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Mining excavator working equipment load forecasting according to a fuzzy-logistic model

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Due to the fact that the loads occurring in the working equipment of mining excavators are determined by a large number of random factors that are difficult to represent by analytical formulas, for estimating and predicting loads the models must be introduced using non-standard approaches. In this study, we used the methodology of the theory of fuzzy logic and fuzzy pluralities, which allows to overcome the difficulties associated with the incompleteness and vagueness of the data in assessing and predicting the forces encountered in the working equipment of mining excavators, as well as with the qualitative nature of these data.

As a result of computer simulation in the fuzzyTECH environment, data comparable with experimental studies were obtained to determine the level of loading of the main elements of the working equipment of mining excavators. Based on a representative sample, a statistical analysis of the data was performed, as a result of which the equation of linear multiple stress regression in the handle of mining excavators was obtained, which allows to make an accurate forecast of the loading of the working equipment of the excavator.

Key words: mining excavator; working equipment; stresses; forecasting; model; fuzzy logic; adequacy; variable

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Introduction. The implementation of plans for the strategic modernization of Russian Federation economy involves the solution of theoretical and applied problems of the domestic mining industry and determines not only the state of production resources of the state, but also its scientific and technical potential. The global development trend of mining is mainly determined by open-pit mining of raw materials, because of its best economic indicators. The open method provides 75-80 % of global mining. In Russia, 60 % of coal and 91 % of iron ore are mined in quarries. Mining of building materials, non-ferrous metals and diamonds in the Russian Federation is almost entirely carried out by the open pit mining [1-7].

By 2035, a 1.2-fold increase in the volume of coal mined is forecasted compared with 2014 (up to 423 million tons) [2]:

Maximum option, million tons	500
Moderate option, million tons	423

Open-pit mining of mineral deposits is currently characterized by an increase in the volume of processed rock mass and overburden ratios, and improvement of production processes due to advanced technologies, which entails the use of mining equipment of large unit capacity. The efficiency and reliability of the operation of such equipment is ensured by its proper operation, minimization of the costs of maintaining and repairing machines, in particular mining ECG excavators.

Formulation of problem. About 490-500 units of hydraulic excavators and open-pit mine shovels are operated in iron ore quarries in Russia and the CIS countries, 90 % of these machines are manufactured by domestic manufacturers that are part of the OMZ holding company, for example, "Uralsmashzavod" PJSC and "IZ-KARTEX named after P.G.Korobkov LLC". This excavator fleet consists of 80 % mechanical shovels with a bucket volume of 5 m³ or more, manufactured in the 80s of the twentieth century. [2]. The production work of mining excavators is about 65-70 % of the total working time, 30-35 % of the time is downtime for various reasons, including 45-50 % of the time is lost as a result of various kinds of malfunctions and accidents [2].

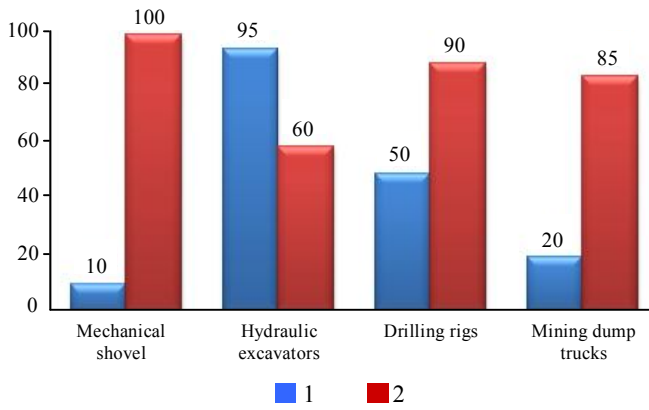


Fig. 1. Current import status and import substitution potential for certain types of mining equipment (%)
1 – import; 2 – localization

In recent years, a significant part of the excavation fleet has reached physical and moral depreciation, which forces changing the structure of the fleet through the purchase of imported equipment. Figure 1 shows the current state of imported equipment in the mining industry [1, 8, 9, 10, 11].

Methodology. A significant problem in establishing the actual loads arising in the working equipment of mining excavators is the presence of a large number of operating factors (many of them are random), which are difficult to describe with mathematical formulas. Often times the assessment and prediction of loads in working equipment when managing a quarry excavator are not amendable to traditional methods of analysis and modeling, which determines the need for using non-standard approaches [3, 6, 14]. In general, the statement of the research problem is presented in Fig. 2.

In this study, it is proposed to use the methodology of the theory of fuzzy logic and fuzzy pluralities [15, 24]. This will allow to overcome difficulties associated with the vagueness and incompleteness of information in the assessment and forecasting of loads in the working equipment of mining excavators, as well as with the qualitative nature of this information. The process of creating a fuzzy model is carried out in four stages: structuring the subject area and building a fuzzy model, performing computational experiments with a fuzzy model, applying the results of computational experiments, correcting and refining a fuzzy model.

Computational experiments were carried out using the specialized computer program fuzzyTECH [5], focused on solving modeling problems using the theory of fuzzy pluralities. To implement the model, it is necessary to specify input and output linguistic variables, rule blocks that optimize data analysis. Each variable is characterized by its range of possible values, which are divided into terms (Fig. 3), linguistic variables are described in Table 1. In this paper the fuzzy model contains eleven input linguistic variables (ILV), grouped into three blocks of indicators (BLOCK1-3).

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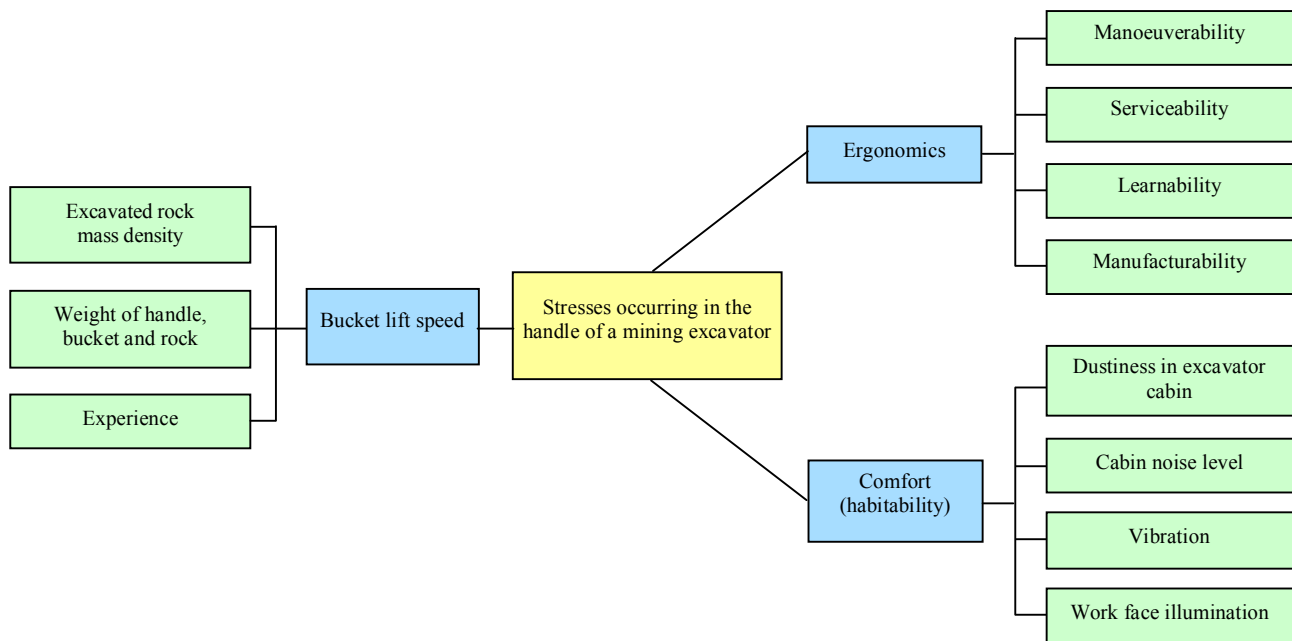


Fig. 2. Structural scheme of stresses arising in the working equipment of mining excavators

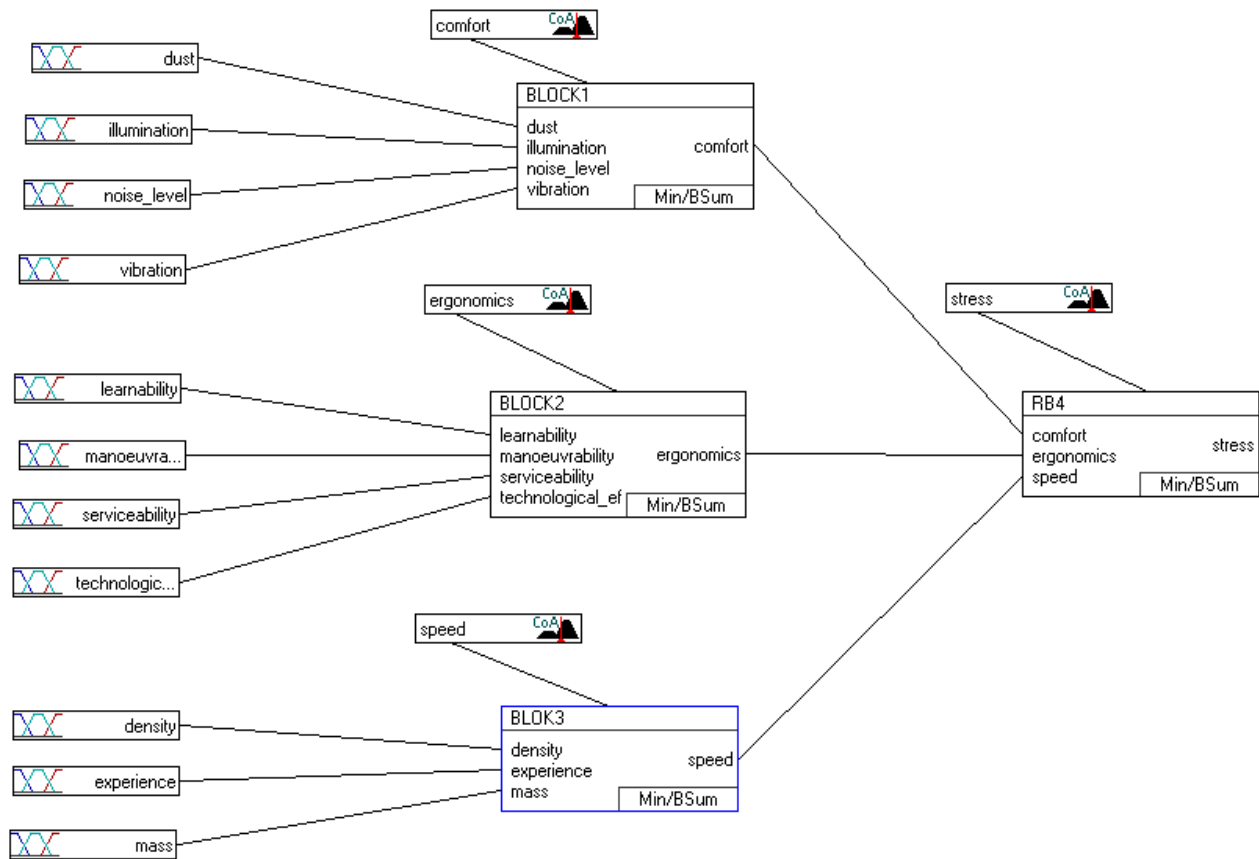


Fig.3. Schematic diagram of a fuzzy model of stress forecasting in the working equipment of mining excavators

Table 1

List of linguistic model variables

Accepted interpretation in the model	Indicators	Terms of linguistic variables	Term definition area
dust	Dustiness in the excavator cabin, mg/m ³	permissible high very_high	0-2 1.5-8.2 7.4-12
illumination	Work face illumination, lx	insufficient moderate sufficient	0-31.4 23.3-56.4 47.2-80
noise_level	Noise level in a cabin, dBA	low medium high	0-38 38-69 69-110
vibration	Vibration (total), dB	low medium high	0-7 7-22 22-30
maneuverability	maneuverability, pts	negative positive	0-4.5 0.5-5
serviceability	Serviceability, pts	negative positive	0-4.5 0.5-5
learnability	Learnability, pts	negative positive	0-4.5 0.5-5
technological_ef	Manufacturability, pts	negative positive	0-4.5 0.5-5
density	Density of excavated rock mass, t/m ³	low medium high	1-2.1 1.9-3.1 2.9-4
experience	ECG driver experience, years	little allowable big	0-1.5 0.5-6 4.5-20



Table 1 end

Accepted Interpretation in the model	Indicators	Terms of linguistic variables	Term Definition Area
mass	The mass of the handle, bucket and excavated rock, t	low medium high	18-21 20-30 28-36.5
speed	Bucket lifting speed, m/s	low medium high	0-0.35 0.25-0.67 0.55-1
comfort	Comfort (habitability), pts	bad medium good	0-2 1-4 3-5
ergonomics	Ergonomics, pts	low medium high	0-1.5 1-4 3.5-5
stress	Stresses arising in the handle of the excavator, MPa	low allowable high very_high	40-78 60-180 120-290 245-350

A general assessment of comfort at the workplace of a mining excavator driver is implemented in BLOCK1, for which the output linguistic variable is *comfort*, which has three terms: *bad*, *medium*, *good*, assignment of terms is evaluated on a five-point scale. Accordingly, the following linguistic input variables are: *dust*, *illumination*, *noise_level*, *vibration*.

Dustiness. It is known that the maximum permissible concentration of dust in the cab of an excavator is $2 \text{ mg} \cdot \text{m}^3$. Important factors in dust formation are the amount of precipitation in the form of snow or rain. The maximum recorded dust concentration in spring is $2.8 \text{ mg} \cdot \text{m}^3$, in autumn – 3.6, in winter – 3.9 and in summer – 8.3. This allows to identify the influence of individual climatic factors, such as temperature and humidity, on the dustiness of the air. The scope of the linguistic variable is $0-12 \text{ mgm}^3$.

Illumination. At night, the quarry should be provided with lighting of the work of mining excavators. The values of the illumination term are calculated taking into account the minimum required illumination (10 lux) in the face where excavation of the rock mass takes place. For illumination in the ECG cab, this indicator is 50 lux. Variable definition area 0-80 lux.

Noise level. Noise is a random combination of sounds of different strength and frequency that can have an adverse effect on the body. The scope of the variable is 0-110 dBA [16-18, 20, 21].

Vibration. A harmful production factor, which is mechanical vibrations that are directly transmitted to the human body or its individual sections. Thus, the vibration can be general, i.e. transmitted to the whole body, or local (local), transmitted only to the hands or other limited parts of the body. The range of the variable is 0-30 dB [22, 23, 26].

Comfort. A favorable combination of microclimate parameters, the absence of harmful production factors leads to the fact that the employee is in a state of comfort, which is of great importance for ensuring labor productivity. A significant deviation of the microclimate of the working area from the optimal and the presence of harmful production factors lead to a number of physiological disorders in the human body, a decrease in working capacity and occupational diseases [19, 20, 25].

To a certain extent, ergonomic indicators, which reflect the convenience for a person during the operation of the product, influence the quality of operation of a mining machine. A person interacts with the product in accordance with its psychological, physiological and anthropometric properties. To take into account these indicators, the output linguistic variable *ergonomics* was adopted, which depends on four ILVs (manoeuverability, serviceability, learnability, manufacturability) included in the BLOCK2.

When predicting the stresses arising in the ECG handle, BLOCK3 implements the ability to take into account the following indicators: *density* of the rock mass, *experience* – length of service for the driver, *mass* of the handle, bucket and rock *mass*, which are ILV. Accordingly, the output linguistic variable of this block is the bucket lifting speed – *speed*. Variable definition area 0-1 m/s.

Density. The estimated average density of the rock mass is one of the important characteristics for estimating stresses in the handle of an excavator. The range of density values is chosen based on the minimum and maximum possible densities of rocks.

ECG driver experience. It has been established that the experience of the driver has a great influence on the loads in the working equipment of the ECG. So, for example, with less than a year of service, the control coefficient is 0.2, and with more than 10 years of experience is 1. The range of the variable is 0-20 years.

Mass. The mass of the handle, bucket and excavated rock plays an important role in assessing stresses, the domain of definition is set in accordance with the type of excavator and its overall characteristics.

For the final assessment and prediction of stresses in the handle of the excavator, the model implements the RB4 block, for which three input linguistic variables are used – *comfort*, *speed*, *ergonomics*, the output variable will ultimately be *stress*. The terms of the output variable are set depending on the permissible stresses – $[\sigma] = 153$ MPa, the excess of which leads to violation of the strength of the element; yield strength: $\sigma_t = 260$ MPa, exceeding which leads to the manifestation of fatigue cracks. The scope of the variable is 0-350 MPa.

Discussion. Figure 4 shows the triangular membership functions of fuzzy pluralities of the linguistic variables corresponding terms that characterize BLOCK1 indices.

In order to assess the adequacy of the proposed fuzzy load forecasting model, the author sampled data $n = 130$ (Table 2). The adequacy of the model is understood as the degree of conformity of the results obtained by the developed model with the experimental data.

Studies [12] proved that the maximum bucket lifting speed during the excavation of rock mass should not exceed 0.55 m/s, and the permissible stresses in the handle of a quarry excavator should not exceed 153 MPa (Fig.5). Moreover, in accordance with the requirements of the operating manual for mining excavators of large unit capacity (more than 15 m³), the operator's experience on such equipment with a bucket with a capacity of more than 4 m³ should be at least 5 years [10, 14]. If the design life is exceeded by the equivalent number of loading cycles that the equipment is designed and physically capable, the normal basic operation of the excavator will be ensured when the operator has over 10 years of experience [13] (Fig.6).

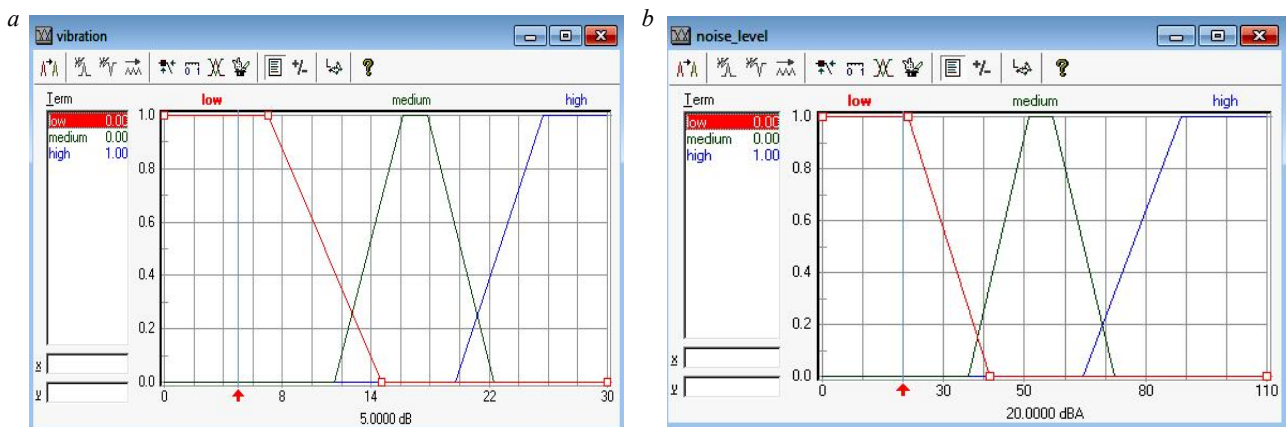


Fig.4. Membership functions of fuzzy sets of the corresponding terms of linguistic variables, characterizing indicators: a – vibration; b – noise level

Table 2

Results of statistical analysis of a data sample

	b^*	Std.Err.	b	Std.Err.	$t(122)$	p -value
Intercept			-40.1151	15.6998	-2.55513	0.011844
density x_1	0.269449	0.052664	17.896	0.34977	5.11643	0.000001
experience x_3	-0.14138	0.040322	-1.2607	0.35954	-3.50628	0.000637
manoeuvrability x_6	0.141613	0.053275	5.5895	2.10274	2.65818	0.008909
mass x_7	0.175005	0.054958	1.4922	0.46861	3.18431	0.001842
noise_level x_8	0.37219	0.04103	0.7528	0.08298	9.0711	0
vibration x_{11}	0.346477	0.045311	2.9163	0.38139	7.64666	0
speed x_{12}	0.289182	0.056711	73.5853	14.43057	5.09926	0.000001

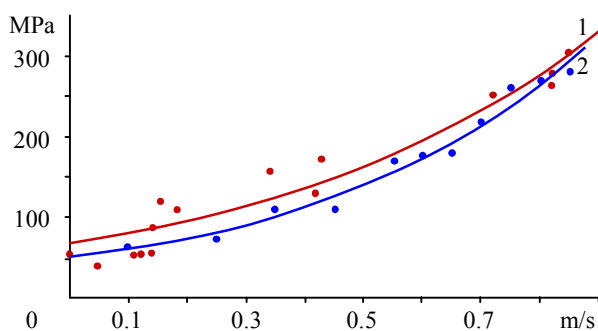


Fig. 5. Stresses in the handle of mining excavators when scooping rock

1 – simulation results; 2 – experiments on tensometric measurement of stresses in the metal structure of the handle

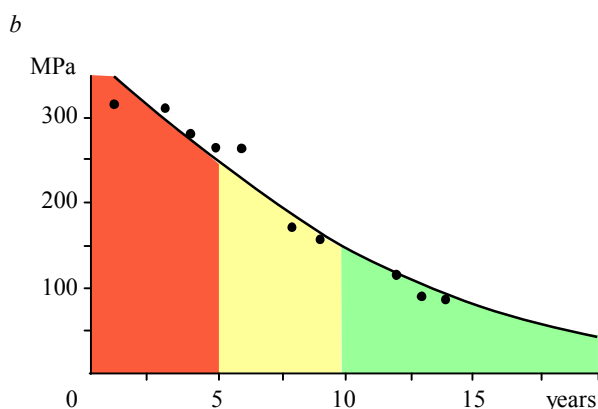
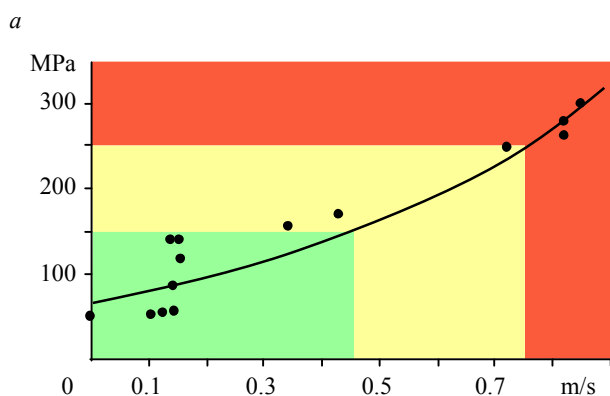


Fig. 6. Stress Simulation Results in the handle of mining excavators when scooping rock: a – bucket lifting speed; b – the experience of the driver

In future, multiple regression is used to determine the degree of influence on the stresses in the handle of several factors.

$$stress = F(speed, vibration, \dots, x_i), \quad (1)$$

where x_1 – density, x_2 – dust, x_3 – experience, x_4 – illumination, x_5 – learnability, x_6 – manoeuvrability, x_7 – mass, x_8 – noise_level, x_9 – serviceability, x_{10} – technological_ef, x_{11} – vibration, x_{12} – speed.

The purpose of using multiple regression is to develop a mathematical model that includes a large number of factors, and to establish the degree of influence of each of the factors individually, as well as their combined effect on the final indicator.

The linear model is the simplest of multiple regression models

$$y = \alpha' + \beta'_1 x_1 + \beta'_2 x_2 + \dots + \beta'_j x_j + \varepsilon, \quad (2)$$

where the coefficients β' are equal to the partial derivatives of the effective attribute y with respect to the corresponding factors

$$\beta'_1 = \frac{\partial y}{\partial x_1}, \beta'_2 = \frac{\partial y}{\partial x_2}, \dots, \beta'_j = \frac{\partial y}{\partial x_j}.$$

The free term α determines the value of y in the case when all the explanatory variables are equal to zero, however, as in the case of pairwise regression, factors often cannot take zero values: the value ε is a random error in the regression dependence.

For statistical data analysis, the “Statistika” program was used.

The final linear multiple regression equation has the form

$$y = -40.12 + 17.89x_1 - 1.26x_3 + 5.59x_6 - 1.49x_7 + 0.75x_8 + 2.92x_{11} + 73.59x_{12}$$

Conclusion. It has been determined that the basic component of mining and loading equipment at most mining enterprises of the Russian Federation are domestic mining wireline excavators with buckets with a capacity of 5-10 m³. The fleet of these machines is 70-90 % worn out. The operation of mining excavators in this state leads to an increase in the cost of their maintenance, which ultimately affects the increase in the cost of production and processing of mining products.

The study substantiates the possibility of using the theory of fuzzy logic and fuzzy pluralities methodology in estimating and predicting loads in the working equipment of quarry excavators. The comparability of simulation results and experimental data on tensometric measurement of stresses in the handle metal structure is proved.

The obtained equation of linear multiple stress regression in the handle of quarry excavators will make it possible to predict the loading of the main elements of excavator working equipment.

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