Identification of failure patterns of excavator equipment failures considering the control factor

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Abstract. Within the conditions of increasing open pit mining, an urgent problem is improving the efficiency of mining excavators. The variety of parameters, properties and characteristics that determine the quality of functioning, poses the problem of using fuzzy methods to evaluate them. Due to the fact that the loads arising in the working equipment of mining excavators are determined by a large number of different factors that are difficult to imagine by analytical formulas, i.e. these factors are mostly random, it is necessary to implement models using non-standard approaches. In this study, we used the methodology of the theory of fuzzy logic and fuzzy sets, which allows overcoming the difficulties associated with the incompleteness and vagueness of the data in assessing the prediction of the forces arising in the working equipment of mining excavators, as well as with the qualitative nature of these data.

1. Introduction
The increase in iron ore and coal production entails an increase in demand for mining equipment. The global market for mining equipment is growing steadily by 8-10% annually, over 70% of mining excavator sales account for Russian mining equipment manufacturers in the domestic market [1, 2].

About 490-500 units are in operation at large iron ore quarries of the Russian Federation open-cast mine shovels and hydraulic excavators, 90% of which are machines made by domestic manufacturers. Most single-bucket open-cast mine shovels are produced, including 7 basic models and 16 of their modifications (with a bucket capacity from 5 to 20 (25) m³). Since the release of the first machine (in 1965), little has changed in the design of the ECC. All modifications that have survived to this day have retained their performance characteristics (Figure 1).

Figure 1. State of the excavation fleet in the coal industry.
Moreover, 80% of the entire fleet of excavators is mechanical shovels with a bucket of 5 m$^3$ or more, released in the 80s of the twentieth century [2]. The number of mining equipment imported does not exceed 5%.

Productive 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 lost due to various kinds of malfunctions and accidents.

As a result of the analysis of evidence, scientific publications and the conclusions of experts, it was found that the percentage of depreciation of fixed assets in the mining industry is quite high and reaches 70-90%.

The operation of mining equipment in this state is associated with an increase in the cost of its maintenance, which ultimately leads to an increase in the cost of production and processing of mining products.

Studies of operating modes and causes of failures in the working equipment of mining excavators (such as ECC -5A, ECC-8, ECC -10, ECC -12) in the quarries of the South Urals over the years have shown that the main causes of failure of the handle of mining excavators are: high level of their dynamic loading exceeding permissible; form of construction leading to a high concentration of stresses; consequences of repair actions; relatively low qualification of drivers [1, 2].

Data analysis shows that the largest number of failures of the handle of mining excavators occurs when it is controlled by drivers with a working experience of 1-5 years.

It has been established that all drivers with the considered work experience have different values of the time between failures of the handle beam, which depend on the change in the speed of the bucket when scooping the rock mass (Table 1) [2, 3].

In most cases, handle failures occur as fatigue cracks, which lead to brittle fractures.

**Table 1.** The results of excavation production observations of mining.

| Drivers’ work experience, years | The average time of digging rock mass, s | Maximum basket lifting speed, m/s | Mean time between failures of a beam stick, thousand m$^3$ |
|---------------------------------|----------------------------------------|---------------------------------|------------------------------------------------------|
| 1-5                             | 12                                     | 0.87                            | 223                                                  |
| 5-10                            | 13.9                                   | 0.75                            | 762                                                  |
| 10-15                           | 17.5                                   | 0.6                             | 1325                                                 |

Thus, the analysis of scientific publications and full-scale studies of the causes of failure of the handle of mining excavators according to breakdown patterns showed that the main causes of failure of the handle of excavators are the qualifications of the drivers and the influence of the shape of the structure (high stress concentration), which requires additional research.

2. Methodology
The data mentioned above is based on taking into account the construction perfection of a mining excavator, i.e. provided by the manufacturer of mining equipment its functionality in the laid-down period of operation time. The physical wear indicator demonstrates external factors affecting the mining excavator during rock excavation operations, which correlates with the main provisions of the theory of system analysis, which examined the element of the excavator and environment system, and the human "- the driver of a mining excavator [1-7].

It is well known that the functionality of any machine, which is constructively laid down by the manufacturer, is implemented by the engineer as far as his skill and work experience, as well as psychophysical compatibility with the system element "machine", which can be expressed as an indicator of the comfort level laid down by the machine manufacturer.

The comfort level of managing a career excavator for a driver is characterized by many features, among which there is a factor of attention span due to external (the object of the technological operation is the environment) and internal (comfort ECC control - stability of the technical condition). Maintaining the driver’s comfort level is directly dependent on the level of loss of excavator
functionality, a decrease in this indicator is compensated by a proportional increase in the load on the driver, the limit of which is within the framework of the psychophysical state of a person.

The influence of the qualifications of excavator drivers on the quality of ECC control is taken into account in the calculated dependencies when determining the performance of a mining excavator, namely with the help of the so-called excavator control coefficient, i.e. coefficient taking into account the experience and practical skills of the excavator driver - \( k_y \). The control coefficient is recommended to be defined as the ratio of the technical productivity of the excavator for 1 hour of good operation to the theoretical productivity, or the ratio of the theoretical duration of the excavation cycle to the actual duration of the cycle in the given operating conditions. The theoretical length of the excavation cycle is usually determined for normal operating conditions at a bottom hole height corresponding to the technical characteristics of a mining excavator, a turning angle of 90°, unloading the rock mass into a dump, and maximally combining work operations.

The actual cycle time is defined as the average length of the excavation cycle during the operation of a mining excavator in specific mining conditions, taking into account the qualifications of the driver.

In this paper, the authors propose a new approach to the implementation of a system for reducing the risk of failure of mining excavators. Generally speaking, there are many definitions of the concept of "system." Relatively, the systems for reducing the risks of failures of mining excavators have determined that this is a set of selectively involved components that interact with each other to increase the efficiency of a mining excavator with a fairly low level of risk of failures due to the quality of management. The structural and functional diagram of the implemented system establishes the functional essence of the individual elements and explains the processes taking place in the system as a whole (Fig. 2).

However, the elements of the scientific and methodological base developed and implemented to date to create this system are scattered and are intended to solve, as a rule, local problems. There are currently no general methods for organizing failures; Criteria and methods have not been developed for evaluating the performance of mining excavators that take into account the features of management and operation in specific operating conditions.

The efficiency of a mining excavator with a minimum level of failures can be achieved, first of all, through the implementation of a set of targeted impacts that provide a given operational performance, which in turn is one of the defining indicators characterizing the quality and effectiveness of managing a mining excavator in specific mining and geological operating conditions.

It is proposed to highlight:

- a group of physical parameters characterizing the properties of the rock mass and individual mass-dimensional characteristics of a mining excavator;
- a group of indicators determining the ergonomics of the workplace of the driver;
- a group of indicators characterizing comfort at the workplace of a career excavator driver.
Group of physical parameters

- Bucket lift speed
- Rock density
- Mass and size characteristics of the working equipment
- Driving experience

Minimizing failures in mining excavators

A group of indicators that determine the ergonomics of the driver’s workplace

- Controllability
- Serviceability
- Masterability
- Manufacturability

A group of indicators that determine comfort in the cabin of a mining excavator

- Dustiness
- Noise level
- Vibration
- Illumination

Figure 2. Mining excavator failure reduction system.

At the same time, the influence of the external and internal loads of the driver, which determine the comfort indicator, leads to an increase in the excavation cycle, the intensification of resource production by a mining excavator, the formation of excess loads in the designs and mechanisms of a mining excavator, as well as a violation of safety regulations. One of the key elements of the system is personnel. To assess the quality of training and selection of drivers in the system, there is a set of methods for assessing professional competencies, training using a multimedia training system, training in a simulator-training system or the joint use of these systems.

This study proposes to use a fuzzy approach to assessing a scorecard. The development of a fuzzy system model is carried out in four stages: structuring the subject area and building a fuzzy model; performance of computational experiments with a fuzzy model; application of the results of computational experiments; correction and refinement of the fuzzy model.

In order to perform computational experiments, specialized computer software FuzzyTECH [8] was used that was oriented to solving modelling problems using the theory of fuzzy sets and fuzzy logic.

To improve accuracy, the developed fuzzy model can be trained, i.e. iteratively change its parameters in order to minimize the deviation of the results of inference from experimental data. It is possible to change both the weight coefficients of the rules and the membership functions of fuzzy terms.

3. Implementation

As an example of the described approach implementation, the influence of a group of physical parameters is presented as applied to a system for minimizing failures in mining excavators.

Experience as a driver. The input linguistic variable “experience” = \{“little”, “allowable”, “good”, “big”\}, where “little” is small, “allowable” is acceptable, “good” is good, “big” is long experience. The range of values is from 0 to 20 years or more.

The mass of the stick, bucket and excavated rock (hereinafter referred to as the "mass"). The input linguistic variable is "mass" = \{"low", "medium", "high"\}, where "low" is low, "medium" is medium, and "high" is high mass. The scope is defined in accordance with the type of mining excavator and its mass overall characteristics.

It is possible to reduce the number of failures in the working equipment of mining excavators by reducing the level of alternating dynamic loads, with the possibility of taking into account not only technical, but also external factors, as well as the current characteristics of the “driver-excavator”
system, therefore, to evaluate the stresses in the working equipment of the excavator in the model, a block is implemented for which we respectively use three input linguistic variables, namely “comfort”, “speed”, “ergonomics”. The output variable will ultimately be the voltage, i.e. “Stress” = \{“allowable”, “high”, “very high”\}, where “allowable” are permissible, “high” are high, “very high” are very high voltages. When setting the terms of the output variable, they were guided by permissible stresses - [\sigma] = 153 MPa, the excess of which leads to a violation of the strength of the element; yield strength: \sigma_y = 260 MPa, the excess of which leads to the manifestation of fatigue cracks. The range of definition is from 0 to 350 MPa.

As a result of the calculation of the developed fuzzy model using actual indicators, a surface is obtained that describes the relationship between fuzzy values (Fig. 3), as well as fuzzy values of controlled parameters. Based on the analysis of the actual values of the flow indicators, the indicators that have a decisive influence on the failure flow of working equipment are selected.

![Figure 3. Response surface of the output variable dependence on two arbitrary input variables of the developed model](image)

4. Conclusions
The conceptual apparatus of the theory of fuzzy sets has been adapted to establish the influence of the external and internal loads of the driver, which determine the comfort indicator, which leads to an increase in the excavation cycle, the intensification of resource production by a career excavator, the formation of excess loads in the designs and mechanisms of a career excavator, as well as a violation of safety rules. The possibility of a formalized description by fuzzy and linguistic variables of single ergonomic indicators of quarry excavators, the values of which can be fuzzy sets mathematically defined as membership functions has been realized.

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