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Borys Sereda[1], Darya Mykovska[2]
1. Dniprovsky State Technical University
2, Dniprobudivska Str., Kamianske, 51900, Ukraine

2. PJSC Zaporozhstal
72, Pivnichne highway, Zaporizhzhia, 69008, Ukraine

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MATHEMATICAL MODELING OF THE EFFICIENCY INDICATOR OF THE FUNCTIONING OF THE TRANSPORT AND PRODUCTION SYSTEM IN THE CONDITIONS OF THE QUARRY OF A METALLURGICAL ENTERPRISE

Summary. *The study of the operation of quarry vehicles made it possible to form the target function of the study, taking into account the criterion of the efficiency of all processes of the system, which provides for the reduction of costs for the operation of the transport and production system of the quarry of a metallurgical enterprise, namely, the subsystems: "Incoming raw materials", "Processing of raw materials", "Sales of raw materials". Factors influencing the cost indicator are highlighted. These factors include the production downtime of motor vehicles, the speed of motor vehicles with cargo, and the speed of motor vehicles without cargo. The values of these factors were obtained in result of timing the operation of motor vehicles on technological routes for four days. The levels of variation intervals and the nature of their changes for the three regimes were calculated for each of the subsystems. A regression analysis of the investigated factors was carried out to model the costs. The response surfaces of the obtained mathematical models are constructed, namely: the influence of the production downtime of motor vehicles and the speed of movement without cargo on the costs of functioning of subsystems, the influence of production downtime of motor vehicles and the speed of movement with cargo on the costs of the functioning of subsystems, the influence of the speed of movement with cargo and speed of movement without cargo for the costs of functioning of subsystems. The optimal values for reducing the cost of functioning of the "Processing of raw materials" subsystem are the value of production downtime – 4–5 min., the speed of motor vehicles without cargo – 9 min., and the speed of motor vehicles with cargo – 9 km/h. The optimal values for reducing the cost of functioning of the "Sales of raw materials" subsystem are the value of production downtime – 4–6 min., the speed of motor vehicles without cargo – 14–16 min., and the speed of motor vehicles with cargo – 13215 km/h. The optimal values for reducing the cost of functioning of the subsystem "Incoming raw materials" are: the value of production downtime is 4–5 minutes, the speed of motor vehicles without cargo is 7–8 km/h, the speed of motor vehicles with cargo is 10 km/h.*

Keywords: *mathematical model, response function, response surfaces, speed of movement, downtime motor vehicle, regression coefficients, transport and production system, variation intervals.*

1. INTRODUCTION

The development of enterprises in the mining industry largely depends on the efficiency of transport and production systems, which consists of the organization of timely transportation of goods in compliance with production requirements with minimal transport costs. A significant share of such enterprises is made up of metallurgical enterprises, in which the organization of freight transportation is connected with the extremely difficult conditions of road transport operation – quarry dump trucks and the provision of continuous technological processes of recycling technological waste of the main production.

The transport and production system in the conditions of the quarry of a metallurgical enterprise includes transport cargo flows, communications, technical means, and route networks that ensure the process of processing technological waste and are directed to the implementation of the plan following the technology and production needs with minimal costs.

In this study, the transport and production system consists of three subsystems: “Incoming raw materials”, “Processing of raw materials”, and “Sales of raw materials”, which consist of a set of functionally interconnected technological parts (elements), which can be attributed to: fleet of rolling stock, fleet loading equipment (excavators, forklifts), technological dumps, route network, cargo fronts, crushing and sorting complex, and warehouses of finished products.

2. RESEARCH RELEVANCE

A significant part of the volume of the transported cargo consists of technological waste of the main production – March slags. The transportation of goods is carried out in environmental conditions that constantly change and is associated with random processes that occur during the maintenance of technological routes – as a result there is an unregulated time in the process of transport maintenance.

3. PROBLEM FORMULATION

In the conditions of modern production, road transport plays a significant role, which is expressed in ensuring the continuity of production processes. With the intensive use of rolling stock, continuous transport service of production units is ensured, and the organization of production processes is of great importance. It leads to the rational use of rolling stock, reduction of transport costs, and improvement of the efficiency of management of road freight transportation. Creating the effective transport and production system for a quarry of a metallurgical enterprise is a priority task for increasing the efficiency of the enterprise in a whole.

4. AIMS AND OBJECTIVES OF THE STUDY

The purpose of the study is to develop a rational model of costs for the operation of the transport and production system of the career of a metallurgical enterprise. Determining the optimal value of the cost indicator of the operation of the subsystems of the transport and production system of quarry enterprise requires constructing the mathematical models of the relationship between the parameters of the studied process.

It is necessary to determine the system optimization parameter, choose independent variables that affect it, define the calculated levels of variation intervals, carry out a regression analysis of experimental data and coding schemes for three modes, construct response surfaces of the obtained mathematical models represented by three-dimensional graphical dependencies.

5. ANALYSIS OF LATEST RESEARCH AND PUBLICATIONS

Many studies [1–12] that highlight the main aspects of the functioning of transport and production systems are dedicated to their research. In paper [1], a comprehensive approach to research rational cargo flow schemes is proposed, in particular, finding rational cargo transportation schemes. In this work, the authors proposed an approach to solving the problem using the Pareto-optimization of the cargo transportation process considering time and cost indicators. In article [2], the issue of production planning with automated controlled vehicles is considered transport and production system consisting of a certain number of vehicles, technological operations, and work at each stage of production. Thus, a model for optimizing a manufacturing system with an automated guided vehicle was presented using mixed integer programming. The paper [3] presents the modeling methodology of the logistics system in the Petri Nets environment.

Peculiarities and possibilities of Petri Nets in transport and production systems were analyzed. In the Petri Net, a model of the transport and production system of product delivery was built. It considers the sequence of operations, the combination of features and the use of resources in each subsystem. A time criterion was proposed to determine the effective option for cargo delivery. The work [4] uses methods of mathematical modeling of flows of various resources in logistics networks. The economic benefit is in implementing the planning concept based on anticipatory indicators. As a result of the methods of system analysis, a mathematical model for the criterion of economic efficiency was developed. In [5], the authors claim that logistics processes that are the basis of freight transportation are rapidly changing due to advances in information technology and an unprecedented increase in consumer participation in supply chains. This development also causes changes in freight traffic flows by all modes of transport. The authors also identified the need for research into freight transportation modeling. They identified three main stages of model improvement: the modeled structural elements of the system, the functional relationships between these elements, and the dynamic properties of the models. In the study [6], the authors consider the possibility of combining modeling with fuzzy methods and optimization methods for the study and operation of systems. In the work [7], the authors highlight the problem of the duration of cargo delivery. As a solution, they propose using model of mixed integer nonlinear programming. With the help of this method, it is possible to reduce the cost of transport and production expenses, reduce the time of transportation and increase the efficiency of the transport and production system as a whole. In paper [8], the authors consider the issue of designing systems using computer modeling and emulation with connection to their real parts. Thanks to this connection, the speed of delivery of raw materials in the system should increase. The authors in [9] considered the problem of evaluating the effectiveness of the functioning of transport and production systems by developing a complex structure including stable elements and establishing an approximate approach to decision-making based on a rough set. The decision support tool is developed by integrating the Laboratory Testing and Evaluation of Numerical Decision Making (DEMATEL) and Multi-Attribute Boundary Approximation Area Comparison (MABAC) methods to evaluate their performance. Coarse numerical methodologies have been found to have advantages over fuzzy or interval models. The authors in [10] proposed a comprehensive basis for assessing the stability of freight transportation systems. Identified Critical Success Factors (CSFs) affecting SFT performance by conducting an extensive literature review and a Delphi survey to elicit the views of industry experts. A hierarchical framework was also developed to establish the relationships between these CSFs, followed by prioritization of these CSFs. This framework will also guide decision-makers in choosing the most sustainable freight transport system. The purpose of the study [11] is a mathematical approach to the combined stability of freight transport. In this work, productivity is evaluated at different levels of stability. The proposed MILP (Mixed Integer Linear Programming) consists of designing a generic logistics chain considering economic and environmental objectives, namely different logistics costs. In the study [12], discrete production systems characterized by dynamism and uncertainty of operations due to the exclusion of production and logistics synchronization are considered. The results of this study allow manufacturers to implement CPS in production environments and create intelligent, flexible production and logistics systems. In paper [13], the factors affecting the efficiency of management of transport and logistics services of an industrial enterprise are analyzed. It activates the need to define a methodological toolkit for evaluating the efficiency of transport and logistics services. The proposed method is based on the determination of integral parameters calculated by the simple formula of the geometric mean. The integral indicators obtained as a result of the calculations can be used to identify the logistics potential of an industrial enterprise. The study [14] considers the feasibility of using evolutionary models to obtain a forecast that is carried out with minimum error. An analysis of modern approaches to the creation of high-quality models for forecasting the volume of cargo loads using modern methods is carried out.

6. PRESENTING MAIN MATERIAL

The transport and production system of the quarry of a metallurgical enterprise in this study is considered a complex system that contains a certain number of subsystems, namely: “Incoming raw materials”, “Processing raw materials”, and “Sales of raw materials”. Many factors influence their effectiveness. These subsystems are technologically connected.

The object of the research is the efficiency indicator for the functioning of the rolling stock subsystems of the transport and production system of the quarry of the metallurgical enterprise.

Costs for the functioning of the rolling stock of each of the subsystems were chosen considering all the technological processes and features of the system's functioning as an efficiency indicator – *an optimization parameter*.

The following factors affecting the optimization parameter were chosen as independent *variables*: the production downtime of motor vehicles, min.; the speed of movement of motor vehicles with cargo km/h; the speed of movement of motor vehicles without cargo km/h.

The values, in our case – the area of determining the factors, were obtained based on timing, which was carried out on the technological routes of the system. The study was conducted using the Wialon software package. The timing results are presented in Table 1.

Table 1

Values of independent variables that affect the object of research

Input parameters	Marking	Subsystems		
		“Incoming raw materials”	“Processing of raw materials”	“Sales of raw materials”
		The domain of independent variables		
Production downtime of rolling stock, min.	x_1	3–9	4–10	4–12
Speed of movement of rolling stock with cargo, km/h.	x_2	4–10	6–12	7–15
Speed of movement of motor vehicles without cargo, km/h.	x_3	5–11	3–15	6–18

Mathematical modeling of costs for the functioning of the subsystems of the transport and production system of the metallurgical enterprise was based on the mathematical planning of experiments.

The developed mathematical models will allow the establishment of rational values of costs for the operation of the subsystems of the transport and production system of the metallurgical enterprise.

The total costs for the operation of the subsystem “Incoming raw materials” are determined by the formula:

$$C_1 = C_1^1 + C_2^1, \tag{1}$$

where C_1^1 – expenses for the payment for the operation of motor vehicles in case of production downtime of motor vehicles in the subsystem “Incoming raw materials”, hryvnias; C_2^1 – expenses for the payment for the operation of motor vehicles during the movement of motor vehicles in the subsystem “Incoming raw materials”, hryvnias.

$$C_1^1 = (t_Z^1 + t_R^1 + t_P^1) \cdot c_{E_1}^1, \tag{2}$$

where t_Z^1 – rolling stock loading time, min.; t_R^1 – rolling stock unloading time, min.; t_P^1 – rolling stock downtime, min.; $c_{E_1}^1$ – cost of machine-hour of production downtime of rolling stock, hryvnias.

$$C_2^1 = (t_{R_1}^1 + t_{R_2}^1) \cdot c_{E_2}^1, \tag{3}$$

where $t_{R_1}^1$ – time of rolling stock movement with cargo, min.; $t_{R_2}^1$ – time of rolling stock movement without cargo, min.; $c_{E_2}^1$ – cost of machine-hour of rolling stock movement, hryvnias.

The total costs for the functioning of the "Processing of raw materials":

$$C_2 = C_1^2 + C_2^2, \tag{4}$$

where C_1^2 – expenses for the payment for the operation of motor vehicles during their production downtime in the subsystem "Processing of raw materials", hryvnias; C_2^2 – expenses for the payment for the operation of motor vehicles during their movement in the subsystem "Processing of raw materials", hryvnias.

$$C_1^2 = (t_Z^2 + t_R^2 + t_P^2) \cdot c_{E_1}^2, \tag{5}$$

where t_Z^2 – rolling stock loading time, min.; t_R^2 – rolling stock unloading time, min.; t_P^2 – rolling stock downtime, min.; $c_{E_1}^2$ – cost of machine-hour of production downtime of rolling stock, hryvnias.

$$C_1^2 = (t_{R_1}^2 + t_{R_2}^2) \cdot c_{E_2}^2, \tag{6}$$

where $t_{R_1}^2$ – time of rolling stock movement with cargo, min; $t_{R_2}^2$ – time of rolling stock movement without cargo, min; $c_{E_2}^2$ – cost of machine-hour of production time of rolling stock, hryvnias.

The total costs for the operation of the subsystem "Sales of raw materials" are determined by the formula:

$$C_3 = C_1^3 + C_2^3, \tag{7}$$

where C_1^3 – expenses for the payment for the operation of motor vehicles during their production downtime in the subsystem "Sale of raw materials", hryvnias; C_2^3 – expenses for payment for the operation of motor vehicles during their movement in the subsystem "Sales of raw materials", hryvnias.

$$C_1^3 = (t_Z^3 + t_R^3 + t_P^3) \cdot c_{E_1}^3, \tag{8}$$

where t_Z^3 – rolling stock loading time, min; t_R^3 – rolling stock unloading time, min; t_P^3 – rolling stock downtime, min; $c_{E_1}^3$ – cost of machine-hour of production downtime of rolling stock, hryvnias.

$$C_1^3 = (t_{R_1}^3 + t_{R_2}^3) \cdot c_{E_2}^3, \tag{9}$$

where $t_{R_1}^3$ – time of rolling stock movement with cargo, min; $t_{R_2}^3$ – time of rolling stock movement without cargo, min; $c_{E_2}^3$ – cost of machine-hour of production downtime of rolling stock, hryvnias.

Mathematical modeling of costs for the operation of the subsystem "Incoming raw materials". The coding schemes for the three modes are presented in Tables 2–4.

Table 2

Estimated levels of variation intervals, the nature of their changes and coding schemes for test 1

Characteristic	Factors		
	Production downtime of motor vehicles, min	Speed of movement of motor vehicles with cargo, km/h	Speed of movement of motor vehicles without cargo, km/h
Code	X_1	X_2	X_3
Basic level	6	7	8
Variation interval	1	1	1
Lower level	5	6	9
Upper level	7	8	10

Table 3

Estimated levels of variation intervals, the nature of their changes and coding schemes for test 2

Characteristic	Factors		
	Production downtime of motor vehicles, min	Speed of movement of motor vehicles with cargo, km/h	Speed of movement of motor vehicles without cargo, km/h
Code	X_1	X_2	X_3
Basic level	6	7	8
Variation interval	2	2	2
Lower level	4	5	6
Upper level	8	9	10

Table 4

Estimated levels of variation intervals, the nature of their changes and coding schemes for test 3

Characteristic	Factors		
	Production downtime of motor vehicles, min	Speed of movement of motor vehicles with cargo, km/h	Speed of movement of motor vehicles without cargo, km/h
Code	X_1	X_2	X_3
Basic level	6	7	8
Variation interval	3	3	3
Lower level	3	4	5
Upper level	9	10	11

The verification of the statistical significance of the coefficients of the regression equation was evaluated based on the calculation of confidence intervals taking into account the variance that characterizes the errors in determining the coefficients of the equation. The results are presented in the Table 5.

Table 5

The results of modeling of costs for the operation of the subsystem "Incoming raw materials"

Characteristic	Feedback functions		
	Y_1	Y_2	Y_3
b_0	37.178	40.044	41.867
b_1	0.7	0.3	-0.1
b_2	0.6	0.8	0.9
b_3	1.8	1.4	1.7
b_4	2.2778	0.9444	1.1667
b_5	0.7778	-0.5556	-0.8333
b_6	0.7778	1.4444	1.1667
b_7	-0.25	0	0.75
b_8	-2	-1.25	-1.25
b_9	1	1.25	1.5
Tb	2.72	2.36	2.68
t- criterion	2.78	2.78	2.78
F- criterion	2.69<5.99	2.39<6.09	2.31<5.99

$$K_1 = 37.178 + 0.7X_1 + 0.6X_2 + 1.8X_3 + 2.2778X_1^2 + \\ +0.7778X_2^2 + 0.7778X_3^2 - 0.25X_1X_2 - 2X_1X_3 + 1X_2X_3. \quad (10)$$

$$K_2 = 40.044 + 0.3X_1 + 0.8X_2 + 1.4X_3 + 0.944X_1^2 - 0.5556X_2^2 + \\ +1.4444X_3^2 + 0X_1X_2 - 1.25X_1X_3 + 1.25X_2X_3. \quad (11)$$

$$K_3 = 41.867 - 0.1X_1 + 0.9X_2 + 1.7X_3 + 1.1667X_1^2 - 0.8333X_2^2 + \\ + 1.1667X_3^2 - 0.75X_1X_2 - 1.25X_1X_3 + 1.5X_2X_3. \tag{12}$$

Moving on to natural variables:

$$X_{ij}^{k} = \frac{X_{ij}^{n} - X_{ij}^{o}}{\Delta_i}, \tag{13}$$

where X_{ij}^{k} – coded value of the i-th factor, which is studied in the j-th equation; X_{ij}^{n} – natural value of the i-th factor, which is studied in the j-th equation; X_{ij}^{o} – the value of the i-th factor, which is studied in the j-th equation at the basic level; Δ_i – the value of the variation interval of the i-th factor under investigation.

By replacing the variables X_i in equations (10)–(12) with the right-hand side of equation (13) and the subsequent reduction of similar ones, we obtain natural equations (14)–(16), which characterize the effects of the speed of movement with cargo and the speed of movement without cargo on the costs of functioning of the subsystem "Incoming raw materials":

$$TK_1 = 396.58 + 55.18T - 1.53V1 - 30.7d + 9.11T^2 + 0.78d^2 - 4(Td) + 0.05(V_1d), \tag{14}$$

$$TK_2 = 690.16 + 36.17T - 1.15V1 - 61.61d + 3.78T^2 + 1.44d^2 - 2.5(Td) + 0.0625(V_1d), \tag{15}$$

$$TK_3 = 638.38 + 15.58T - 0.73V1 - 55.72d + 4.67T^2 + 1.17d^2 + 0.08(TV_1) - 2.5(Td) + 0.075(V_1d). \tag{16}$$

The response surfaces are shown in Fig. 1–3.

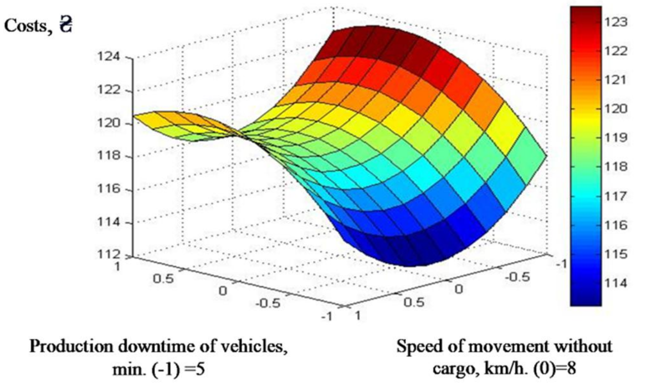

Fig. 1. The influence of production downtime of vehicle and speed of movement without cargo on the costs of functioning of the subsystem "Incoming raw materials"

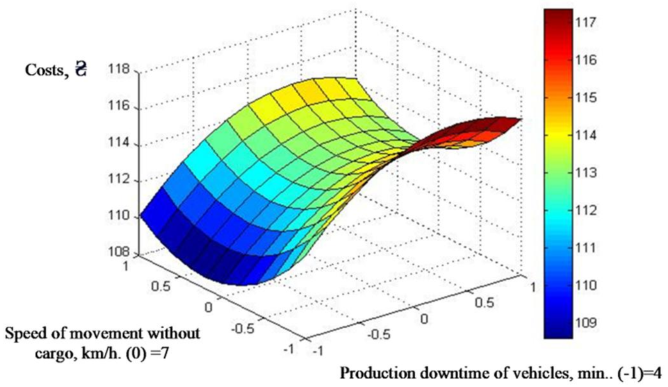

Fig. 2. The influence of the production downtime of vehicles and the speed of movement with cargo on the costs of functioning of the subsystem "Incoming raw materials"

Fig. 1–3 illustrates the influence of production downtime and the speed of movement of vehicles with and without cargo on the costs of subsystem operation. The optimal values for reducing costs for the operation of the "Incoming raw materials" subsystem are the value of production downtime – 4–5 minutes, the speed of motor vehicles without cargo – 7–8 km/h, the speed of motor vehicles with cargo – 10 km/h.

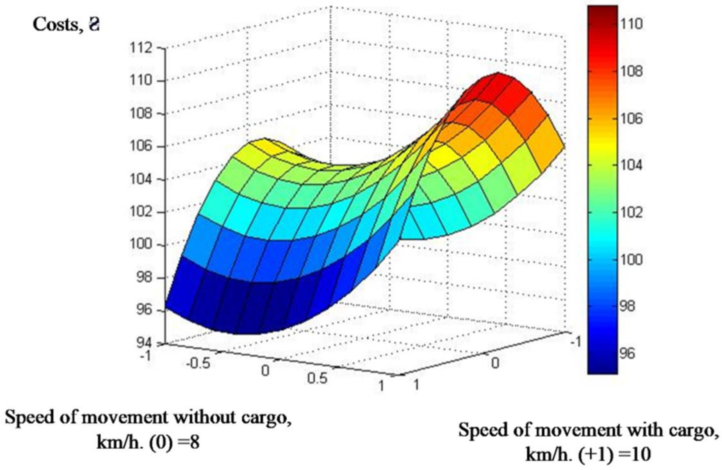

Fig. 3. The influence of the speed of movement with cargo and the speed of movement without cargo on the costs of functioning of the "Incoming raw materials" subsystem

Mathematical modeling of costs for the operation of the "Processing of raw materials" subsystem. The estimated levels of variation intervals are presented in Table 6–8.

The test of significance by the Student's criterion and the assessment of the model's adequacy by the Fisher's criterion are presented in Table 9.

Table 6

Estimated levels of variation intervals, the nature of their changes and coding schemes for test 1

Characteristic	Factors		
	Production downtime of motor vehicles, min	Speed of movement of motor vehicles with cargo, km/h	Speed of movement of motor vehicles without cargo, km/h
Code	X_1	X_2	X_3
Basic level	7	7	9
Variation interval	1	1	2
Lower level	6	6	7
Upper level	8	8	11

Table 7

Estimated levels of variation intervals, the nature of their changes and coding schemes for test 2

Characteristic	Factors		
	Production downtime of motor vehicles, min	Speed of movement of motor vehicles with cargo, km/h	Speed of movement of motor vehicles without cargo, km/h
Code	X_1	X_2	X_3
Basic level	7	9	9
Variation interval	2	2	4
Lower level	5	7	5
Upper level	9	11	13

$$B_3 = 75.289 - 1.2X_1 - 2.8X_2 - 0.9X_3 + 2.8889X_1^2 - 8.1111X_2^2 + \\ + 6.3389X_3^2 - 3.25X_1X_2 + 1.75X_1X_3 - 0.25X_2X_3, \quad (17)$$

$$B_4 = 86 - 2.2X_1 - 3.3X_2 + 0.4X_3 - 4X_1^2 + 0.5X_2^2 + \\ + 5X_3^2 - 0.875X_1X_2 - 2.125X_1X_3 - 0.125X_2X_3, \quad (18)$$

$$B_5 = 279.98 - 5X_1 - 0.9X_2 - 2.6X_3 - 4.2222X_1^2 - 4.7222X_2^2 + \\ + 1.7778X_3^2 - 3.75X_1X_2 + 3.75X_1X_3 - 0.5X_2X_3. \quad (19)$$

Table 8

Estimated levels of variation intervals, the nature of their changes and coding schemes for test 3

Characteristic	Factors		
	Production downtime of motor vehicles, min	Speed of movement of motor vehicles with cargo, km/h	Speed of movement of motor vehicles without cargo, km/h
Code	X_1	X_2	X_3
Basic level	7	9	9
Variation interval	3	3	6
Lower level	4	6	3
Upper level	10	12	15

Table 9

The results of the regression analysis of experimental data for the modeling of costs for the functioning of the "Processing of raw material" subsystem

Characteristic	Feedback functions		
	Y_4	Y_5	Y_6
b_0	75.289	86	279.98
b_1	-1.2	-2.2	-5
b_2	-2.8	-3.3	-0.9
b_3	-0.9	0.4	-2.6
b_4	2.8889	-4	-4.2222
b_5	-8.1111	0.5	-4.7222
b_6	6.3889	5	1.7778
b_7	-3.25	-0.875	-3.75
b_8	1.75	-2.125	3.75
b_9	-0.25	-0.125	0.5
Tb	3.25	2.682	2.11
t- criterion	2.78	2.78	2.78
F- criterion	3.38<6.56	1.04<6.38	5.82<6.16

We move on to natural variables using the conversion formula (13).

By replacing the variables X_i in equations (17)–(19) with the right-hand side of equation (13) and then reducing them to similar ones, we obtain natural equations (20)–(22), which characterize the effects of the speed with cargo and the speed without cargo on the costs of the subsystem "*Processing of raw materials*":

$$TB_4 = 88,23 + 12.98V1 - 12.78V2 - 0.32V1^2 + 0.26V2^2, \tag{20}$$

$$TB_5 = 208.2 + 3.2T - 0.66V1 - 10Si - 4X_1^2 + 0.5T^2 + 5V2^2, \tag{21}$$

$$TB_6 = 218.03 + 1.63T + 9.06V1 - 2.02V2 - 0.17T^2 - 0.19V1^2 - 0.15TV1 + 0.15TV2. \tag{22}$$

The response surfaces are shown on Fig. 4–6.

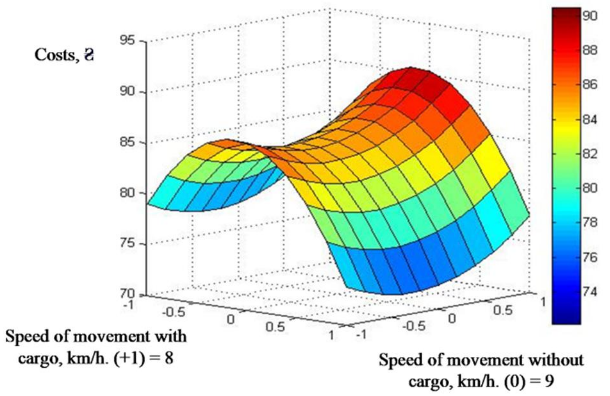

Fig. 4. The influence of the speed of movement with cargo and the speed of movement without cargo on the costs of the functioning of the subsystem "Processing of raw materials"

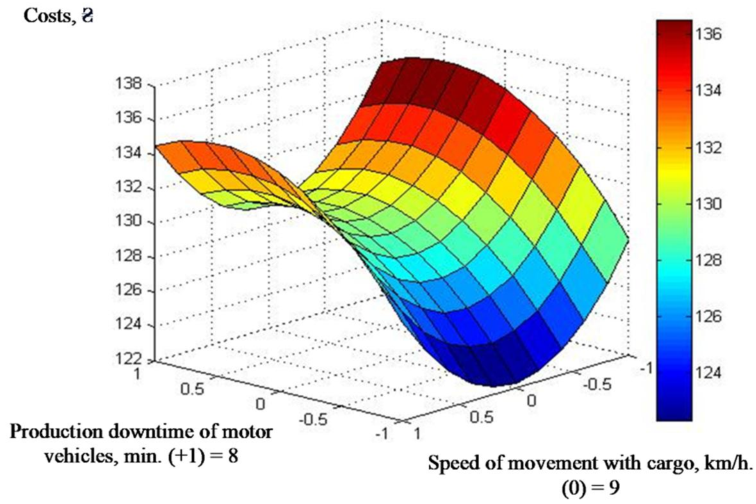

Fig. 5. The influence of production downtime and the speed of movement with cargo on the costs of functioning of the subsystem "Processing of raw materials"

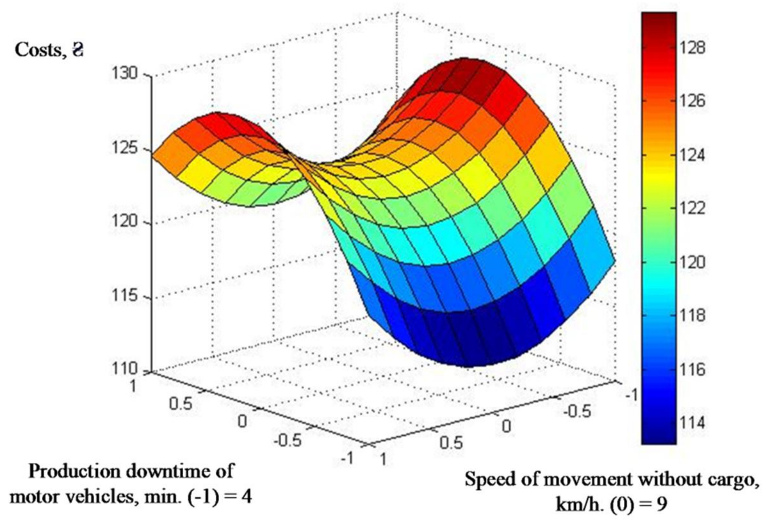

Fig. 6. The influence of production downtime and the speed of movement without cargo on the costs of functioning of the subsystem "Processing of raw materials"

Fig. 4–6 illustrates the influence of production downtime and the speed of movement of motor vehicles with and without cargo on the costs of functioning of the "Processing of raw material" subsystem. The optimal values for reducing the cost of functioning of the subsystem "Processing of raw material" are: the value of production downtime – 4–5 min., the speed of motor vehicles without cargo – 9 min., the speed of motor vehicles with cargo – 9 km/h.

Mathematical modeling of costs for the functioning of the "Sales of raw materials" subsystem. The calculated levels of variation intervals, the nature of their changes and the coding schemes for the three modes are presented in Table 10–12.

Table 10

Estimated levels of variation intervals, the nature of their changes and coding schemes for test 1

Characteristic	Factors		
	Production downtime of motor vehicles, min	Speed of movement of motor vehicles with cargo, km/h	Speed of movement of motor vehicles without cargo, km/h
Code	X_1	X_2	X_3
Basic level	8	11	12
Variation interval	2	2	2
Lower level	6	9	10
Upper level	10	13	14

Table 11

Estimated levels of variation intervals, the nature of their changes and coding schemes for test 2

Characteristic	Factors		
	Production downtime of motor vehicles, min	Speed of movement of motor vehicles with cargo, km/h	Speed of movement of motor vehicles without cargo, km/h
Code	X_1	X_2	X_3
Basic level	8	11	12
Variation interval	3	3	4
Lower level	5	8	8
Upper level	11	14	16

Table 12

Estimated levels of variation intervals, the nature of their changes and coding schemes for test 3

Characteristic	Factors		
	Production downtime of motor vehicles, min	Speed of movement of motor vehicles with cargo, km/h	Speed of movement of motor vehicles without cargo, km/h
Code	X_1	X_2	X_3
Basic level	8	11	12
Variation interval	4	4	6
Lower level	4	7	6
Upper level	12	15	18

The numerical value of the regression coefficients, as well as the significance test by the Student's criterion and the assessment of the model's adequacy by the Fisher's criterion are presented in Table 13

Table 13

The results of the regression analysis of experimental data for the modeling of costs for the functioning of the "Sales of raw materials" subsystem

Characteristic	Feedback functions		
	Y_7	Y_8	Y_9
b_0	70.756	55.889	42.711
b_1	-3.1	-3	-0.4
b_2	0.6	-2.4	-1.1
b_3	-2.6	-1.7	-0.1
b_4	-4.9444	3.8889	0.1111
b_5	4.5556	5.8889	5.6111
b_6	-3.4444	-3.6111	-5.3889
b_7	-2.75	0.625	-5.5
b_8	1.5	1.625	0
b_9	1.25	-0.375	0.25
Tb	2.110423	3.041443	1.548627
t- criterion	2.77	2.77	2.78
F- criterion	$1.39<6.09$	$4.27<6.39$	$4.65<6.39$

$$C_6 = 70.756 - 3.1X_1 + 0.6X_2 - 2.6X_3 - 4.9444X_1^2 + \\ +4.5556X_2^2 - 3.4444X_3^2 - 2.75X_1X_2 + 1.5X_1X_3 + 1.25X_2X_3, \tag{23}$$

$$C_7 = 55.889 - 3X_1 - 2.4X_2 - 1.7X_3 + 3.8889X_1^2 + \\ +5.8889X_2^2 - 3.6111X_3^2 + 0.625X_1X_2 + 1.625X_1X_3 - 0.375X_2X_3, \tag{24}$$

$$C_8 = 42.711 - 0.4X_1 - 1.1X_2 - 0.1X_3 + 0.1111X_1^2 + \\ + 5.6111X_2^2 - 5.3889X_3^2 - 5.5X_1X_3 + 0.25X_2X_3, \quad (25)$$

We move on to natural variables using formula (13).

Statistically insignificant coefficients can be excluded from the models. By replacing the variables X_i in equations (23)–(25) with the right-hand side of equation (13) and then reducing the similar ones, we obtain natural equations (26)–(28), which characterize the effects of the speed with cargo and the speed without cargo on the costs of the subsystem “Sales of raw materials”:

$$TB_7 = 10.96 + 5.54T - 6.19V1 + 6.37V2 - 0.2T^2 + 0.18V1^2 - 0.14V2^2 - 0.11TV1, \quad (26)$$

$$TB_8 = 66.39 - 3.11T - 9.42V1 + 7.22V2 + 0.16T^2 + 0.24V1^2 - 0.14V2^2, \quad (27)$$

$$TB_9 = 16.23 + 4.4T - 6.78V1 + 10.78V2 + 0.22V1^2 - 0.22V2 - 0.22TV1. \quad (28)$$

The response surfaces are shown in Fig. 7–9.

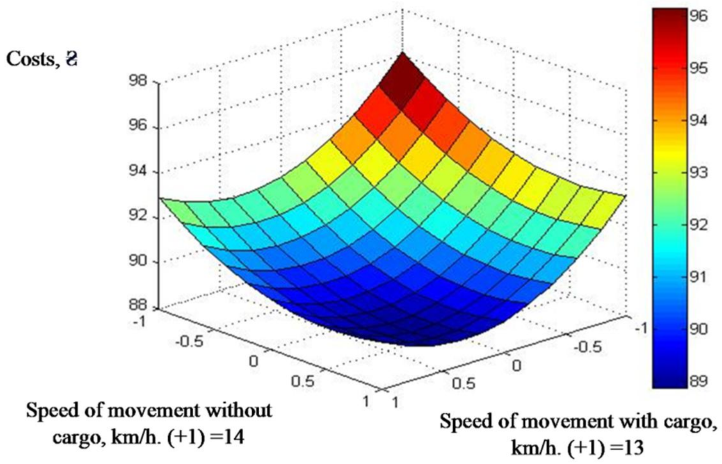

Fig. 7. The influence of the speed of movement with cargo and the speed of movement without cargo on the costs of functioning of the “Sales of raw materials” subsystem

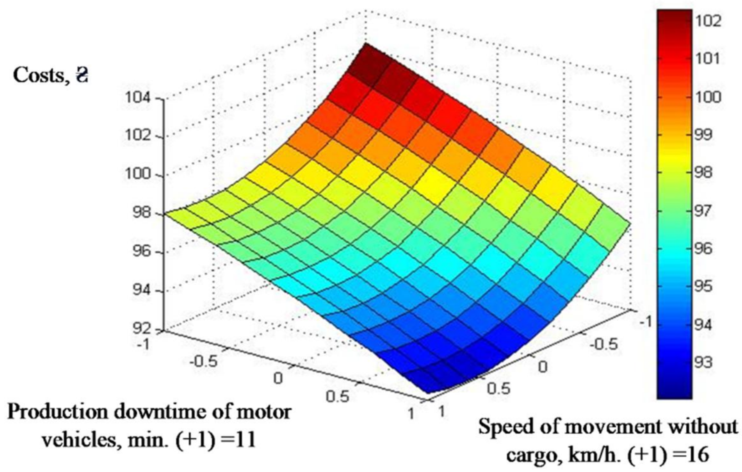

Fig. 8. The influence of production downtime and the speed of movement without cargo on the costs of functioning of the “Sales of raw materials” subsystem

Fig. 7–9 illustrates the influence of production downtime and the speed of movement of motor vehicles with and without cargo on the costs of functioning of the “Sales of raw materials” subsystem. The optimal values for reducing the cost of functioning of the “Sales of raw materials” subsystem are: the value of production downtime – 4–6 min., the speed of motor vehicles without cargo – 14–16 min., the speed of motor vehicles with cargo – 13–15 km/h.

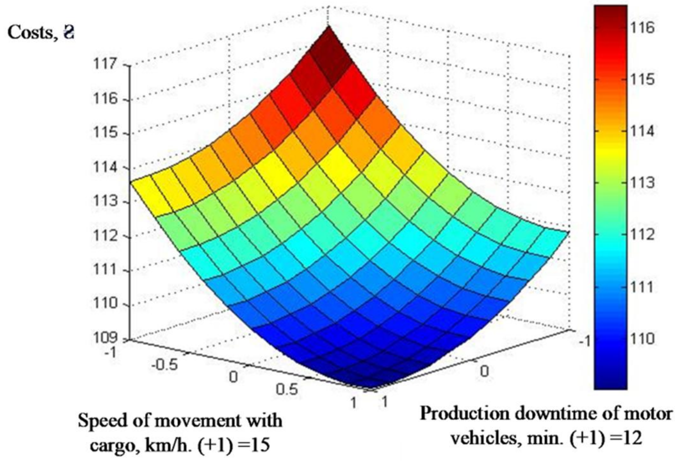

Fig. 9. The influence of the dump truck operating time and the speed of movement with cargo on the costs of functioning of the subsystem "Sales of raw materials"

7. CONCLUSIONS

As a result of mathematical modeling of the costs for the operation of the subsystems, mathematical models were developed that allowed establishing the optimal values of independent variables – factors, at which the costs for the functioning of the subsystems will be minimal.

The optimal values for reducing the cost of functioning of the "Processing of raw materials" subsystem are: the value of production downtime within 4–5 minutes, the speed of movement of motor vehicles without cargo – 9 minutes, the speed of movement of motor vehicles with cargo – 9 km/h.

The optimal values for reducing the cost of functioning of the "Sales of raw materials" subsystem is: the value of production downtime within 4–6 min., the speed of movement of motor vehicles without cargo within 14–16 min., the speed of movement of motor vehicles with cargo within 13–15 km/ hours

The optimal values for reducing the cost of functioning of the "Incoming raw materials" subsystem are: the value of production downtime within 4–5 minutes, the speed of movement of motor vehicles without cargo within 7–8 km/h, the speed of movement of motor vehicles with cargo – 10 km/h.

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МАТЕМАТИЧНЕ МОДЕЛЮВАННЯ ПОКАЗНИКА ЕФЕКТИВНОСТІ ФУНКЦІОНУВАННЯ ТРАНСПОРТНО-ВИРОБНИЧОЇ СИСТЕМИ В УМОВАХ КАР’ЄРУ МЕТАЛУРГІЙНОГО ПІДПРИЄМСТВА

Анотація. *Зазначено, що дослідження роботи кар’єрного автотранспорту дало змогу сформувати цільову функцію дослідження з урахуванням критерію ефективності всіх процесів системи, яка передбачає зниження витрат на функціонування транспортно-виробничої системи кар’єру металургійного підприємства, а саме, підсистем: “Надходження сировини”, “Переробка сировини”, “Збут сировини”. У процесі дослідження були виокремленні основні фактори, які впливають на показник витрат на функціонування підсистем. До цих факторів належать: виробничий простій автотранспорту, швидкість автотранспорту з вантажем, швидкість автотранспорту без вантажу, значення яких були отримані в результаті хронометражу роботи автотранспорту на технологічних маршрутах протягом чотирьох діб. Для кожної з підсистем були розраховані рівні інтервалів варіювання та тип їх змін для трьох режимів. Для моделювання витрат був проведений регресійний аналіз досліджуваних факторів. Побудовані поверхні відгуку отриманих математичних моделей, а саме: вплив часу виробничого простою автотранспорту та швидкості руху без вантажу на витрати на функціонування підсистем, вплив часу виробничого простою автотранспорту та швидкості руху з вантажем на витрати на функціонування підсистем, вплив швидкості руху з вантажем та швидкості руху без вантажу на витрати на функціонування підсистем. Оптимальним значенням для зменшення витрати на функціонування підсистеми “Переробка сировини” є: значення виробничого простою 4–5 хв, швидкості руху автотранспорту без вантажу 9 хв, швидкості руху автотранспорту з вантажем 9 км/год. Оптимальним значенням для зменшення витрати на функціонування підсистеми “Збут сировини” є: значення виробничого простою 4–6 хв, швидкості руху автотранспорту без вантажу 14–16 хв, швидкості руху автотранспорту з вантажем 13–15 км/год. Оптимальним значенням для зменшення витрати на функціонування підсистеми “Надходження сировини” є: значення виробничого простою 4–5 хв, швидкості руху автотранспорту без вантажу 7–8 км/год, швидкості руху автотранспорту з вантажем 10 км/год.*

Ключові слова: *математична модель, функція відгуку, поверхні відгуку, швидкість руху, простій автотранспорту, коефіцієнти регресії, транспортно-виробнича система, інтервали варіювання.*