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# Predicting the loads in quarry excavator work equipment when controlling by fuzzy simulation method

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**Abstract.** The article considers the basics of fuzzy simulation as a promising direction for solving practical problems. The paper deals with the example of practical simulation on a computer in the FuzzyTECH package to determine the level of loading the main elements of the mining excavator work equipment. The structural and parametric identification of the developed fuzzy model has been carried out.

## 1. Introduction

To date, the development of mining operations is carried out mainly by the open method, which provides competitive economic indicators of the mining industry. The quarry mining of mineral deposits is characterized by an increase in the volume of the processed rock mass and overburden coefficients; production processes are being improved through advanced technologies, which entail the use of mining equipment of large unit capacity. The efficiency and reliability of such equipment is ensured by its proper operation, minimizing the cost of maintenance and repair of machines, in particular, career excavators.

The increase in mining operations provides not only an increase in the demand for mining equipment, but also the maintenance of a large fleet of existing mining machines at the required technical level, which is one of the dominant components of the efficient operation of mining enterprises. However, taking into account today's realities, this is not enough. It is necessary to address a whole range of issues that allow the mining industry to be brought to a higher level in terms of efficiency, productivity and safety. This requires the fulfillment of three conditions: technical re-equipment of the industry, through the introduction of new, more productive mining equipment; development of new technologies for processing of extracted raw materials and natural resources; staff development of mining enterprises of all levels.

Modern quarry excavators used in surface mining operations are high-performance, large-size electromechanical systems of high unit power, operated by an excavator driver. The analysis of the reliability of career excavators in specific operating conditions shows a high proportion of failures of electromechanical equipment (50 ÷ 70% of their total number). This is due to the fact that they are operated in harsh conditions and do not always meet safety requirements for some operational parameters that affect both productive work and the health of the excavator driver (fatigue in managing work processes, monitoring the state of the face, etc.) [1, 3].

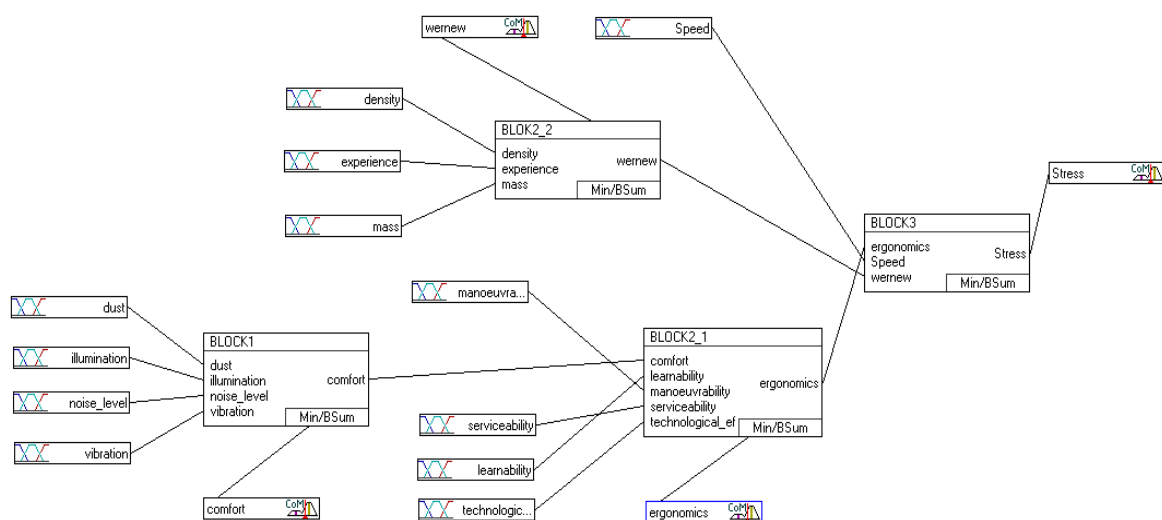


## 2. Methodology

The significant problem of determining the actual stresses arising in the working equipment of mining excavators is a large number of influencing factors that are difficult to imagine using analytical formulas, i.e. most factors are random. Evaluation of loads in the working equipment when managing a mining excavator, most often, slightly depends on traditional methods of analysis and modeling, which determines the need for developing new models using non-standard approaches [4].

Based on the analysis of scientific and technical literature, it is determined that solution for problems with a large number of influencing and not fully defined factors is advisable from the point of using the mathematical apparatus of the theory of fuzzy logic and fuzzy sets [5].

The paper determines the sequence of two-stage development of mathematical models with elements of fuzzy logic in defining the loading level of the main elements of the working equipment during management of a career excavator [6-11]. In accordance with this, the stages of structural and parametric identification have been implemented (figure 1).



**Figure 1.** Developed fuzzy model for estimating the working equipment loads when driving a mining excavator.

Structural identification of the model includes:

1. Number determination of the input and output linguistic displaced, characterizing the influence of various natural-technical factors on the magnitude and nature of the loads in the work equipment. The definition for each linguistic variable of the number of its values - terms.

2. Definition of the name of linguistic variables and their terms, setting the universe (domain of definition) of linguistic variable terms.

3. The choice of types of membership functions for terms of linguistic variables in their universes.

4. Determining the structure of the logical control rules "if ... then".

The relationship between input and output variables is presented in the form of logical rules of control "if ... then", the conditions and conclusions in which are formulated using linguistic variables that characterize the process of assessing and determining the level of ergonomics [12, 13]. The structure of the logical rule depends on the number of input and output variables of the control process:

- by direct experiment on a full-scale object or its modeling;

- by mathematical modeling to study the influence of control parameters on the parameters of the state of ergonomic indicators;
- based on the combination of these methods.

In the first case, the questionnaire method extracts in verbal form the experience of a skilled worker, knowledge of a specialist engineer or a scientist, which are then generalized using logical rules "if ... then" using the mathematical apparatus of fuzzy sets theory and fuzzy logic. The importance of this method is in the fact that it allows formalizing the valuable facts observed in real production conditions.

The second method allows summarizing the numerous scattered information published in the scientific and technical literature on this issue, about the manifestations of cause-effect relationships and present this information in a single form - in the form of logical rules of control "if ... then".

The third method is effective when you can conduct a direct experiment on real equipment or physical modeling using similarity theory on a simulation model with obtaining the necessary data on the influence of control parameters on ergonomic indicators. The obtained information serves as a source for the formation of the logical control rules "if ... then."

It should be noted that one of the leading software development tools for calculations using fuzzy logic and fuzzy neural networks is the FuzzyTECH package from Inform Software Corporation. It is important to note that the program contains a wide range of different types and forms of membership functions. After specifying the membership functions of terms of linguistic variables in the FuzzyTECH package, the decision maker, as the approbation and analysis of control results in the dialogue mode, can correct them (improve), also they have the property of learning and adaptation, which allows using neural networks also supported by the considered program.

The determination of the load level of the main elements of the working equipment driving a mining excavator with elements of fuzzy logic meets the requirements of completeness and consistency. Completeness is expressed in the fact that for each current state of the process of managing indicators there is at least one governing logic rule, the condition of which has a non-zero degree of belonging to this state, and consistency consists in the absence of rules having similar conditions and different or mutually exclusive consequences.

At the stage of structural identification, the total number of input and output linguistic variables (the area of their definition and the number of terms for each variable) was determined, which characterize the process of establishing loads in the working equipment when driving a career excavator.

### 3. Results

Parametric identification of the model, which consists in determining the parameters of the membership functions for all terms of the input and output linguistic variables, as well as the definition of fuzzy relations necessary to form a base of logical rules "if ... then" and their weights, based on the results of modeling and experimental research loads in the working equipment when managing a career excavator. When presenting the values (terms) of the input and output linguistic variables on their universes, Z-shaped and S-shaped membership functions were used.

When creating a fuzzy rule base, the data obtained from experts or from measurements are used. In practice, a mixed type is most often used when the rule base is built on the basis of expert opinions, and its refinement and adjustment is carried out using experimental data.

The determining disadvantage in the development of a fuzzy rule base on the basis of expert opinions is growth of rules number, with a certain number of factors and their possible values. Ensuring the completeness, consistency and coherence of the rule base is very difficult in such conditions. Therefore, in this paper it is proposed to create for each one.

In order to implement the model, it is necessary to specify input and output linguistic variables, rule blocks, as well as intermediate blocks and input variables that optimize data analysis. Each variable is characterized by its range of possible values, which are divided into terms.

Linguistic input variables (LIV) with terms for the rule block BLOCK1:

1) Dustiness. It is known that the threshold limit value (TLV) of dust in the excavator cabin is 2 ( $\text{mg}\cdot\text{m}^3$ ). Important factors in dust formation are precipitation in the form of snow or rain. The maximum recorded concentration of dust in spring is 2.8 ( $\text{mg}\cdot\text{m}^3$ ), in the fall - 3.6 ( $\text{mg}\cdot\text{m}^3$ ), in winter - 3.9 ( $\text{mg}\cdot\text{m}^3$ ) and in summer of 8.3 ( $\text{mg}\cdot\text{m}^3$ ). This allows identifying the influence of individual climatic factors, such as temperature and humidity, on the dustiness of the air. Analyzing the data, we simulated LIV "Dust" = {"permissible", "high", "very\_high"}, where "Dust" - dustiness, "permissible" - acceptable, "high" - high, "very\_high" - very high concentration. The definition range is from 0 to 12 ( $\text{mg}\cdot\text{m}^3$ ).

2) Illumination. When working at night in quarries, the workplaces of mining excavators should be covered. LIV "illumination" = {"insufficient", "moderate", "sufficient"}, where "illumination" is lighting intensity, "insufficient" is poor, "moderate" is medium, and "sufficient" is adequate. The values of the term are compiled taking into account the minimum required illumination (10 lx) in the bottom, where excavation takes place. For illumination in the QCS (quarry crawler shovel)cabin, this figure is 50 lx. The scope is from 0 to 80 lx.

3) The noise level. Noise is a disorderly combination of sounds different in strength and frequency; it may have adverse effects on the body. Prolonged exposure to noise on the human body leads to the development of fatigue, often turning into overwork, to a decrease in productivity and quality of work. Therefore, the model takes into account this linguistic variable - "noise\_level" = {"low", "medium", "high"}, where "noise\_level" is the noise level, "low" is low, "medium" is medium, "high" is high noise levels. At the maximum level of noise occurring in the QCS cabin, all possible excesses relative to the remote control panel (RCP), which is 50 dBA, LIV "noise\_level" are based.

4) Vibration. Vibration as a production hazard is a mechanical oscillatory motion, directly transmitted to the human body or its individual parts. Due to the mechanization of many types of work and the use of pneumatic and electric tools, its value has sharply risen, and now vibration disease among occupational diseases occupies one of the first places. It is customary to distinguish between local (local) and general vibration: the first is transmitted to the hands or other limited areas of the body, the second to the whole organism (staying on an oscillating platform, a seat).

Based on the limiting vibration parameters, we introduce LIV "vibration" = {"low", "medium", "high"}, where "vibration" is vibration, "low" is low, "medium" is medium, and "high" is high level of noise. The definition range is from 0 to 30 dB

5) Comfort (habitability). Favorable combinations of microclimate parameters, the absence of harmful production factors leads to the fact that workers experience a state of comfort, which is an important condition for labor productivity. A significant deviation of the microclimate parameters of the working area from the optimal ones and the presence of harmful production factors cause a number of physiological disorders in the human body, decreased performance and even occupational diseases. Therefore, for the overall assessment of LIV: "dust", "illumination", "noise\_level", "vibration", we introduce an intermediate LV "comfort" - comfort (habitability), having three terms: "bad" - bad, "medium" - average, "good" is good. The assignment of terms is evaluated on a five-point scale.

Ergonomic indicators, reflecting the product use ease by a man, largely affect the wear of the machine. Human interaction with the product is expressed through a complex of anthropometric, physiological and psychological properties of a person. In order to take into account these indicators, an intermediate LIV "ergonomics" was introduced - ergonomics based on five LIVs: "maneuverability" - manageability, "comfort" - comfort (habitability), "serviceability" - maintainability, "learnability" - absorbability, "technological\_ef" manufacturability of the rule block "BLOCK2\_1".

In order to simplify the rules for assessing the stresses arising in the QCS handle, an intermediate "wear" (wear) was introduced, having 4 terms: {"low", "medium", "high", "very\_high"}, where "low" is low, "medium" - medium, "high" - high, "very\_high" - very high wear. Moreover, these terms are derived by the code of rules of BLOK2\_2, which are based on three LVs: "density"; "experience"; "mass".

1) Density. The calculated average density of the rock mass is one of the important characteristics for estimating the stresses in the excavator handle, since this parameter is proportional to the category of rocks by hardness, coefficients of loosening of the rock mass and bucket filling. The range of density values is selected based on the minimum and maximum possible density of rocks. For LV “density” = {“low”, “medium”, “high”}.

2) QCS driver’s experience. It has been established that the driver’s experience has a great influence on the QCS load. So, for example, with an experience of less than a year, the coefficient of controllability is 0.2, and with an experience of more than 10 years it is equal to 1, which indicates a significant difference in the dependence of the QCS driver’s experience on the wear of working bodies. LV “experience” = {“little”, “allowable”, “good”, “big”}, where “little” is small, “allowable” is permissible, “good” is good, “big” is a great experience.

Values range is from 0 to 20 years.

3) Mass. The mass of the handle, bucket, and excavated rock (hereinafter simply referred to as “mass”) plays an important role in the evaluation of stresses. The dependence of mass on stress has a direct proportionality. LV “mass” = {“low”, “medium”, “high”}, where “low” is low, “medium” is medium, and “high” is high mass. The term definition is defined taking into account the mass of the empty bucket, the handle and the mass of the bucket, the handle with the maximum possible mass of rock in the bucket, which is calculated taking into account occupancy and density of the rock.

As a final estimate for predicting the stresses in the excavator handle, we use three LIVs, two of which are also intermediate; the third is the “Speed”. The output of the resulting LV will eventually be voltage, i.e. “Stress”, the rules of which are presented in the “BLOCK3”. Using the well-known dependence of the voltages in the QCS handle on the change in the bucket lifting speed during the period of digging of the rock mass, which was built by measuring the strain gauge voltage sensors on the excavator handle, the terms for the LIV “Speed” and the output LV “Stress” are created. As a result, LV “Speed” = {“low”, “medium”, “high”}, where “low” is low, “medium” is medium, and “high” is high speed. The definition range of terms is from 0 to 1 m/s. When compiling the terms of these two LVs, one should be guided by permissible stresses -  $[\sigma] = 153 \text{ MPa}$ , the excess of which leads to a violation of the strength of the element; yield strength:  $\sigma_T = 260 \text{ MPa}$ , the excess of which leads to the manifestation of fatigue cracks. Based on all the results, the “Stress” LV is modeled: = {“allowable”, “high”, “very\_high”}, where “allowable” is permissible, “high” is high; “very\_high” is very high voltage. The scope is from 0 to 350 MPa.

Figure 2, as an example, gives the membership functions of fuzzy sets, corresponding to the terms of linguistic variables characterizing the indicators of unit 1, namely  $\xi_1$ - “vibration” and  $\xi_2$ - “noise level” and ergonomic indicator  $\omega_1$ - “comfort” figure 3. The indicators characterizing the degree of illumination of the face, the level of vibration of the driver's seat of the excavator were taken as input linguistic variables. The output linguistic variable is an ergonomic indicator denoting comfort in the quarry excavator driver’s cab (figure 4).

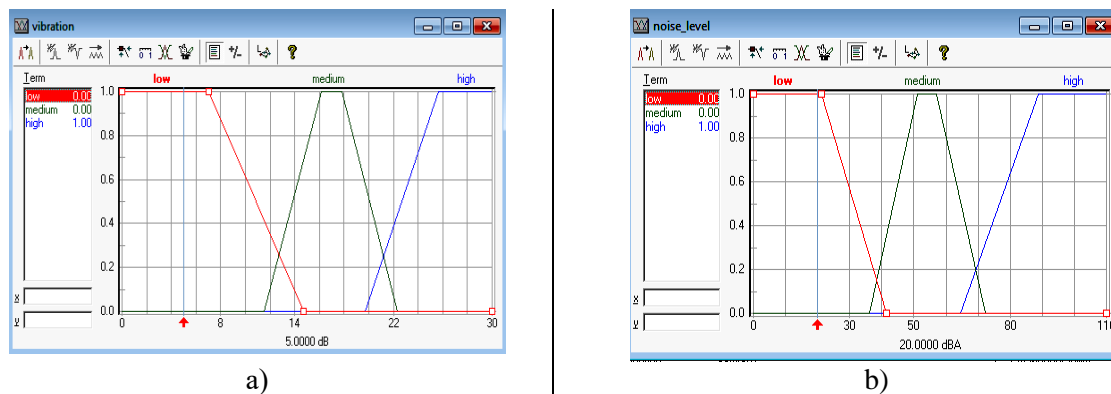
Input linguistic variables are given:

$$\xi_1\text{- “vibration”} = (\text{<small, medium, high>, [0 - 30 dB]}) \quad (1)$$

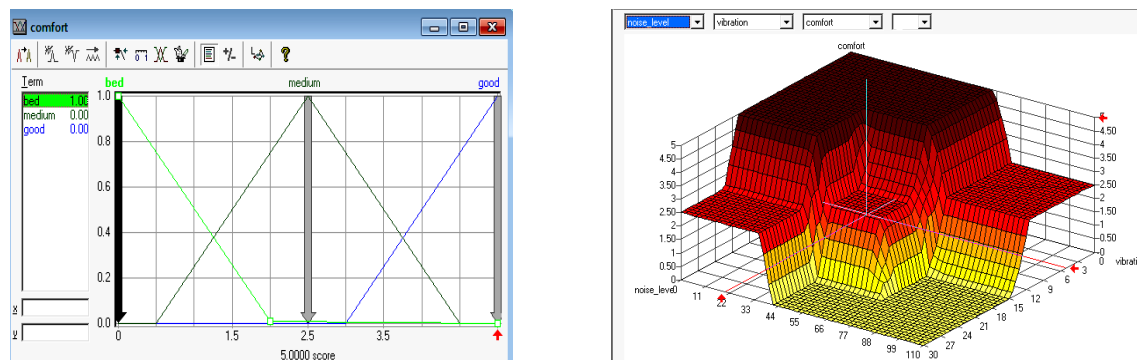
$$\xi_2\text{- “noise level”} = (\text{<small, medium, high>, [0 - 110 dBA]}) \quad (2)$$

Output linguistic variables were defined in the form:

$$\omega_1\text{- “comfort”} = (\text{<bad, average, good>, [0 - 5 point]}) \quad (3)$$



**Figure 2.** Fuzzy sets membership functions of corresponding terms of linguistic variables characterizing indicators: a) vibration; b) noise level.



**Figure 3.** Membership function, characterizing “comfort” in the driver’s cab.

**Figure 4.** Input variables response type of output variable surface.

#### 4. Conclusion

The process of research and analysis of the developed fuzzy model includes: performing a fuzzy inference for various values of input variables, as well as evaluating the results in order to establish the adequacy of the model and make the necessary changes in it in case of inconsistency of the results.

Thus, the most reasonable choice of strategy in determining the level of loading the main elements of the working equipment of mining excavators is based on the mathematical apparatus of fuzzy sets, since the complex use of analysis procedures based on this approach allows solving the problem of higher quality.

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