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Measures to prevent damage and to extent the service life of a rotary excavator

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Abstract
The rotary excavator is a complex machine system, the main part of the ECS (excavator-conveyer-spreader) system, used in open-pit mining. Such a machine's service life can last for decades, it generally operates in the harsh exploitation conditions, which requires that its vital structures must be continuously controlled and well maintained. Damage or fracture of parts or assemblies of a rotary excavator can be caused by influence of various manufacturing, construction, exploitation conditions or environmental factors. Analysis of those eventual failures can be performed by various methods, out of which the most suitable are the failure analysis methods, for example the fault-tree analysis (FTA), the Ishikawa fishbone (cause-and-effect) diagrams or the failure modes and effects analysis (FMEA). In this article are presented results of the fault tree analysis of possible causes of rotary excavator's parts, as well as measures to prevent their damages and/or fractures and to extend the service life of an excavator as a whole. The model of the organizational system for the rotary excavator's maintenance is given, as well.

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1. Introduction.

The rotary excavator for exploitation in open-pit mines is the main part of the so-called ECS system (E-rotary excavator, C-conveyor/transporter, S-spreader/dumper) for digging the exploited material (ore, coal, etc.) and/or disposal of tailings. This is a complex machine, consisting of numerous assemblies and parts, usually manufactured in small batches, sometimes even as a single unit, aimed for the specific purpose and/or the operating conditions and environment. The size, shape and construction of rotary excavators mainly depend on the required capacity, the method of loading the material and the specific excavation or disposal conditions. The rotary excavators usually have a long service life (measured in decades) in the hard exploitation conditions, which poses as an imperative that their vital structures have to be controlled both continuously and periodically. Various unpredictable failures (damages and/or fractures) of parts or assemblies of the rotary excavator may occur during operation, which could be caused either by the operating conditions or applied load.

Due to the widespread use of rotary excavators, there is a whole range of different types of those machines, which differ from each other in shape and size of their vital elements, like in the diameter of the working wheel, in the number and shape of buckets on the working wheel, in the length of the working boom, etc. The analyses of the rotary excavator's performance and reliability, were considered in different researches, focusing either on specific or general problems. The research is now primarily related to study of the parametric reliability, determination of dynamic load, wear and aging as possible causes for parts or assemblies' failure (Krynke, et al., 2022). This is why it is obvious that there are new tendencies of researching the integrity and reliability of these continuous production systems. One of the ways to analyze the eventual failures are the well-known methods of failure analysis, that can be used to detect the cause of failure, like the fault-tree analysis (FTA), the Ishikawa fishbone (cause-and-effect) diagrams or the failure modes and effects analysis (FMEA), (Aliya, 2002). The service life can be successfully predicted, (Verma, 2023, Jovanović, 2023) so it is of great importance to apply all the necessary measures to avoid breakdowns.

2. Literature review

(Arsić, M. et al., (2021a) have investigated the causes of damages of the bucket wheel excavator boom's welded lattice structures, which needed to be repaired. The structure's performance prior to and after the repair was analyzed. The tensometric measurements of the stress-strain state of the structure, and calculations of stresses by the finite element method (FEM), allowed authors to conclude that the damage was initiated in the parent metal and fracture of the welded joints was caused by manufacturing defects.

(Medjo et al., 2020) delved into the study of the pipe-line section from a hydropower plant. They determined the limit pressure values using the 3D and 2D models of pipes with axial cracks on external surface and circumferential cracks. The assessment of integrity of pipes was performed by application of the failure assessment diagrams (FAD).

(Đurđević et al., 2021) presented the numerical simulation of the supporting base structure behavior, used for power equipment in mining, with a focus on the fracture toughness KIc. They proposed a new design solution of a base structure. The calculated critical crack length significantly exceeded the dimension of the considered part of the base. Thus, the part would fail due to stresses exceeding its load-carrying capacity and not due to eventual crack propagation.

(Vicen et al., 2022) were dealing with the influence of the shot peening on the wear behavior of the medium carbon C55 steel. Their analysis included obtaining values of the compressive residual stresses. The surface roughness profile parameters were measured after the shot-peening treatment, while the friction test was executed, as well. The test results confirmed appearance of the compressive residual stresses and an increase of the surface roughness. The increase of the coefficient of friction from 1.44 to 1.85 times was recorded.

(Arsić, D. et al., (2016) analyzed, both numerically and experimentally, effect of the elevated temperatures on mechanical properties of structural high-strength steel class S690QL. The objective was to find out the limiting temperature at which this material still retains those properties at the levels required for normal functioning of parts made of it. The critical temperature identified was 550 °C, by both types of analysis.

The subject of analysis by (Arsić, M. et al., (2021b) was determining the causes why the damages appear on the support structure of the boom of the bucket-wheel excavator (BWE). The non-destructive test results pointed to the fact that there are the stress concentrator points from which the cracks are usually initiated, those being the areas of the radii transitions, as well as the welded joints.

(Arsić, D. et al., (2014) executed both experimental and theoretical analyses for occurrence of fractures of a responsible machine part, subjected to short and high dynamic loads, simultaneously with constant pressure. The results testified to appearance of multitude of impermissible nonmetallic inclusions segregation in the steel matrix. Mainly phosphorus inclusions were the causes for appearance of micro and macro cracks, during the forging, which were extending during the subsequent heat treatment and in operation.

(Misita et al., 2021) were analyzing the issue of the mining machinery efficiency, via the effect of different types of downtimes. The comparison of impact of the mining machinery downtime in fault and impact of the mining machinery downtime frequencies, on the machine work done, was proposed as the new methodology for measuring the mining machines efficiency. Authors determined the critical pattern of the downtime influence on the machine efficiency via the multi-criterion analysis.

The objective of the study by (Bošnjak et al., 2018) was to diagnose the cause of chain link breakdown occurrence. Those chain links are parts of the crawlers on which leans the superstructure of a Stacker ARs 2000 in an open pit mine in Serbia. After only 1000 working hours (about three months), 30 chain links fractured, causing a substantial financial loss due to the stacker's downtime. The numerical-experimental analysis, and metallographic examinations results, showed that the chain link fractures were predominantly caused by substantial deviation of the material's mechanical properties from the standard prescribed values, as well as by the existence of macro and microcracks in the material structure.

The results of microstructure testing of crane wheels, along with the repair welding procedure performed by hard-surfacing, are presented in (Tanasković et al., 2017). The repair welding involved the application of a welded layer to the crane wheel, to remedy the damage caused by wear. After the repair, the detailed analyses of the mechanical and chemical properties of the materials, both of the crane wheels and of the repair welding, were performed. Numerical simulations of the contact between the rail and wheel were done by the finite element method, for the stress analysis of the wheel, with or without a crack, to determine the crack influence on the crane wheel integrity, and to compare the results to the values obtained theoretically.

(Viveros et al., 2014) used the root cause analysis integrated by a method for identifying coherent and sustainable solutions, to identify the failure causes of production systems, for effective recovery solutions. The integration of these methodologies is implemented and demonstrated on a real case of potential failure of the equipment used in the torque test, performed on truck engines used in high-tonnage mining operation. Authors stated that the incorporation of a key performance indicator analysis allowed to realistically evaluate the results obtained and to determine the success of the solution.

(Huang et al., 2023) demonstrated the use of RBI, risk-based approach to inspection planning, which is an established pipeline integrity management method. Corrosion and dents are the primary threats to pipeline integrity, often treated separately in RBI, without considering their interactions. In this study authors proposed an RBI planning framework for pipelines, considering both external corrosion and dents. They introduced an optimization model of loss-maintenance total expected costs to determine the optimum inspection period, using maximum acceptable risk (MAR) and the lowest total expected cost, and implemented the cost-benefit analysis (CBA) to choose appropriate risk reduction measures. Authors concluded that the proposed framework is robust and well-validated by a case study.

3. Technical diagnostics

During the exploitation of rotary excavators, a gradual loss of useful properties of assemblies and their components usually occurs. In addition, the degradation of material properties and/or deformation of elements can be accelerated due to exploitation and repair errors. Therefore, a periodic or constant diagnostic measurements and the execution of periodic tests are necessary to provide that the processes, which could create conditions for system failures, are constantly kept under the systematic control.

The technical diagnostics' performance must be based on three basic principles:

a. The scope of testing and measurements must follow from the history of the rotary excavators use with expert knowledge of its construction and operating conditions.

b. Testing and measurement must be carried out according to specific procedures, using adequate equipment and qualified personnel.

c. The test results should be presented in such a way that the conclusions include the exploitation of production and technical systems, availability of the test personnel and a team of experts with appropriate experience and knowledge in the fields of design, construction, assembly, exploitation, maintenance, reliability, fracture mechanics, etc.

Correctly conducted diagnostics ensures that the excavator parts will not suffer the sudden breakdown, the safe work for employees and rational techno-economic exploitation, as well as the maintenance.

Large production systems, such as the ECS (excavator-conveyer(transporter)-spreader) system, are very difficult to analyze due to the complexity of the structure, operating conditions and large number of components. In cases like this, using smaller, necessary simplifications depending on the needs, the fault (failure) tree analysis is effectively applied, Figure 1. The FMEA (Failure Modes and Effects Analysis) method, as a method of qualitative and quantitative reliability analysis of the components of technological systems, and preventive analysis of all the potential failures of system elements and their effects, is applied for the analysis of failure modes and their effects in all the phases of the excavator system life cycle, Figure 2.

The optimal setting of the system for continuous diagnostics of the reducer of the excavator digging drive on the PLC (programmable logic controller)-PC coupling can be done based on several elements. The first one is the performed investigation of failures and causes of malfunctions of the excavator's digging drive and the reducer of the digging drive, using the fault tree method; the second is analysis of the mode of effects and the criticality of failure, using the FMEA method, while the third are the reliability indicators, obtained based on the analysis of the collected data for real exploitation conditions.

Figure 3 shows a symbolic - schematic representation of the system configuration for continuous control, monitoring and diagnostics of the excavator digging reducer through all the system levels. The figure shows that it is possible to directly connect an operator interface and a manual programmer to the PLC. The manual programmer has a numeric keypad with light indicators for indicating the status, as well as an operator terminal on which up to 200 messages with numeric and variable messages can be defined.

The operator interface has an alpha-numeric display with a functional keyboard and is used to display the values of process variables, status, alarms and messages, logs of system errors and those defined by the user program with the time of occurrence and set parameters by name or address.

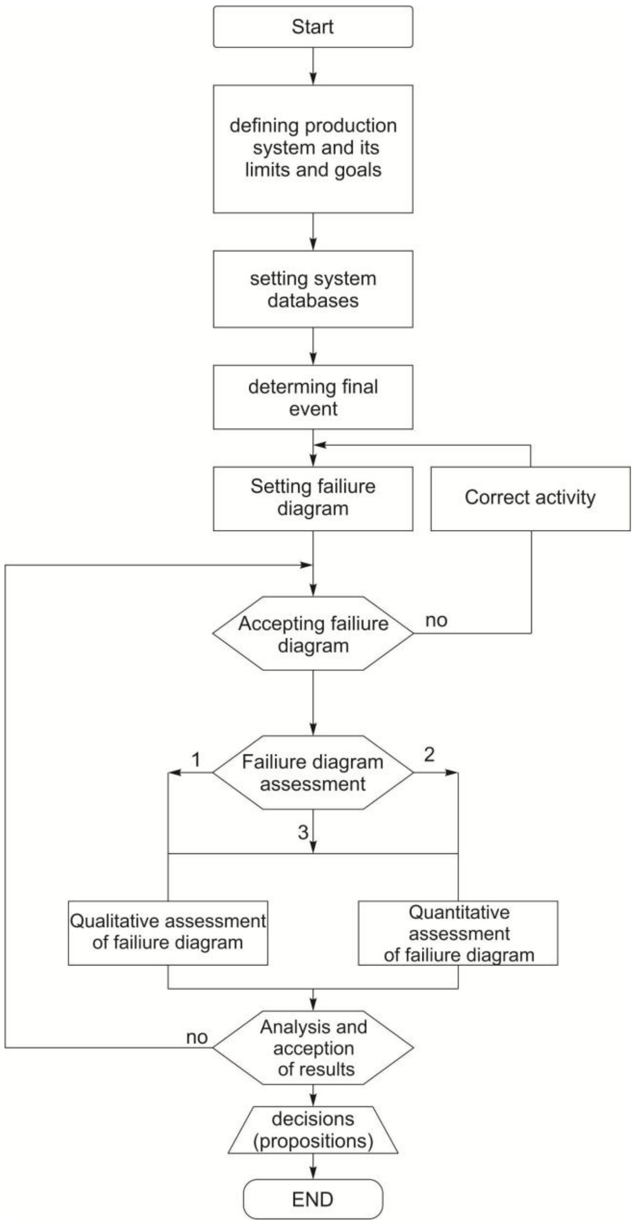

Fig. 1. Block diagram of the fault tree analysis procedure

4. Data bases

Databases of conducted research on adequate structures provide great opportunities in extensive analyses of behavior of the responsible parts and elements of supporting structures, to determine changes in the mechanical properties of materials, parts and welded joints of structures when varying a large number of influencing factors. They also help to reduce some undesirable effects to a tolerable value, that is, to implement a favorable structural solution as a whole.

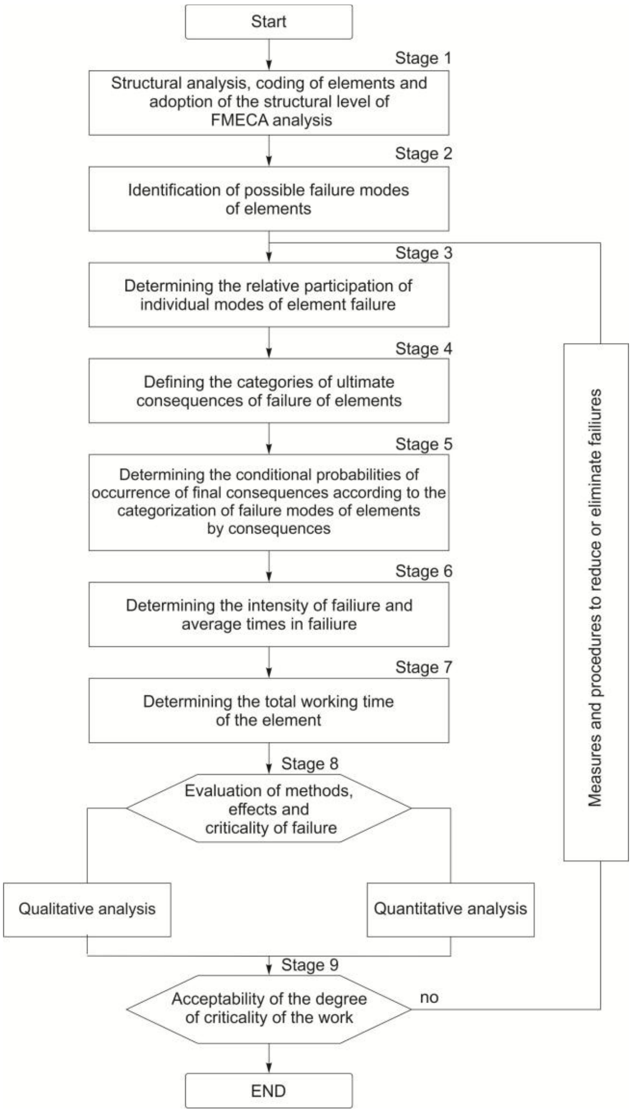

Fig. 2. Block diagram of the FMEA analysis procedure

Analyses of damage and breakage of parts and elements of supporting structures provide the important information for improving the methods of design and construction of the responsible parts and elements of supporting structures, and for improving the properties of existing materials and technologies for their processing, as well as for development of new materials. In addition, analyses of damage and fracture enable development of the new technical solutions and test methods, even at the prototype stage. Analysis of damage and fracture also makes possible to determine the causes that lead to them, for the purpose of their preventing and/or eliminating. That is a process that requires a systematized approach to the problem, Figure 3.

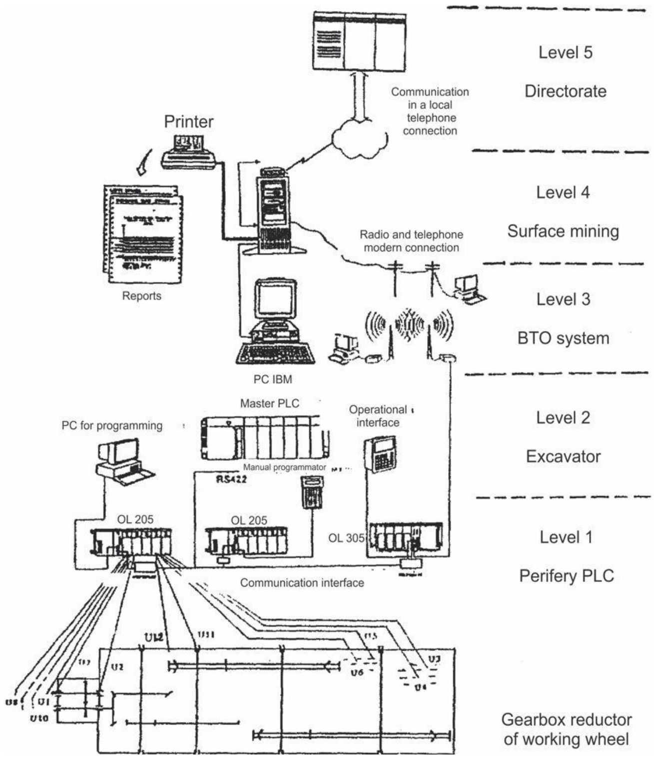

Fig. 3. Display of the system configuration for control and diagnostics of the digging reducer

Data on the load, characteristics of the base material and its welded joints, production technology, technical and physical characteristics of the recorded fractures, and anticipated measures to prevent damage and destruction, are entered into the appropriate database. Additionally, the databases should contain the data collected during the examination of the previous similar (adequate) supporting structures. Figure 4 shows the structure of the required database for responsible parts and elements of the supporting structures of rotary excavators.
A quick and reliable assessment of the integrity and suitability for use of responsible parts and elements of the supporting structures of rotary excavators can be made exclusively by creating a database and the basis for the development of computer programs. Accompanying software packages would enable more efficient use of the database, analysis of individual influencing factors, improvement techniques, possibilities of preventing their destruction and searching for variant solutions in all phases of design and construction development.

5. Measures to prevent damage and fracture

By analyzing the damage and breakage of the responsible parts and elements of the supporting structures, the causes that lead to the destruction are determined and it is possible to make a decision on the exclusion of a specific technical solution or failure prevention measure, Figure 5.

Fig. 4. The database structure for vital welded structures of bucket-wheel excavators

The decision to exclude a specific technical solution implies the development of a new optimal structural solution, as well, whereby the loads are varying in different operating modes, dimensions of parts and elements of supporting structures, forms of welded joints, types of materials, procedures and quality of production. Changing the character of the load to comply with the exploitation conditions consists of experimentally determining the working loads of the responsible parts and elements of the supporting structures and changing the structural solution or in determining the working conditions and load regime for the reliable operation of a specific technical solution.

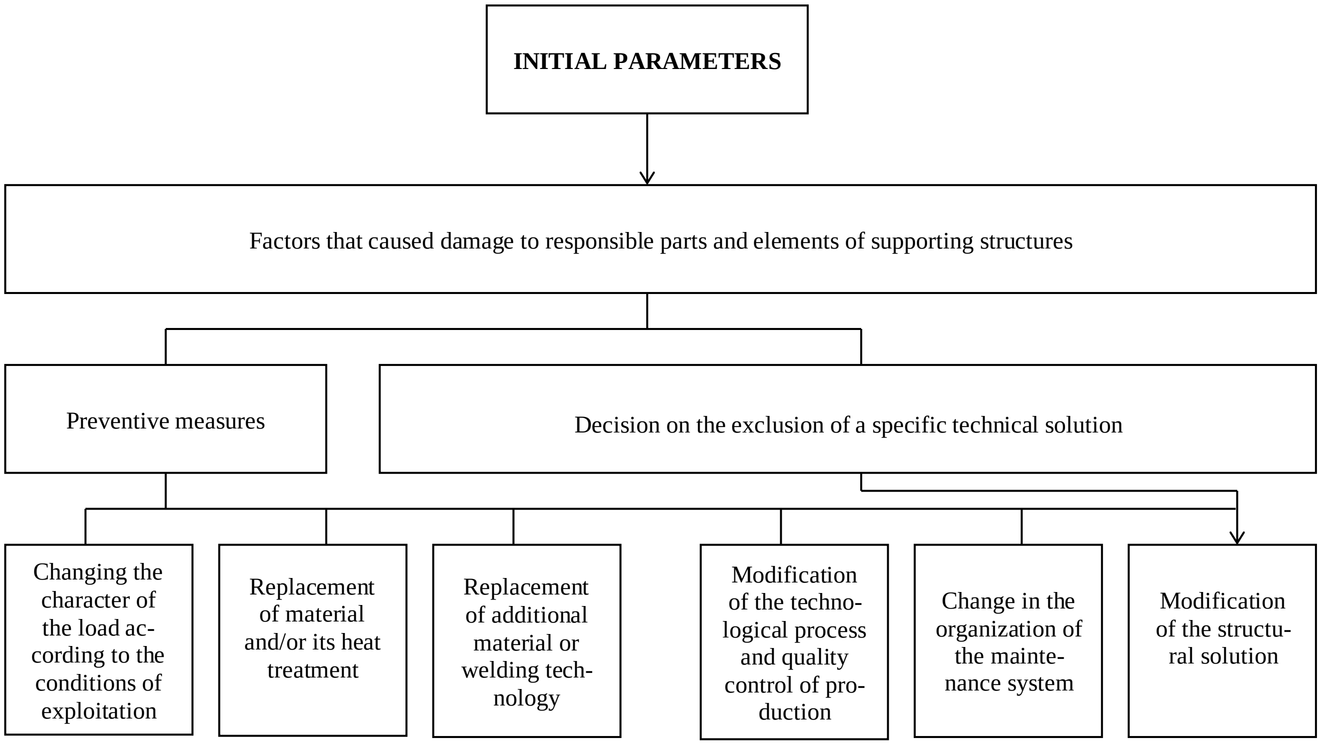

Fig. 5. Measures to prevent failures

The change in the production technological process consists of the search for different shapes and dimensions of parts and elements of supporting structures, welding procedures, base material and heat treatment procedures.

Considering that the mentioned measures to prevent damage and fracture represent complex and expensive solutions to increase the safety of responsible parts and elements of supporting structures, in recent years many eminent world institutes have carried out extensive experimental research to find techniques and methods for simpler and cheaper improvement of static and fatigue characteristics of parts and structural elements.

6. Model of the organizational system for the rotary excavators' maintenance

The continuous technological process of excavation, transport and disposal of tailings and depositing of coal is realized by the compact ECS complexes. A compact ECS system consisting of a rotary excavator, a conveyor with a rubber belt and a dumper, requires a special organization of the maintenance system. The organization of the rotor excavator maintenance system depends primarily on its size, shape and construction, the number of employees, the experience of experts and appropriate databases from the maintenance and testing of previous power units and supporting structures of different types of excavators.

Based on the conducted research and the author's own experience in the ECS system maintenance, Figure 6 shows the proposed organizational model of the rotor excavator maintenance system.

7. Conclusions

Premature damage or fracture of parts and structural elements of rotary excavators is caused by the simultaneous influence of a large number of technological - metallurgical, construction and exploitation factors. That is why the optimal structural solutions, which would ensure the operational safety of parts and the integrity of structures, can only be realized only with complete knowledge of their behavior in different operating regimes.

The fault tree analysis and the FMEA analysis enabled creating the preventive measures to eliminate the ECS system failures. The bottom line is that the events that directly disrupt the considered function, as well as the logical interdependence of those events, have been identified.

Analyzing the failure modes and effects of the ECS's subsystems using the FMEA method as a method of qualitative and quantitative reliability analysis of the components of technological subsystems, it is shown that it can be successfully used in all the phases of ECS subsystems' life cycle. The same applies for the preventive analysis of all the potential failures of elements and their effects.

A quick and reliable solution to the problem of the responsible parts and elements of the supporting structures can only be achieved by creating a database and the basis for the development of computer programs. Accompanying software packages could enable more efficient use of databases, analysis of certain influential factors, improvement techniques, possibilities of preventing the parts' fractures and destruction, as well as searching for alternative solutions in all the phases of design and development of rotor excavator constructions.

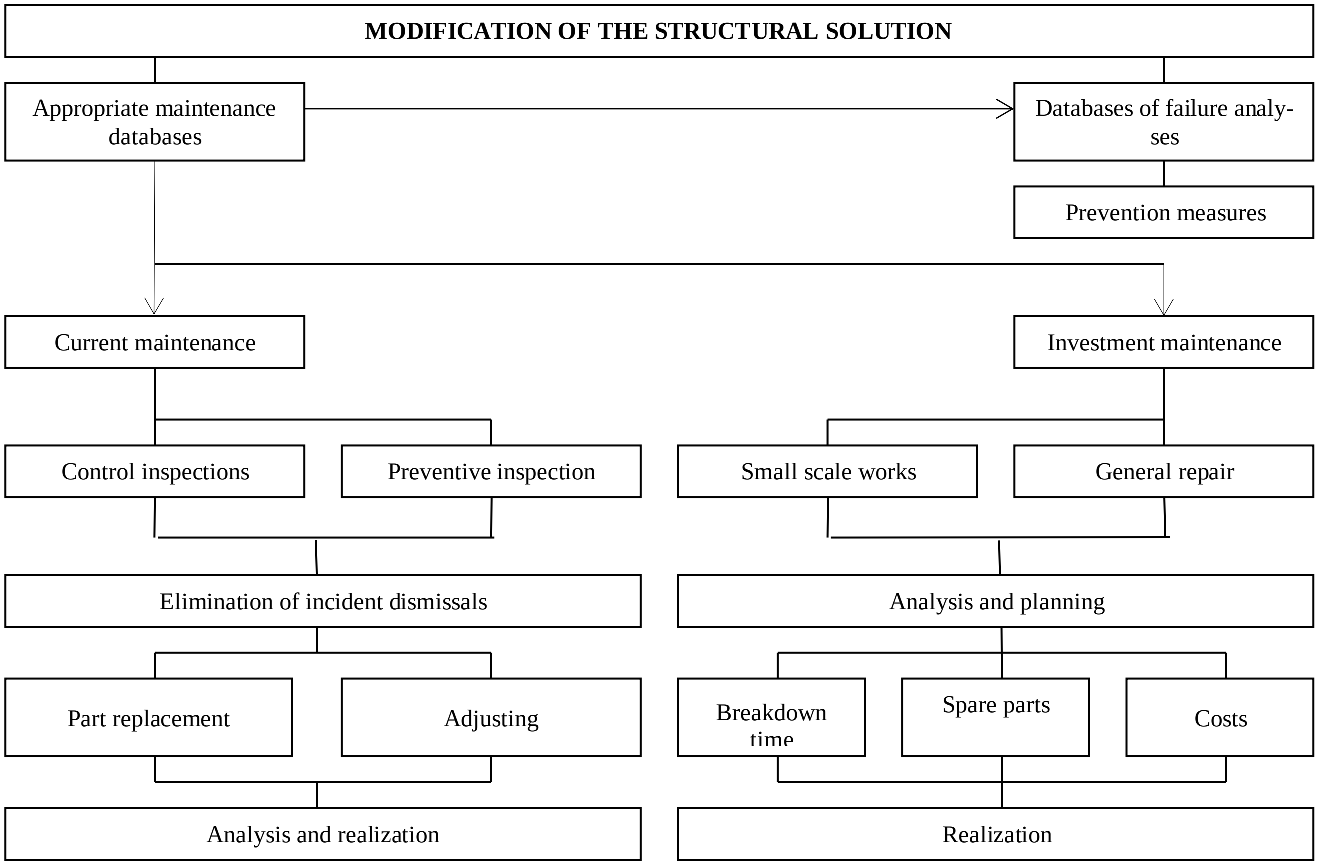

Fig. 6. Model of the organizational system of maintenance of rotary excavators

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Conflicts of interest

The authors declare that they have no known financial or personal conflicts of interest that could influence the work reported in this paper. Furthermore, all listed authors have reviewed and approved the final version of the manuscript.

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