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Mathematical Model of Optimizing Mechanized Machine Sets Gathering When Construction Highways

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Abstract. *A mathematical model is presented for obtaining data on reduced costs, which can be used in the optimization of machine sets to improve the recruitment process for mechanized detachments during road construction. The mathematical model for calculating the reduced costs, taking into account the probability coefficients for the use of equipment in the set, is built on the basis of a matrix that includes nine columns for types of machines and six rows for the main road construction technologies. By changing the basic input data, the model allows you to automatically recalculate all data. By applying the minimization criterion, it is possible to choose such a set that the total reduced costs for each set of machines and for each technology would be minimal. Optimization of a set of machines of various sizes for mechanized detachments, when designing roads, will reduce the time for building roads and reduce costs.*

Keywords: *optimization, mathematical model, road construction machines, unit costs, machine sets, machine complete, road construction, machine park, optimization of gathering machines.*

Introduction. The main working units of construction and installation processes are sets of machines that provide machine parks of road construction organizations. Their effectiveness depends on many factors. If the same production capabilities are available at the enterprise, different results can be obtained depending on how optimally the sets of machines are formed, the structure of machine sizes is determined, and what is the level of organization of construction production [1, 2].

The practice of building processes shows that depending on the nature of the interaction of mechanization means and the integrated use of equipment under the same conditions and the same resources, different results can be obtained.

In connection with the above search for alternative proposals to make the best decision involves research using a mathematical model with subsequent analysis of the results obtained, which are very relevant in road construction. These actions are relevant at the design stage, which helps to prevent problems during the implementation of the project [3-5].

Literary review. The scientific works of Permyakov V.B. (5), Ivanov V.N. (6), Repin, S., Zazykin, A., & Gordienko, V. (7), Minaei, M. (8) which considered the optimization of a set of machines not for a general system but for a specific technological operation (subgrade, road clothes, etc.) Therefore, by optimizing certain subsystems, such as the construction of subgrade, road base, pavement, etc., it is possible to provide not general, but particular optimization [9].

Performance and specific reduced costs were chosen as the optimization criterion. The capabilities of modern road construction machines have increased markedly, their productivity, reliability, and efficiency have increased. But along with this, their selling price and operating costs have increased significantly. Therefore, deviation from optimal organizational decisions leads to significant economic losses. Based on the analysis of the above works, we have proposed a mathematical model for optimizing a set of machines for the entire technological operation [10, 11].

The proposed simulation is aimed to improve the system of theoretical views and planning methods for the use of the fleet of vehicles of road construction organizations with the highest possible indicators of the efficiency of the use of equipment.

During road construction choice means of mechanization depend on climatic, economic and production factors. It is very important, after completing the composition of mechanization means, to make a mathematical justification and search for the most optimal variant of the organized set of machines. Optimization of the entire work management system during the construction of a highway is a complex technical and economic task.

The aim of the work is the development and research of a mathematical model for optimizing the acquisition of the working fleet of machines in the construction of roads.

To achieve this goal, it is necessary to solve the following tasks:

- to determine the list of types of work required to complete the road construction task;
- select the necessary brands and models of machines from the general list of road construction equipment;
- to form sets of machines from the proposed list to perform the corresponding operations by type of work;
- to develop a mathematical model for processing unit costs for sets of machines.

Formulation of the problem. The main problem of road construction in Central Kazakhstan is the high cost and the use of only the equipment that is available in the park of the road construction organization.

The main disadvantage of building roads is their high cost. The construction of one kilometer of the road in Kazakhstan costs from 500 thousand to two million dollars, depending on the category of the road. In addition, the climatic conditions of Kazakhstan do not allow construction work to be carried out throughout the calendar year, therefore, enterprises engaged in the production of construction work have limitations associated with the loss of time.

The vast territory of Kazakhstan increases the length of roads, which means the distribution of working equipment along the entire facility under construction. Accordingly, the enterprises of the road industry should have a wide fleet of vehicles and a large variability of their standard sizes, and also, already at the stage of road design, plan the optimal distribution of equipment on a multi-kilometer construction site [4-5].

A scientific approach to optimizing the distribution of machines of various sizes across mechanized complexes, in the design of roads, will significantly reduce the construction time of roads and save costs for the construction of roads in Kazakhstan [6].

In that work a mathematical model for optimizing a set of machines in the construction of roads is proposed, which contributes to the improvement of the process of recruiting mechanized groups.

Road construction technology includes the following six operations:

1. Clearing of the right of way (removal of the vegetation layer, profiling and compaction of the right of way.

2. Construction of subgrade (delivery of soil by dump trucks, leveling, profiling and soil compaction).

3. Preparation of the base of the pavement (layout and compaction of the upper surface of the subgrade, distribution of sand and profiling of the sandy base).

4 Construction of a crushed stone base (preparation of the surface for a crushed stone base, arrangement of a road trough, filling the trough with crushed stone, its leveling and compaction, filling the wedged fraction of crushed stone, its distribution and compaction).

5. Construction of the main pavement (cleaning the base for the pavement, pouring bitumen, laying and compacting asphalt concrete).

6. Arrangement of a protective layer of pavement (cleaning the base for the protective layer, pouring bitumen, laying and compacting the protective layer of asphalt concrete).

Operations of the technological process of road construction and the recommended list of machines that can be used in construction are shown in Table 1.

Research methods. For this technological process of road construction, many construction organizations have a diverse fleet of machines. In order for the acquisition of mechanized units to be as effective as possible, it is necessary to form sets of machines based on a scientific approach using modern optimization methods [2].

To compile a mathematical model, we will take the following notation and assumptions. Index W denote the technological operations in the construction of the road:

- W1 – operation for clearing the right-of-way;
- W2 – operation on construction of subgrade;
- W3 – operation on preparation of the sand base of the pavement;
- W4 – operation on construction of a crushed stone foundation;
- W5 – operation for the construction of the main pavement of the road clothes;
- W6 – operation on the device of a protective layer of pavement.

The letter index j denotes the type of one or another construction and road equipment:

- j1 – bulldozers;
- j2 – motor graders;
- j3 – soil-compacting rollers;
- j4 – dump trucks;
- j5 – watering machines;
- j6 – crushed stone distributors;
- j7 – rollers with smooth rollers (light, medium, heavy);
- j8 – asphalt pavers;
- j9 – truck distributors.

As the specific reduced costs for the performance of the i-th type of work of the j-th machine, we take the variable yij, which is shown in Table 2. Then y23 will denote the specific reduced costs for the construction of the subgrade, compactors (Amman AV 16 or Bomag BW 138 AC brands) [3].

Denote by p, the probability of using the jth car. We assume that this probability for each machine in the set in each technological operation has a different value. Then the condition of not exceeding the given level of specific reduced costs in the line of each technology will be written as an inequality:

$$y_{11}p_1 + y_{12}p_2 + ... + y_{ij}p_j + ... + y_{impm} < y_i \quad (1)$$
$$(i = 1, 2..., n),$$

which, expanded line by line, will look like this:

Table 1 – Variable choice of road equipment for various operations

Name and content of the operation	Equipment type	Brand, model
1 Right-of-way clearing (vegetation layer removal; right-of-way profiling; right-of-way compaction)	1 Bulldozers	Bell 700J
		DresstaTD-40E
	2 Motor graders	ChanglimPY 165H
		CAT 20M
	3 Ground compactors	Ammann AV 16
		Bomag BW138AC
2 Construction of the subgrade (delivery of soil by dump trucks; leveling the soil with a bulldozer; profiling with a motor grader; compaction with a soil-compacting roller; watering with a watering machine)	1 Bulldozers	Bell 700J
3 Preparation of the sand base of the pavement (leveling the upper surface of the subgrade with motor graders; compacting this surface with soil-compacting rollers; importing sand with dump trucks; spreading sand with bulldozers; spreading sand and profiling it with motor graders; watering sand with watering machines.)	2 Motor graders	CAT D7Rll
		Shehwa SD6G
		CAT 20M
	3 Ground compactors	Ammann AV 16
		Bomag BW138AC
	4 Dump trucks	Kamaz 45143-6012-50
		Kamaz 65111
	5 Watering machines	Tekhmash TM-10.0PM:
		ARB-8
4 Construction of a crushed stone base (preparation of the surface for the construction of a crushed stone base by motor graders; arrangement of a road trough by motor graders; compaction of the trough by compacting rollers; delivery of crushed stone by dump trucks; leveling of crushed stone by bulldozers; planning of a crushed stone base by motor graders; crushed stone fraction by a crushed stone distribution machine; compaction of the jammed crushed stone fraction by a heavy roller.)	1 Bulldozers	Bell 700J
		CAT D7Rll
	2 Motor graders	Changlim PY 165H
		CAT 20M
	3 Ground compactors	Ammann AV 16
	4 Dump trucks	Kamaz 45143-6012-50
		Kamaz 65801
	6 Gravel spreaders	BCM-70
		ONU-2300
		ZIL MDK-433362-03
	5 Smooth rollers for crushed stone compaction (light, medium and heavy)	DU-84
		Lutong 2YJ6x8
5 Construction of the main pavement (cleaning the base for the pavement with a watering machine; pouring bitumen with an asphalt distributor; transporting asphalt concrete mix by dump trucks; laying asphalt concrete with an asphalt paver; compacting asphalt concrete pavement with light, medium and heavy rollers.)	4 Dump trucks	Kamaz 45143-6012-50
		Kamaz 65111
	5 Watering machines	Tekhmash TM-10.0PM:
		ARB-8
		Samangan CHD5167CQX4
	9 Auto-hydraulic-nators	BCM-65
		PMB-7
	8 Asphalt pavers	Vogele Super 1103-2
		Volvo P5770C
	7 Light, medium and heavy rollers with smooth drums	DU-84
		HammHVV90B/10
6 Construction of a protective layer of pavement (cleaning the base for the protective layer with a watering machine; pouring bitumen with an asphalt distributor; transporting fine-grained asphalt concrete mixture by dump trucks; laying asphalt concrete with an asphalt paver; compacting asphalt concrete pavement with light, medium and heavy rollers.)	4 Dump trucks	Kamaz 45143-6012-50
		Kamaz 65111
	5 Watering machines	Tekhmash TM-10.0PM:
		ARB-8
	7 Light, medium and heavy rollers with smooth drums	DU-84
		YTO 3Y8x12
	8 Asphalt pavers	Vogele Super 1103-2
		Volvo P5770C
	9 Auto-hydraulic-nators	BCM-65
		ARB-8
		PMB-7

$$\begin{cases} y_{11}p_1 + y_{12}p_2 + y_{13}p_3 < y_1 \\ y_{21}p_1 + y_{22}p_2 + y_{23}p_3 + y_{24}p_4 + y_{25}p_5 < y_2 \\ y_{31}p_1 + y_{32}p_2 + y_{33}p_3 + y_{34}p_4 + y_{35}p_5 < y_3 \\ y_{41}p_1 + y_{42}p_2 + y_{43}p_3 + y_{44}p_4 + y_{46}p_6 + y_{47}p_7 < y_4 \\ y_{54}p_4 + y_{55}p_5 + y_{57}p_7 + y_{58}p_8 + y_{59}p_9 < y_5 \\ y_{64}p_4 + y_{65}p_5 + y_{67}p_7 + y_{68}p_8 + y_{69}p_9 < y_6 \end{cases}, \quad (2)$$

In addition, it is obvious that the sum of the probability coefficients for the use of all machines for each row of the matrix, often called the normalization condition, is equal to one:

$$\sum_{j=1}^{m} p_i = p_1 + p_2 + p_3 + p_4 + p_5 + p_6 + p_7 + p_8 + p_9 = 1. \quad (3)$$

Building a mathematical model. We form a mathematical model based on EXCEL spreadsheets. Using the data of table 1, we will prepare table 3, in the cells of which we place a sign of congestion (number 1) with certain types of road machines, typical for each road construction technology.

To ensure the operability of the mathematical model, it is proposed to use a random number generator when forming an array of specific reduced costs for each machine in the fleet. And in every technology. In practice, an array of statistical data in previous periods of operation can be used. With the random nature of the values of unit costs, different values are modeled for each technology, since the use of certain machines is different. The results of generating random values are obtained in accordance with table 3, in which the distinguishing feature «1» marks the running machine. Table 4 shows the values obtained using a random number generator, and table 5 gives the results of automated calculations. At the same time, for cells without a distinguishing feature, the values are not shown. If the distinguishing features change.

Given the distinguishing feature indicated in Table 3, values are hidden for empty cells.

Similarly, we organize a table of 5 random probabilities for each row. At the end of the line, it is neces-

Table 2 – Matrix of completing machines by technological operations and specific costs of equipment operation in general form

Technol. operation	j1 (B)	j2 (A)	j3 (GK)	j4 (C)	j5 (P)	j6 (P)	j7 (K)	j8 (Ac)	j9 (Av)
W1	y11	y12	y13						
W2	y21	y22	y23	y24	y25				
W3	y31	y32	y33	y34	y35				
W4	y41	y42	y43	y44		y46	y47		
W5				y54	y55		y57	y58	y59
W6				y64	y65		y67	y68	y69

Table 3 – Acquisition of road machines for technological operations

	j1	j2	j3	j4	j5	j6	j7	j8	j9
W1	1	1	1						
W2	1	1	1	1	1				
W3	1	1	1	1	1				
W4	1	1	1	1		1	1		
W5				1	1		1	1	1
W6				1	1		1	1	1

Table 4 – Array of generated random values of unit costs

	y1	y2	y3	y4	y5	y6	y7	y8	y9
W1	13	11	8						
W2	14	10	8	9	16				
W3	11	10	8	18	19				
W4	17	15	13	11		14	13		
W5				14	10		11	16	17
W6				12	15		10	20	16

sary to check the sum of the probability coefficients, which should be equal to 1. If the sum is not equal to 1, the probability correction coefficient is calculated and the sum of the obtained probability coefficients for the use of machines in the set is checked. The sum of the probabilities is 1, table 6.

Table 7 calculates the mathematical expectation of the reduced costs by multiplying the previously generated data in Table 4 by the corresponding probability coefficients after correction (Table 6) and their sum by row.

The sum of the reduced costs for each set and technology depends on the initial data on the reduced costs and probability coefficients, as well as the composition of the set of equipment. If you change the values of these quantities in the source tables, all values are automatically recalculated, and the final amount of the given costs will change up or down. The choice of a set will be determined by the established criterion of minimum, maximum and final number, which is evaluated visually according to the calculated options of the final table.

A comparison of possible options for the mechanization of the construction process cannot provide optimal solutions if it is not produced at all or is limited to two or three sets. It must be borne in mind that the losses from underutilization of the potential capabilities of the machines included in the kits are so significant that the organization of work without a proper approach to the choice of mechanized complexes can be very unprofitable.

This mathematical model makes it possible to carry out variable simulation modeling, in which it is possible, by changing the initial data with automatic recalculation of the final results, to obtain several options for completing equipment for the production of work. Separate options can be fixed by copying to named sheets of tables. Having fixed several alternative options, each of them is analyzed and the most preferable according to the established criteria is selected.

The practical value lies in obtaining a relatively objective indicator of complex unit costs that allows you to choose the most optimal option from several

Table 5 – Values of the probabilities of using a set of machines without correction

	p1	p2	p3	p4	p5	p6	p7	p8	p9	Sum pi	Kcorr
W1	0,195	0,292	0,285							0,772	1,295
W2	0,221	0,199	0,185	0,358	0,435					1,398	0,715
W3	0,210	0,466	0,265	0,320	0,293					1,554	0,644
W4	0,315	0,330	0,125	0,399		0,254	0,376			1,799	0,556
W5				0,403	0,279		0,216	0,463	0,149	1,510	0,662
W6				0,128	0,470		0,435	0,175	0,338	1,546	0,647

Table 6 – Values of the probabilities of using a set of machines after correction

	x1	x2	x3	x4	x5	x6	x7	x8	x9	Sum
W1	0,253	0,378	0,369							1,00
W2	0,158	0,142	0,132	0,256	0,311					1,00
W3	0,135	0,300	0,171	0,206	0,189					1,00
W4	0,175	0,183	0,070	0,222		0,141	0,209			1,00
W5				0,267	0,185		0,143	0,307	0,099	1,00
W6				0,083	0,304		0,281	0,113	0,219	1,00

Table 7 – The mathematical expectation of the reduced costs for each machine

	м1	м2	м3	м4	м5	м6	м7	м8	м9	Sum
W1	3,29	4,16	2,95							10,4
W2	2,21	1,42	1,06	2,30	4,98					11,97
W3	1,49	3,00	1,37	3,71	3,59					13,16
W4	2,98	2,75	0,91	2,44		1,97	2,72			13,77
W5				3,74	1,85		1,57	4,91	1,68	13,75
W6				1,00	4,56		2,81	2,26	3,50	14,13

possible ones. The minimum value of the complex indicator of unit costs is optimal.

Conclusions

In this work, as a result of theoretical studies, the following tasks are solved:

- a list of types of work recommended by the regulatory documentation for road construction was selected. Each type of work includes technological operations that further determine the choice of appropriate equipment;
- for each technological operation, brands and models of road construction equipment are selected;
- sets of machines have been formed for the full implementation of each type of work;
- to develop a mathematical model in Excel spreadsheets, an array of random values of unit costs was formed, the possible probabilities of operation of each unit of equipment were determined, the probability coefficients were adjusted so that the sum of the obtained adjusted values was equal to one; multiplying the corresponding specific indicators of tables 3 by the adjusted probability coefficients of table 6 and we get the reduced costs.

For the next option, a similar mathematical model is created and the obtained values of the complex indicator of unit costs are compared with the previous values, the smallest is selected.

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Автомобиль жолдарын салу кезіндегі машиналардың механикаландырылған отрядтарының құрамын оңтайландырудың математикалық моделі

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***Аңдатпа.** Жол құрылысында механикаландырылған кешендерді жинақтау процесін жақсарту үшін машиналар жиынтығын оңтайландыруда қолдануға болатын шығындарды азайту деректерін алудың математикалық моделі келтірілген. Жол-құрылыс техникаларын пайдалану ықтималдығының коэффициенттерін ескере отырып, төмендетілген шығындарды есептеуге арналған математикалық модель машина түрлеріне арналған тоғыз бағаннан және жол құрылысының негізгі технологиялары үшін алты жолдан тұратын ма-*

трицаға негізделген. Негізгі кірістерді өзгерту арқылы модель барлық деректерді автоматты түрде қайта есептеуге мүмкіндік береді. Минимизация критерийін қолдана отырып, машиналардың әр жиынтығы үшін және әр технология үшін жалпы төмендетілген шығындар минималды болатын жиынтықты таңдай аламыз. Жолдарды жобалау кезінде механикаландырылған отрядтар үшін әр түрлі көлемдегі машиналар жиынтығын оңтайландыру жол салу мерзімін қысқартады және шығындарды азайтады.

Кілт сөздер: *оңтайландыру, математикалық модель, жол-құрылыс техникалары, үлесті келтірілген шығындар, машина отряды, машина кешені, жол құрылысы, машина паркі, машина кешендерін оңтайландыру.*

Математическая модель оптимизации комплектования механизированных отрядов машин при строительстве автомобильных дорог

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Аннотация. *Представлена математическая модель для получения данных о снижении затрат, которая может быть использована при оптимизации комплектов машин для улучшения процесса комплектования механизированных отрядов при дорожном строительстве. Математическая модель для расчета сниженных затрат с учетом коэффициентов вероятности использования оборудования в комплекте построена на основе матрицы, включающей девять столбцов для типов машин и шесть строк для основных технологий дорожного строительства. Изменяя основные входные данные, модель позволяет автоматически пересчитывать все данные. Применяя критерий минимизации, можно выбрать такой набор, при котором общие сниженные затраты для каждого набора машин и для каждой технологии были бы минимальными. Оптимизация набора машин различных размеров для механизированных отрядов при проектировании дорог сократит время на строительство дорог и снизит затраты.*

Ключевые слова: *оптимизация, математическая модель, автомобильная дорога, удельные затраты, отряд машин, комплект машин, строительство дорог, парк машин, оптимизация комплектования машин.*

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