex intended to mechanize work can be the mathematical work success expectation, which is the ratio of the permissible work duration to the time actually spent by the machinery complex to perform this work.

$$K_{ef} = \frac{M[\langle T_o \rangle]}{T} > 1$$

where $[\langle T_o \rangle]$ is the permissible duration of the k-th type work ($k = 1, 2 ...$),

$T$ is the actual time spent to perform the k-th type work.

The optimal set is:

A Doosan DX 300LCA excavator with a bucket capacity of 1.50 m$^3$, a KAMAZ 6520 dump truck with a load-carrying capacity of 20 t, a KS-55729B Galichanin truck crane, and a bulldozer TM-10.10 GST10 (calculations are given above).

4. Discussion

The machinery complex performance is determined by the main (leading) machine output; the calculations are true if the performance of the auxiliary machines in the complex ensures the design operational performance of the main machine. This takes place when the complex composition is constant while performing uniform work for a short period.

When performing dispersed non-uniform work, the impact of random and organizational factors on the performance of auxiliary machines should be considered. These factors lead to a certain decrease in the output of auxiliary machines, which affects the performance of the entire complex.

An important estimate of the machinery complex application options is the justification and choosing the optimality criterion.

5. Conclusions

As such a criterion, the minimum duration of construction and installation work at the facility restored, minimum workload, and minimum reduced costs can be used. Along with the chosen optimality
criterion, other indicators characterizing the efficiency of construction and installation work should also be used. These indicators include the level of concentration and use of the material and technical and labor resources. Choosing one or another optimality criterion depends on the specific work performance conditions, the scope, and the accident elimination deadlines.

6. References

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