applied sciences

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Formation of Rational Sets of Machines for Excavation Work in Urban Areas

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Abstract: The study is aimed at developing a tool for the formation of a rational set of machines for excavation work in urban areas. The instrument to be developed will affect the main project parameters, such as the project cost and term of implementation. An expert survey was launched among the leading specialists of the construction industry to make a set of significant parameters and identify the weighting ratio, since both are required to select the machines for rational sets designated for excavation work in urban environments. The equation of multiple regression was solved to determine the extent of significance by calculating Fisher's ratio. This equation shows that significant parameters are inter-related and can be used in this method. A method for making a rational set of machines, designated for the performance of excavation work in urban environments, has the following stages: at the first stage, the choice of the necessary excavation work at the construction site is made; at the second stage, limitations, arising at the site, are introduced; at the third stage, the minimum number of major machines is determined; at the fourth stage, a rational set of machines is made step by step. If implemented, this study demonstrates the high economic efficiency of the proposed method of expanding excavation work in urban environments. The study shows that the use of a mathematical model will boost the project's success, as it demonstrates the critical factors of risk at the initial stage of the life cycle of a construction project.

Keywords: excavation work; set of machines; multi-criteria choice; method of expert evaluations

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Citation: Lapidus, A.; Topchiy, D.; Kuzmina, T.; Efimov, V. Formation of Rational Sets of Machines for Excavation Work in Urban Areas. *Appl. Sci.* **2023**, *13*, 7023. https://doi.org/10.3390/app13127023

Academic Editor: Luís Picado Santos

Received: 24 April 2023

Revised: 1 June 2023

Accepted: 9 June 2023

Published: 11 June 2023

1. Introduction

The problem of improving the structure of a fleet of construction machines remains relevant despite a high level of excavation mechanization. The fleet structure must be reconsidered to ensure high quality earthwork, reduce manual work and enhance the efficiency of the machinery in operation [1,2]. This problem is particularly relevant for excavation work to be performed in built-up urban environments, characterized by high-density development and the challenging conditions of excavation [3,4].

The transition to the market economy has greatly increased the variety and number of excavation machines. However, it has little effect on improving the quality and reducing the duration of excavation work. The main reason is the use of machines with a minimal or expired service life, as well as insufficiently qualified personnel. The generalization of experience in the construction of various earthwork structures, identification of their characteristic features and methods of soil processing underlie the development of progressive provisions ensuring the adequate compliance between the engineering processes and excavation, earth transportation and auxiliary machinery, which is the basis for the formation of rational sets of machines [5–8].

The principles of making sets of machines for excavation purposes were different at the various stages of technological development.

In the 80s, specialists of the Central Institute for Research, Design and Pilot-testing of Mechanization of Construction ("the Institute") developed the software titled the "System of machines" to calculate the number of construction machines needed. This software was a science-based parametric series of machines for various types of construction and installation works [9]. If a machine model did not exist, its technical specifications were devised to develop and produce the machine that had all the necessary functions. In addition, this software determined the structure of machinery fleets for the entities that performed the construction and installation work.

The Institute also selected major road-building machines [10]. In this work, the length of the work area and the optimal composition of major machines is determined. Kilometers of roads built and the maximum output of one shift are used as the main values. However, this method was not applied in industrial and civil engineering.

This method was further developed in [11–13], which were focused on a more detailed selection of a set of machines and mechanisms by selecting the individual major machines and matching them with minor machines by means of analyzing their reliability. This is the way, the effectiveness of a set of machines for construction in real conditions is prognosticated, because if some project information, needed to evaluate the effect of the main factors on the project cost and duration, is missing, it is impossible to calculate the cost of construction, taking into account any changes in the cost of the operation of construction machinery [14–16].

Institute specialists and several other researchers focus on making an optimal set of machines for one single entity, which greatly reduces the applicability of the majority of machines in different construction conditions. Due to the fact that a large number of entities can neither buy, nor operate, a large fleet of machines, these entities lease construction machinery, and their principal task is to make such a set of machines that will perform the work, on the one hand, and save time and resources, on the other hand.

Below are the basic principles underlying the formation of sets of construction machines (Table 1).

Table 1. Basic principles underlying the formation of sets of construction machines.

№	Method	Principle	Weaknesses
1	System of machines software developed by the Institute	The software offers a science-based parametric series of machines for different types of work.	1. Determines the structure of the fleet for one single contractor
2	Selection according to the "capacity vs. cost" principle	A number of major machines, whose capacity is about 85–110% of the design value, is selected and the cheapest option is chosen to meet the pre-set requirements. In the same way, minor machines are selected to match the major machine.	1. The set is not considered as a whole 2. Selection is made on the basis of the two parameters; therefore, this procedure cannot be called multi-criteria choice 3. The capacity range is too large
3	Formation of the set by setting the target function as well as the material and engineering reliability (MER) of the subset of the set	When sets of machines are selected, all the possible options are considered for which the value of the target function and MER of the construction machines is determined. According to the minimum value of the latter, the final choice of the set of machines is made.	1. Determines the structure of the fleet for one single contractor 2. Multi-criteria choice is made individually for each subset, while the set is not considered as a whole

The main problem, arising during the formation of excavation works sets, is the lack of a quality selection tool. This conclusion can be made because only two parameters, such as capacity and cost, are used to make a set of machines for excavation works from the pool of available machines having similar characteristics. Alternatively, an additional selection parameter is the target function analysis showing the dependence of the MER on the parameters of machines and the construction site.

Another problem of making the sets of machines for excavation works is the fact that sets are made from those machines that are available to the entity in charge of construction, which, in turn, reduces the number of options of machine sets and offers an advantage to those entities that have a larger fleet of machines and can select a set more thoroughly.

A rational set of machines is a set of machines made using the multi-criteria selection procedure [17,18]. In other words, a large number of parameters are used to make a set of machines needed for the performance of work; these parameters affect the choice of the set. In addition, we should not forget about constraints, such as little space, noise restrictions, etc., that arise during construction work performance.

The purpose of this study is to form a rational set of machines for earthworks in urban conditions. To do this, it is assumed that the formation of such sets will be carried out according to the following algorithm (Figure 1).

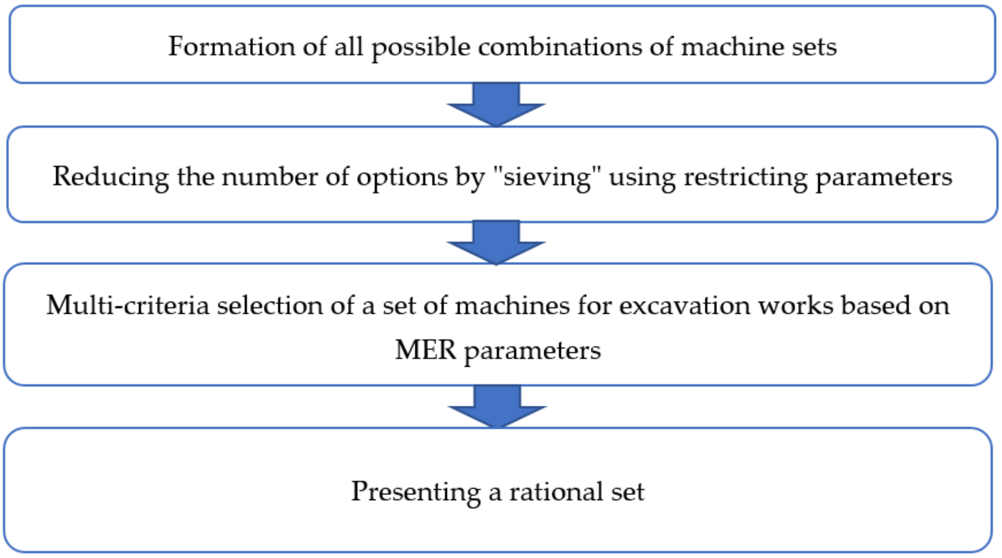

Figure 1. The block diagram for selecting a rational set of machines.

2. Methods of Research

It is necessary to systematize machines, used to perform the work, to ensure the higher quality formation of machine sets. First of all, systematization requires a solution to the problem of types of work performed in the course of excavation. Three types of excavation work are performed to build a facility in urban environments:

1. Grading and levelling of areas;
2. Making an excavation and compacting its bottom;
3. Excavation backfilling.

It should also be noted that works related to dewatering, the arrangement of surface runoffs, water discharge outlets and drainages are not principal types of work, and they depend on the type of soils, applicability of versatile techniques and other factors. Since there is a small number of machines, having different characteristics, that can be used to perform such works, the influence on the choice of a rational set of machines for excavation works is minimal. Accordingly, the above types of work will not be considered in this study.

A group of parameters was identified [19].

Parameters are the values that determine the effectiveness of a machine using a certain criterion. Having analyzed the research literature and with experience in forming sets of machines, a number of parameters were identified:

1. Machine capacity (x_1)
2. Cost of a set of machines (x_2)
3. Type of soil (x_3)
4. Excavator boom reach (x_4)
5. Backhoe bucket capacity (x_5)
6. Work cycle time (x_6)
7. Volume of earth to be relocated (x_7)

8. Maximum speed in the loaded condition (x_8)
9. Maximum speed when empty (x_9)
10. Body volume (x_{10})
11. Cutting width (x_{11})
12. Cutting depth (x_{12})
13. Maximum travel speed (x_{13})
14. Availability of a ripper (x_{14})
15. Type of the excavator bucket (x_{15})
16. Excavation pattern (x_{16})

These parameters were offered to experts in the course of the expert survey. According to the calculation results, 16 parameters were enough to interview at least 5 experts [20–22]. The experts were to have higher education, at least 5 years of experience in the field of study and the status of a member of the National Association of Surveyors and Designers (NASD) and/or the National Association of Builders (NAB).

As part of the expert survey, the experts arranged in descending order the parameters that, in their opinion, have the greatest impact on the formation of a rational set of machines for earthworks (Table 2).

Table 2. Results of the expert survey.

Parameters \ Expert	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	Sum of Ranks	d	d^2
x_1	15	15	15	16	16	16	16	16	15	15	16	16	15	15	14	15	16	15	277	124	15,376
x_2	16	16	16	14	14	15	14	15	14	14	14	14	14	14	15	16	15	16	266	113	12,769
x_3	14	14	14	15	15	14	15	14	16	16	15	15	16	16	16	14	14	14	267	114	12,996
x_4	12	13	13	13	13	13	13	13	13	13	13	13	12	12	11	12	12	13	227	74	5476
x_5	13	11	12	12	11	12	11	10	10	10	10	11	11	11	12	13	11	12	203	50	2500
x_6	11	10	11	10	10	11	12	12	12	11	11	12	13	13	10	11	10	10	200	47	2209
x_7	10	12	10	11	12	10	10	11	11	12	12	10	10	10	13	10	13	11	198	45	2025
x_8	1	2	2	2	2	2	2	2	3	4	4	5	4	5	4	4	1	5	54	−99	9801
x_9	2	1	1	1	1	1	1	1	5	5	5	3	5	4	5	5	4	3	53	−100	10,000
x_{10}	9	9	9	8	9	9	9	6	6	8	7	7	7	7	8	8	7	7	140	−13	169
x_{11}	8	8	8	7	8	6	8	7	9	9	6	9	6	6	6	6	6	6	129	−24	576
x_{12}	7	6	7	6	6	7	7	8	8	7	8	8	8	8	7	9	8	9	134	−19	361
x_{13}	6	7	6	9	7	8	6	9	7	6	9	6	9	9	9	7	9	8	137	−16	256
x_{14}	4	5	4	3	5	3	4	4	2	2	1	4	3	3	1	3	2	2	55	−98	9604
x_{15}	5	3	5	5	4	5	5	5	1	1	2	2	1	1	3	1	5	1	55	−98	9604
x_{16}	3	4	3	4	3	4	3	3	4	3	3	1	2	2	2	2	3	4	53	−100	10,000
$\sum$	136	136	136	136	136	136	136	136	136	136	136	136	136	136	136	136	136	136	2448		103,722

The Kendall concordance coefficient was applied to determine the consistency of the expert opinions:

$$W = \frac{12 \cdot S}{m^2 \cdot (n^3 - n)} \quad (1)$$

where S was the sum of squares of the deviation of the sum of ranks from the arithmetic mean sum of ranks, n was the number of parameters to be studied and m was the number of experts.

$$W = \frac{12 \cdot 103722}{18^2 \cdot (16^3 - 16)} = 0.942 \quad (2)$$

Since $W \geq 0.5$, the consistency of the experts' opinions is proven.

After determining the consistency of expert opinions, it was necessary to calculate the consistency coefficient.

To do this, it is necessary to calculate the Pearson correlation coefficient.

$$\chi^2 = \frac{12 \cdot S}{m \cdot n \cdot (n+1)} = n \cdot (m-1) \cdot W \quad (3)$$

$$\chi^2 = 18 \cdot (16-1) \cdot 0.942 = 254.22 \quad (4)$$

Since the calculated Pearson's coefficient $\geq$ the tabulated one ($254.22 \geq 24.99579$), W = 0.942 is a non-random value, and therefore, the results are valid and they can be used in further research.

To determine the significant factors, it is necessary to remove factors belonging to the "noise field" from the total list of factors [23,24]. For this purpose, it is necessary to rank them by the factor that has the greatest sum of ranks. The upper boundary of the "noise field" level is about 15–20% of the main factor (the lines highlighted in orange are the factors of the "noise field" and the significant factors are highlighted in green). It is also necessary to determine the weight of the parameter. For this purpose, it is necessary to divide the total rank of the parameters by the total sum of ranks (Table 3).

Table 3. Determining the level of the noise field and the weight of the parameters.

Parameters	Sum of Ranks	%	Parameter Weight
x_1	277	100	0.113
x_2	266	96	0.109
x_3	267	96.4	0.109
x_4	227	81.9	0.093
x_5	203	73.3	0.083
x_6	200	72.2	0.082
x_7	198	71.5	0.081
x_8	54	19.5	0.022
x_9	53	19.1	0.022
x_{10}	140	50.5	0.057
x_{11}	129	46.6	0.053
x_{12}	134	48.4	0.055
x_{13}	137	49.5	0.056
x_{14}	55	19.9	0.022
x_{15}	55	19.9	0.022
x_{16}	53	19.1	0.022

Since it is assumed that the rational set of machines for excavation works will be made using a multicriteria choice, it is necessary to identify the dependence between the parameters and determine the degree of their significance. Towards this end, we will use the multiple regression equation [25]:

$$\begin{gathered} x_2 = 56{,}807.486 + 17{,}714.1702 \cdot x_1 - 19{,}576.0615 \cdot x_3 + 244.1002 \cdot x_4 - 83{,}679.961 \cdot x_5 + \\ 105{,}622.557 \cdot x_6 - 1{,}491{,}979.0636 \cdot x_7 + 1237.2075 \cdot x_{10} - 100.6329 \cdot x_{11} + \\ 2388.921 \cdot x_{12} - \ldots \ldots \ldots \ldots - 0.0159 \cdot x_{13} \end{gathered} \quad (5)$$

To check the statistical significance, it is necessary to calculate Fisher's F-ratio and compare it with the one in the table:

$$F = \frac{R^2}{1-R^2} \cdot \frac{(n-m-1)}{m} \quad (6)$$

$$F = \frac{0.7157}{1-0.7157} \cdot \frac{33-10-1}{10} = 5.538 \quad (7)$$

Knowing the calculated value, one needs to determine the critical value (F_{kp}) based on the level of significance $\alpha = 0.5$ and two degrees of freedom, according to the Fisher–Snedecor distribution:

$$k_1 = m = 10 \tag{8}$$

$$k_2 = n - m - 1 = 33 - 10 - 1 = 22 \tag{9}$$

Since the actual value is greater than the critical one, we can conclude that the equation of multiple regression is significant. Therefore, there is joint significance of the parameters that can be used in the model of selection of a rational set of machines for excavation works.

3. Result and Discussion

After determining the type of the construction site, it is necessary to determine the composition of the works to be performed at construction sites.

The main types of works performed during excavation are as follows.

Grading and leveling: this work is performed to level the construction site. Grading and leveling are performed by cutting and filling. This type of work allows preserving greenery on the construction site by transferring the soil to unoccupied areas; it also ensures the proper arrangement of the drainage system, continuous work of the personnel and operation of the machinery thanks to the absence of height gradients. The scope of work usually includes:

1. Stripping;
2. Cutting and filling;
3. Grading;
4. Using a self-propelled roller to compact soil.

Excavation and compaction of the bottom of an excavation pit is the process that includes earth separation in the course of excavating a pit to reach the level at which the foundation is to be made. This type of work consists of:

1. Excavation performed by an excavator;
2. Transportation of earth in dump trucks;
3. Using a bulldozer to clean the excavation pit bottom;
4. Soil compaction.

The excavation pit walls need strengthening due to the fact that many advanced construction projects have multi-level parking lots, as a means of the rational use of territories. Therefore, such projects encompass deep excavation pits. If the excavation depth is great, and if an excavation pit is deep, its walls need strengthening systems. Having analyzed several construction sites, the authors determined that sheet piling was the best strengthening method. This type of work includes:

1. Using vibrating pile hammers to drive piles at the edge of the excavation;
2. Backfilling of excavation pit hollows to be followed by compacting
3. Using a bulldozer to deliver backfill soil;
4. Soil a plate compactor to compact soil.

When making a rational set of machines, needed for excavation works, it is necessary to justify the selection criteria. Here is our algorithm that has the selection criteria.

Step 1.1. Determining the types of work to be performed within the framework of making an excavation pit (Figure 2).

Step 2.1. Limiting the choice of machines to make a rational set of machines for excavation works using the limiting parameters.

To make a rational set of machines for excavation works, it is necessary to consider the parameters that limit the performance of work.

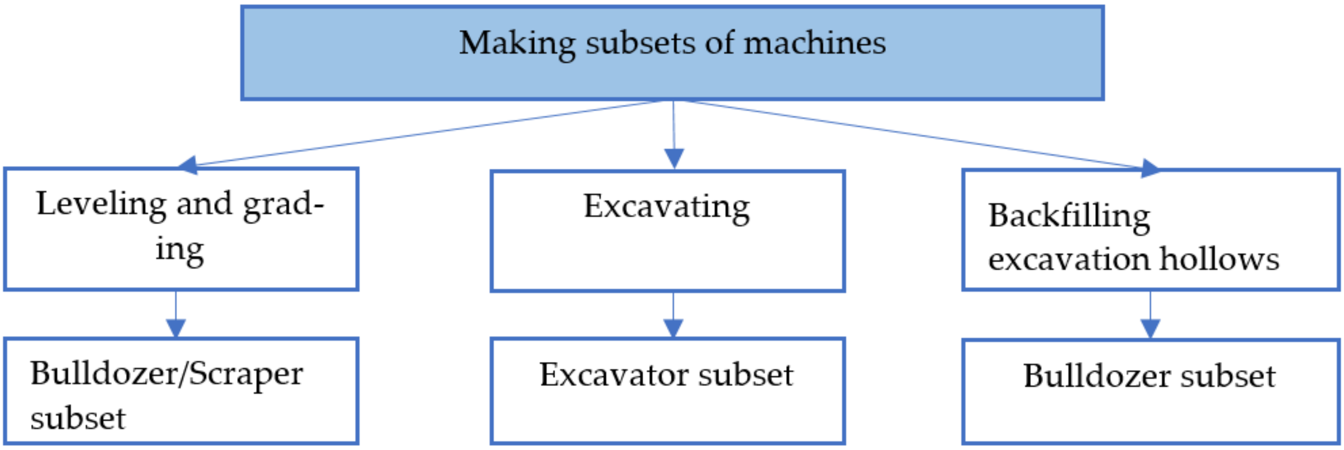

Figure 2. Making the subsets of machines.

Such parameters include:

The environmental class of the machine's internal combustion engine. Some restrictions are imposed on the machinery in operation in certain areas of Moscow, they deal with the environmental class of the internal combustion engine; for instance, within the Third Ring Road, vehicles and mechanisms are equipped with Euro 3 engines; Euro 2 engines are allowed within the Moscow Ring Road (MRR); and there are no restrictions outside the MRR.

Own vs. rented equipment. Since some of the equipment used to perform the works is not available to the entity performing the excavation works, there is an option to rent some models that will be suitable for the works.

Soil characteristics is the parameter used to break down the soils into excavation difficulty classes. Each type of soil belongs to an excavation difficulty class that requires a particular excavation technique.

The geometric dimensions of the excavation pit. The dimensions of the excavation pit are necessary to determine the 3D dimensions of the structure and select the rational volume of the bucket to ensure the best quality and intensity of earth removal.

Outdoor temperature is the parameter that affects the physical condition of water in the soil. At negative temperatures, the soil needs additional loosening, which raises the costs and duration of work.

The range of soil removal is the parameter that shows how far you need to take the earth using the earthmoving equipment. Depending on this range, the type and capacity of the earthmoving machine is selected.

Step 3.1. Determining the number of machines required to perform the work.

The number of major machines is determined by the composition of works to be performed.

Step 4.1. Formation of a rational set of machines.

The following model is proposed to form the sets of machines for excavation works:

Step 4.2. Making all possible the sets of machines.

The sets of machines, suitable for excavation works, are formed with regard for the pre-set conditions of the construction site, the requirements outlined in the second chapter and the requirements concerning the composition of work. Since the overall set of machines is formed, all the possible combinations of subsets, capable of performing the work, are specified. This step allows analyzing all sets in the course of final selection (Table 4).

Table 4. The options of machine sets and values of parameters.

Sets \ Parameters	x_1	x_2	x_3	...	$x_{(n-1)}$	x_n
1	$x_{1;1}$	$x_{2;1}$	$x_{3;1}$	...	$x_{(n-1);1}$	$x_{n;1}$
2	$x_{1;2}$	$x_{2;2}$	$x_{3;2}$	...	$x_{(n-1);2}$	$x_{n;2}$
3	$x_{1;3}$	$x_{2;3}$	$x_{3;3}$	...	$x_{(n-1);3}$	$x_{n;3}$
...	...	...	...	...	...	...
m−1	$x_{1;m-1}$	$x_{2;m-1}$	$x_{3;m-1}$	...	$x_{(n-1);\, m-1}$	$x_{n;m-1}$
m	$x_{1;m}$	$x_{2;m}$	$x_{3;m}$	...	$x_{(n-1);\, m}$	$x_{n;m}$

Step 4.3. Parameter scoring according to Harrington's psychophysical scale.

This technique makes the parameters suitable for the further selection process.

To do this, according to the Harrington psychophysical scale (Table 5), we translate the obtained parameter values to a single form (Table 6).

Table 5. Harrington's psychophysical scale.

Quantitative Grade on the Scale of Desirability	Psychophysical Scoring
1.00–0.80	1
0.80–0.63	2
0.63–0.37	3
0.37–0.20	4
0.20–0.00	5

Table 6. Parameters scoring according to Harrington's psychophysical scale.

Sets \ Parameters	x_1	x_2	x_3	...	$x_{(n-1)}$	x_n
1	$F_{1;1}$	$F_{2;1}$	$F_{3;1}$	...	$F_{(n-1);1}$	$F_{n;1}$
3	$F_{1;3}$	$F_{2;3}$	$F_{3;3}$	...	$F_{(n-1)3}$	$F_{n;3}$
...	...	...	...	...	...	...
132	$F_{1;132}$	$F_{2;132}$	$F_{3;132}$	...	$F_{(n-1);132}$	$F_{n;132}$
...	...	...	...	...	...	...
m−1	$F_{1;m-1}$	$F_{2;m-1}$	$F_{3;m-1}$	...	$F_{(n-1);\, m-1}$	$F_{n;m-1}$
m	$F_{1;m}$	$F_{2;m}$	$F_{3;m}$	...	$F_{(n-1);\, m}$	$F_{n;m}$

Step 4.4. Equalizing scores of parameters

To equalize the weighting parameter, it is necessary to multiply the obtained score by the "weighting" coefficient (Table 7), because it is necessary to have parameters that are equal in importance to improve the quality of final sampling of a set of machines.

Table 7. Parameter scoring according to Harrington's psychophysical scale multiplied by the "weighting" coefficient of the parameter.

Sets \ Parameters	x_1	x_2	x_3	...	$x_{(n-1)}$	x_n
1	$F_{1;1} \times W_1$	$F_{2;1} \times W_2$	$F_{3;1} \times W_3$	...	$F_{(n-1);1} \times W_{(n-1)}$	$F_{n;1} \times W_n$
3	$F_{1;3} \times W_1$	$F_{2;3} \times W_2$	$F_{3;3} \times W_3$	...	$F_{(n-1);3} \times W_{(n-1)}$	$F_{n;3} \times W_n$
...	...	...	...	...	...	...

Table 7. *Cont.*

Sets \ Parameters	x_1	x_2	x_3	…	$x_{(n-1)}$	x_n
132	$F_{1;132} \times W_1$	$F_{2;132} \times W_2$	$F_{3;132} \times W_3$	…	$F_{(n-1);132} \times W_{(n-1)}$	$F_{n3;132} \times W_n$
…	…	…	…	…	…	…
m−1	$F_{1;m-1} \times W_1$	$F_{2;m-1} \times W_2$	$F_{3;m-1} \times W_3$	…	$F_{(n-1);(m-1)} \times W_{(n-1)}$	$F_{n;(m-1)} \times W_n$
m	$F_{1;m} \times W_1$	$F_{2;m} \times W_2$	$F_{3;m} \times W_3$	…	$F_{(n-1);\,m} \times W_{(n-1)}$	$F_{n;m} \times W_n$

Step 4.5. Using the criteria to select the sets [26].

To select a rational set of machines for the earthworks in urban conditions, it is necessary to calculate the values of criteria for subsequent sampling.

1. the Maximin criterion is the criterion used to select the best effect at the minimum risks. Accordingly, the choice of a set of machines is made by selecting the lowest score, which is summarized in a separate column, and then the set with the highest score is selected.

2. the Maximax criterion is the criterion that is used to choose the best effect at the maximum risk. The highest score is chosen and summarized in the column. Then the options with the highest score are chosen.

3. the multiplication criterion is the criterion within the framework of which risks are "smoothed" and then the best effect is chosen. Accordingly, the parameter scores are multiplied for each option, and products are summarized in the column. Further, options with the highest product are chosen.

4. the Savage criterion is the criterion that identifies "regret", i.e., the maximal score is found in each set, and then other scores are subtracted from the maximal one. After that, the highest score is found for each option, then the minimum effect is chosen from among the maximum "regret".

Step 4.6. Applying the Paretto principle.

After selecting the sets according to four criteria, only those sets that were selected according to at least one criterion remain for the final consideration. This is the Paretto principle. The remaining combinations will form a Paretto set, on the basis of which the choice of a rational set of machines for excavation works will be made (Table 8).

Table 8. The Paretto set.

	Maximin	Maximax	Multiplication	of Savage
113	$F_{3;113} \times W_3$	$F_{(n-1);113} \times W_{(n-1)}$	$(F_{1;113} \times W_1) \times (F_{2;113} \times W_2) \times (F_{3;113} \times W_3) \times \ldots \times (F_{(n-1);113} \times W_{(n-1)}) \times (F_{n;113} \times W_n)$	$F_{(n-1);113} \times W_{(n-1)} - F_{3;113} \times W_3$
124	$F_{n;124} \times W_n$	$F_{33;124} \times W_3$	$(F_{1;124} \times W_1) \times (F_{2;124} \times W_2) \times (F_{3;124} \times W_3) \times \ldots \times (F_{(n-1);124} \times W_{(n-1)}) \times (F_{n;124} \times W_n)$	$F_{(n-1);124} \times W_{(n-1)} - F_{3;124} \times W_3$
125	$F_{n;125} \times W_n$	$F_{23;125} \times W_2$	$(F_{1;125} \times W_1) \times (F_{2;125} \times W_2) \times (F_{3;125} \times W_3) \times \ldots \times (F_{(n-1);125} \times W_{(n-1)}) \times (F_{n125} \times W_n)$	$F_{(n-1);125} \times W_{(n-1)} - F_{n;3125} \times W_n$
126	$F_{n;126} \times W_n$	$F_{13;126} \times W_1$	$(F_{1;126} \times W_1) \times (F_{2;126} \times W_2) \times (F_{3;126} \times W_3) \times \ldots \times (F_{(n-1);126} \times W_{(n-1)}) \times (F_{n;126} \times W_n)$	$F_{(n-1);126} \times W_{(n-1)} - F_{1;126} \times W_1$
128	$F_{n;128} \times W_n$	$F_{13;128} \times W_1$	$(F_{1;128} \times W_1) \times (F_{2;128} \times W_2) \times (F_{3;128} \times W_3) \times \ldots \times (F_{(n-1);128} \times W_{(n-1)}) \times (F_{n;128} \times W_n)$	$F_{n;3128} \times W_n - F_{13;128} \times W_1$
713	$F_{n;713} \times W_n$	$F_{(n-1);713} \times W_{(n-1)}$	$(F_{1;713} \times W_1) \times (F_{2;73} \times W_2) \times (F_{3;713} \times W_3) \times \ldots \times (F_{(n-1);713} \times W_{(n-1)}) \times (F_{n;713} \times W_n)$	$F_{3;713} \times W_3 - F_{n;3713} \times W_n$

Step 4.7. Applying the linear convolution rule and selecting a set of machines.

To choose one option of a rational set of machines for the excavation works, it is necessary to apply the rule of linear convolution, according to which if any of the options has been chosen according to one of the criteria, it obtains the score of 1, if not selected, then its score is equal to 0. Further, it is necessary to sum up the scores and choose the option whose score is highest (Table 9).

Table 9. Choosing the final option.

	Maximin	Maximax	Multiplication	of Savage	∑
113	1	1	0	0	2
124	0	0	0	1	1
125	0	0	0	1	1
126	0	0	0	1	1
128	0	0	1	0	1
713	1	1	1	1	4

4. Conclusions

The analysis of existing approaches to the formation of sets of machines for excavation works has shown that the problem of improving the structure of the fleet of machines and the choice of their rational sets is extremely relevant for the conditions of urban development. The solution to this problem can only be found by identifying the features of urban conditions, expanding the criterial basis for the selection of machines and leveraging the most significant parameters of sets of machines.

The following conclusions are formulated according to the results of the research conducted by the authors.

1. When sets of machines for excavation works are selected, the principles of the multi-criteria approach are not applied, and sets are made according to two parameters only, they are the capacity and cost of sets. As a result, the current methods do not take into account several features of the urban development and, therefore, they cannot be considered as effective.
2. The authors propose a principally new approach to the formation of sets of machines for excavation works, based on the identification of objective correspondence between the parameters of the technological processes and the structure of machines, with the maximum account taken of the characteristics of urban conditions in the course of leveling and grading, making and backfilling excavation pits.
3. There are 16 parameters that can influence the choice of kits. An expert survey was conducted in order to determine the significant parameters and their weight coefficients.
4. The correlation between the cost of a set of machines for excavation works and significant parameters was identified in the form of an equation of multiple regression, and its high degree of reliability was proven. As a result, a toolkit was devised for the development of a model and an algorithm for selecting a rational set of machines for excavation works in urban areas.
5. The authors developed a new methodology for making a rational set of machines for excavation works in urban environments, which includes the main types of work, the set of parameters limiting the choice of machines, the step-by-step analysis of the set of machines, which includes sieving the unsuitable machines, scoring the parameters of sets of machines according to Harrington's psychophysical scale, selecting sets of machines according to four criteria and identifying a rational set.

Author Contributions: Conceptualization, A.L.; methodology, A.L. and D.T.; software, V.E.; investigation, V.E. and T.K.; data curation, D.T. and T.K.; writing—original draft preparation, V.E. and T.K.; writing—review and editing, V.E. and T.K. All authors have read and agreed to the published version of the manuscript.

Funding: National Research Moscow state University of Civil Engineering (NRU MGSU) funded this research order № 618/130 от 09.08.2022.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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