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CHANGES IN OPERATING TIME OF MODERN DOMESTIC EKG EXCAVATORS IN DEPENDENCE OF THEIR FUNCTIONING CONDITIONS

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Domestically produced opencast excavators are shown to be serious competition for foreign hydraulic machinery. It is suggested to estimate the potential of an opencast excavator via its basic operation effectiveness factor equal to the ratio of the scoop payload to the nominal cost of excavator operations under its normal operational conditions. Comparing the theoretical values of standard operations of hydraulic excavators of the third type-and-size group during coal mining with domestically produced EKG-18R on their operation effectiveness factor shows that the excavator exceeds foreign hydraulic models from that group 2.7-3.3 times.

Theoretical foundation is provided for a complex of factors that affect the operating time of single scoop opencast excavators, a structure is offered for the model of comprehensive assessment of operating time for opencast excavators. Complex indicators are substantiated and proposed for supporting operational effectiveness of such excavators. Assessment is offered of operational effectiveness of EKG-18R excavators following the criterion of energy consumption per excavation of a unit of rock mass. Generalization analysis is given of a set of factors that affect the value of operating time for EKG-18R excavators. Proposals are put forward on upgrading the regulations for technical maintenance and repairs of EKG-18R excavators.

The task of assessing the technical state of machinery calls for using integral criteria that would enable one to identify the current technical state and the residual resource of machine aggregates, their failure potentially resulting in emergency situations accompanied by considerable property damage. It is feasible to use an integrated indicator of the degree of degradation of s machinery item for such an integrated indicator, retrieved in the course of assessing the current technical state of that item during diagnostic procedures. In its turn, such and integral indicator of the state of an item is defined by the averaged value of diagnostic indicators reduced to their basic values with the account of their individual weight factors.

Key words: opencast excavator; resource; operating time; potential usage factor; operation effectiveness factor; reliability; simulation.

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Introduction. Build-up in the amount of opencast mining of solid mineral resources depends on the effectiveness of operations of modern cyclic and cycle flow complexes of single-scoop opencast machines. Currently the Russian Federation has about 180 mechanical shovels of domestic production operating, manufactured by the «KARTEX» and «UZTM» plants, their scoops of 12-32 m^3, plus about 20 excavators with scoops of 35-55 m^3 belonging to approximately 300 hydraulic opencast excavators with scoops of 12-45 m^3 by the Komatsu Mining Germany (KMG), Liebherr, Hitachi, Caterpillar, P&H and Taiyuan HM Group [8, 10, 11].

The autonomous nature and maneuverability of opencast excavators results in their efficient applicability to complex operational conditions in front of the stall, facing a wide variety of features of both the mined resources and waste rock excavated. Assessing the functional and technological capabilities of excavators using electric and hydraulic drives indicates that their basic parameters are quite comparable [8]. In actual operation conditions of opencast mining technology concentrating such machinery in the immediate vicinity of their operation zones leads to perturbations in operation rhythm of both the excavators themselves and technological transportation vehicles that works to transport the excavated rock mass from the stall further down the implemented technology chain. Such a situation results from lack of balance between the organizational and technical activities on the one hand and the actual operations on the other, featuring numerous varying situations of the moment.

Hydraulic excavators are mostly used in tight stall situations while developing a opencast when the height of the stall is limited by the reach of excavator scooping. Joining the arm with the excavator beam with a ball joint enables reducing the scooping radius of a hydraulic excavator, so such excavators are positioned closer to the cliff wall, thus providing more maneuvering space on the one hand, but undermining the safety of operations on the other, as compared to cable operations.

The advantage of electrically driven excavators over hydraulic machines consists in robustness of relatively simple well-tested electric motors and steel cables compared to hydraulic cylinders of more complex design. Servicing and maintaining electric excavators does not require any advanced experts in hydraulic systems, which reflects noticeably in the rate of maintenance and repair works.

Market economy puts forward effectiveness as the primary criterion, so it is suggested to estimate the potential of an opencast excavator via its basic operation effectiveness factor equal to the ratio of payload in the scoop to the nominal expense on excavator operations under its normal operational conditions [3]. When comparing the excavators according to the proposed operation effectiveness factor preference should be given to models with its highest value. Comparing such indicators one may conclude that modern cable excavators of the EKG line of Russian make are capable to compete with excavators of foreign make under equal operational conditions. Modern electric EKG opencast excavator lags behind the EG-150 excavator by 40 % and exceeds the RS8000-6 excavator by 20 % [8].

Comparing the basic operation effectiveness factor of the excavator with a machine similar in its actual loaded mass of rock mass over the estimated period and the actual cost of energy consumed by the excavator (for a hydraulic excavator that would be its fuel cost), it is easy to assess ineffectiveness of excavator operations in any specific operational conditions and identify its weak points [8, 17]. Comparing the theoretical values of standard operations of hydraulic excavators of the third type-and-size group, their scoop capacity being 21-22 m^3 (CAT6040, Komatsu PC4000, Hitachi Ex3600, Libherr9400) during coal mining with the domestically produced EKG-18R on their operation effectiveness factor shows that the EKG excavator exceeds noticeably foreign hydraulic models. The usage factor for domestic model is 1.82, which is 2.7-3.3 times better than that for hydraulic excavators of group three [8].

Disagreement between the operational conditions and standard output rates (SOR) results in significant deviation of excavator operating time from its nominal value, intensifies machinery degradation processes that lead to accelerated shrinking of residual resource of excavators' units and aggregates, so that the number of downs grows, complexity and labor intensity of repair works grows and self-costs of rock mass excavation increases.

Despite numerous theoretical and experimental studies [4-7, 9] in improving the effectiveness of operation of modern opencast excavators, their design features and operation modes and conditions are far from being accounted in full considering the technical state of machinery and the system of technical maintenance and repairs used . To assess reliability of opencast excavators and the effectiveness of their operations they often tend to use non-standardized indicators, that are not always objective since clear objective criteria are lacking to account for machine idle time, making the task of comprehensive assessment of factors controlling the operating time and operational effectiveness of opencast excavators especially topical against the development of a new line of EKG type excavators [1]. Excavators of the new product line by «P.G.Korobkov IZ-KARTEX» LLC meet modern ergonomic requirements and safety regulations in mining. One of the type-sizes of new excavators in high demand is EKG-18R/20K. In its technical characteristics it competes successfully with foreign excavator models in the range of scoop payload of 35-40 t [1, 2, 13]. Consider factors that affect the operations of electric opencast excavators in more detail.

Comprehensive operating time assessment model for opencast excavators. Going by the analysis of scientific and methodological base used to assess and provide for operation effectiveness and technical state of opencast excavators in dependence of conditions and modes of their operations, factors are identified and classified that affect productivity of opencast excavators of cyclic operation [15, 16]. According to the classification offered such factors are split into six basic groups: 1 – mining geological and technical factors; 2 – climate factors; 3 – quality of stall and rock mass preparation ; 4 – excavator management; 5 – technical state of the excavator; 6 – organization of mining operations.

Building a model of comprehensive assessment of operating time for opencast excavator of cyclic functioning is explained by the need to obtain objective comprehensive assessment of effectiveness of excavator use as a piece of equipment of specific application (which has a single basic purpose) working in certain conditions and operational modes that undergoes certain technical maintenance and storage procedures. Such an assessment is carried out against the normal (basic or standard) conditions and operational modes, in application to which the excavator is designed. Following such comparative assessment a forecast is generated of changes in the technical state of the machinery, its operating time and/or residual excavator resource with the account of possible negative effect of those factors that deplete its operational capabilities and of optimizing the system of technical maintenance. Extensive methodology material available from freely accessible sources was used as study basis.

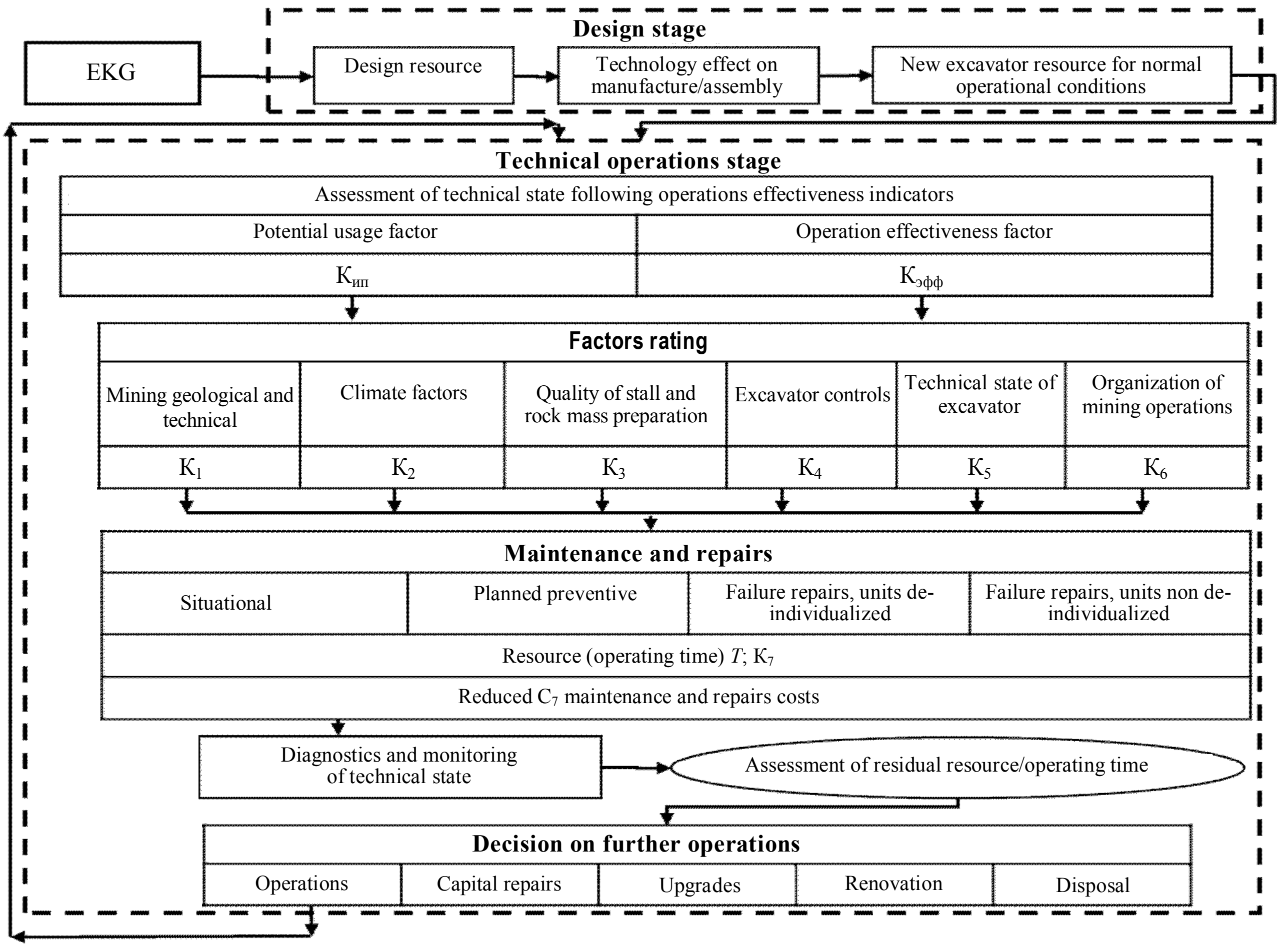

Fig. 1. Model structure for assessing excavator operating time

The structure of the model for assessment of operating time of opencast excavator (Fig.1) describes changes of the operating time in dependence of the listed groups of factors in the course of operating the excavator [3, 17]. This model is an instrument enabling one to assess the intensity of spending the resource of a given excavator in the course of its operations; that model is used correctly to treat the excavator as a single piece of technology and to analyze separate elements and systems of such mining machine. The nomenclature of blocks in the analogue information model complies with the sequence of members in the series of simple numbers.

The initial assumption is that during the project design stage the machine design resource is stipulated that corresponds to the excavator service life under the normal operational conditions, defined by its parameters and construction specifics. Namely, for opencast excavators of EKG-10 and EKG-15 types their design service life for normal operational conditions is 17 years with two overhaul repair sessions. Meanwhile service life of excavators of new product line (EKG-12K, EKG-32PR, EKG-18R/20K) is 20 years operational with a single overhaul repairs session. Note that the manufacturer plant warrants operating time for their main drive reducers of 65-75 thousand .machine-hours which is equivalent to 10 operational years to capital repairs.

Effect of manufacturing and assembly technology depletes design resource of excavator units and elements. Such effect may vary considerably in dependence of manufacturing and assembly quality and may result in resource dropping by 90% of its nominal value.

In the course of the study it was found that operational effectiveness and functionality of opencast excavators at mining enterprises of the RF and CIS are often assessed via the technical readiness factor $К_{тг}$ and equipment usage factor $К_{ио}$ which are both subjective and do not belong to the nomenclature of standardized indicators [3]. Techniques of their assessment vary strongly from enterprise to enterprise.

E.g., the values of technical readiness factor for EKG-18R excavators (Figs. 2 and 3) remain practically unchanged for the conditions found at «UK «Kuzbassrazrezugol» OJSC. The value of *X*- ineffectiveness (deviation of the actual indicator from its basic value) is 2-3 % when these factors are used. Therefore, employing the factor $К_{тг}$ as an indicator of the actual state of the machine and of its opera-

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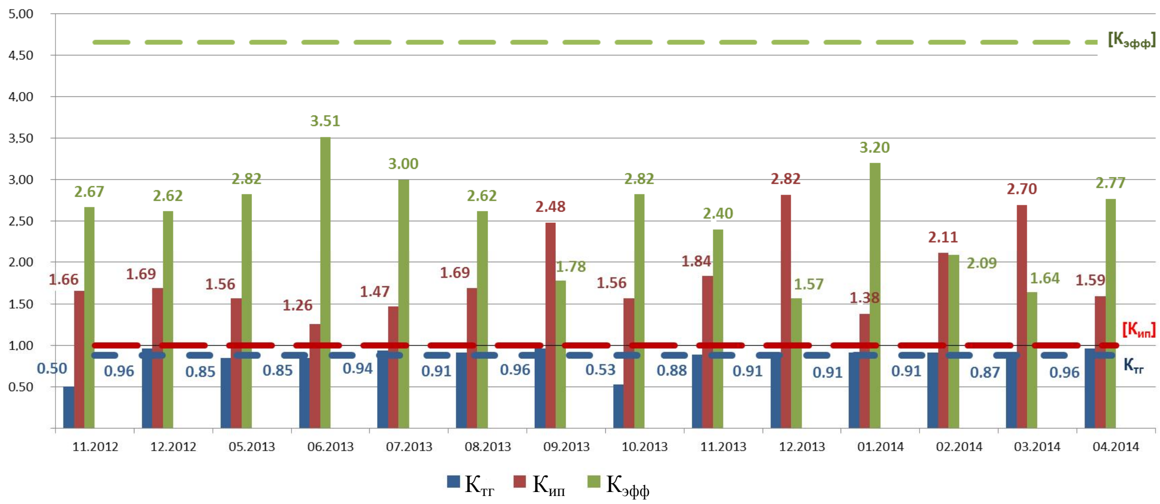

Fig. 2. The actual values of technical readiness factor, potential usage factor, operation effectiveness factor and their theoretical basic values for EKG-18R N1 excavator

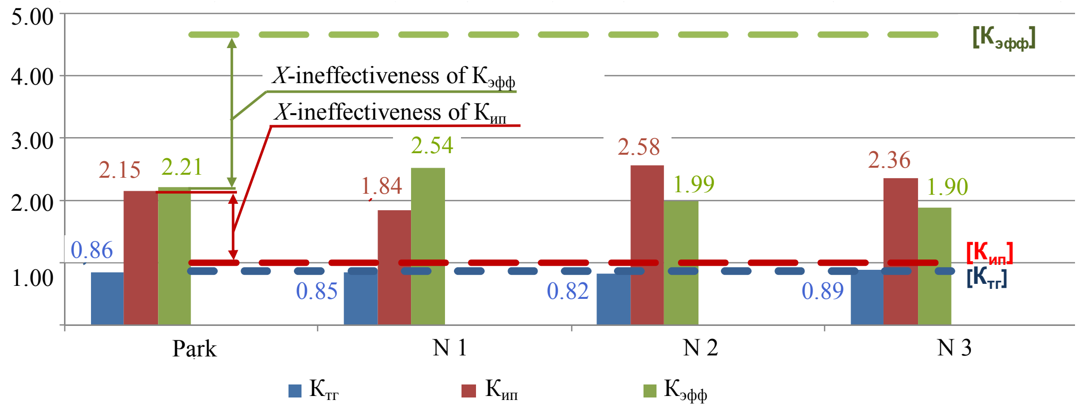

Fig. 3. Mean values of the technical readiness factor, potential usage factor, operation effectiveness factor and their theoretical basic values

tional effectiveness is not feasible, since its reaction to changes in the external conditions and the internal processes remains minimal due to high inertia.

To remove such contradictions it is suggested to assess the effectiveness of operation of opencast excavators using the following indicators: the potential usage factor, $К_{ип}$ and the operation effectiveness factor, $К_{эфф}$, which enable one to assess reliability, serviceability and durability of the item.

The potential usage factor for excavator, $К_{ип}$ is given by the ratio of specific actually spent work to that basic for the given type of excavator, as given by expression [3]:

$$К_{ип} = \frac{W_{\mathbf{o}} Q_{ф}^{-1}}{[W_{о.н}] P_{ayload}^{-1}}, \tag{1}$$

where $W_о$ is the actual electric energy spent, yielded by the excavator power meter, kW hr; $[W_{о.н.}]$ is the nominal electric energy spent by the excavator under the normal operational conditions, per cycle, kW hr; $Q_ф$ is the actual rock mass loaded over the estimated period, t; P_{ayload} – scoop payload.

To assess non-productive operational time losses for excavators an indicator is proposed equal to the ratio of cumulative operating time of excavator to the respective energy consumption over the same calendar interval: the operation effectiveness factor, given by the expression:

$$К_{эфф} = \frac{Q_ф}{W_о}. \tag{2}$$

The *X*-ineffectiveness of $К_{эфф}$ factor when energy consumption is monitored shall be assessed by its deviation from the basic value given by the ratio of the excavator scoop payload to theoretical nominal electric energy consumption.

The theoretical value of the nominal energy consumption over a single excavation cycle is defined from the example of opencast caterpillar excavator EKG-18R/20K as the result of analyzing cycle diagrams of its main drives with the account of energy consumption for the excavator own needs, yielding a figure of 8.61 kW hr. The nominal electric energy consumption per cycle, yielded by theoretical studies correlates with the results of experimental assessment of energy consumption by the excavator drive in conditionally nominal operational situation, undertaken by the designer of that electric drive for the EKG-18R excavator («Obyedinyonnaya Energia» (United Energy) Company).

Experimentally the effectiveness of operation of opencast excavators EKG-18R/20K NN 1, 2 and 3 was assessed using the suggested factors under the production conditions of «UK «Kuzbassrazrezugol». The values of actual energy consumption were taken from the readings of the standard information diagnostics system, and the excavator operating time was taken from the information reported by coal opencasts.

The actual values of $К_{ип}$ and $К_{эфф}$ (see Figs. 2 and 3) are highly dynamic with the actual operational conditions changing, which testifies to their high response to external changes. Going by the deviation of $К_{ип}$ and $К_{эфф}$ from their theoretical basic values (the red and green dotted lines, respectively) one may assess the value *X*-ineffectiveness of excavator operations. The objective nature of assessments using the proposed effectiveness retention factors is guaranteed by the data from dispatching service on the excavators operating time and monitoring of energy consumption by the standard information diagnostic system [3].

Theoretical basic values of the factors $К_{эфф}$ and $К_{ип}$ for the EKG-18R/20K excavator functioning under the normal operational conditions are set at 4.61 t/kW hr and 1, respectively.

It is found that the average deviation of actual values of the proposed factors from their theoretical (basic) values over the pool of EKG-18R excavators reaches about 2.2. Therefore, the *X*-ineffectiveness of operation of the considered excavators in relative terms is 110 %, which characterizes their use as ineffective.

Such an approach may be used for assessing the level of effectiveness of operating hydraulic excavators by their diesel fuel consumption. In that case the factor of potential usage acquires the form

$$К_{ип} = \frac{Э_ф (Q_ф)^{-1}}{[Э] P_{ayload}^{-1}} = \frac{q_ф q_е^{-1} 10^3}{[Э] P_{ayload}^{-1}}, \qquad (3)$$

where $Э_ф$ is the actual energy consumption, kW hr; $Q_ф$ is the actual operating time of the excavator over the considered calendar period, t; [Э] is the theoretical energy consumption under the nominal operational conditions, kW hr; P_{ayload} is the scoop payload, t; $q_ф$ is the actual consumption of diesel fuel by the hydraulic excavator, kg/t; $q_е$ is specific fuel consumption by the engine, g/kW hr.

Thus assessing the operational effectiveness of excavators according to proposed indicators , namely the potential usage factor and the factor of operation effectiveness is the one most objective and reliable, while also corresponding to the nomenclature of comprehensive reliability indicators.

Implementing the assessment of operating time for opencast excavators. The initial data for the designed model (see Fig. 1) are: the excavator scoop payload, P_{ayload}, t; service life to repairs/post-repairs, years, *Y*; machinist's work experience, *S*, years; the actual usage of calendar time fund, $К_{фкв}$. The theoretical basic value of excavator operating time under the normal operational conditions $[Q_{год}]$ is defined as the annual operational productivity [3].

The excavator annual operating time for any period of its service life is given by the suggested expression with the account of its service to/past capital repairs

$$Q_{год\,Y} = [Q_{год}](6 \cdot 10^{-4} Y - 5 \cdot 10^{-4} Y^2 + 1). \qquad (4)$$

It is suggested to assess the nominal operational term to capital repairs, $T_{кр}$, retrieved with the account of V.I.Rusikhin's formula, using the expression:

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$$T_{\text{кр}} = \frac{1{,}75(1{,}7P_{ayload} - 18)}{[Q_{\text{год}}]}. \quad (5)$$

The excavator annual operating time in actual operational conditions, $Q_{\text{год}}$ is defined as the product of the basic value of that operating time and the set of operational conditions consisting of the indicators $К_1$-$К_6$., $К_7$, as per blocks 5 and 7 of the algorithm (see Fig. 1) which characterize the change of operating time in dependence of its affecting factors.

E.g., $К_1$ fixes changes in the operational conditions and characterizes the effect of mining geological and technical conditions, in particular the types of rocks according to the difficulty of excavating them, while rocks of Cat III are considered normal (basic). When assessing the climatic factors ($К_2$) one needs to account for the agreement of the climatic version of opencast excavator and its outfitting to the actual climatic conditions of its operation. One needs to consider its effect on the excavator machinist (operator) first and foremost, not the machine alone. In case the climatic version of opencast excavator to the conditions of its operation, plus additional comfortable environment for the machinist, $К_2 = 1$. In case the machinist's environment is uncomfortable, any deviations from the normal conditions would automatically downgrade his/her qualification one step.

The indicator $К_3$ characterizing the quality of stall and rock mass preparation is given by the ratio of excavator operating time to its basic value for normal conditions, equal to: 1.0 («Good»); 0.5 («Satisfactory»); 0.15 («Unsatisfactory»).

The «excavator management» group of factors is described by the indicator $К_4$. The reduced number of loading cycles for excavator machinists with work experience in excess of 10 years is taken for unit. The fact is taken into account that the machinist's qualification is raised with time so that change in the excavator operating time is presented by a broken line (Fig.4). In case the excavator is continuously managed by machinists with less than one year of experience (a training excavator) its service life is reduced to 6 years.

Assessing the $К_5$ indicator. «The excavator technical state» follows the effect of OEM and no-name spares used for excavator repairs. The estimate of $К_5$ is only done going by the excavator main units that affect its functionality and is taken as: 0.2 for non-name spares; 0.7 for the combined OEM and no-name spares; 1 for the OEM spares.

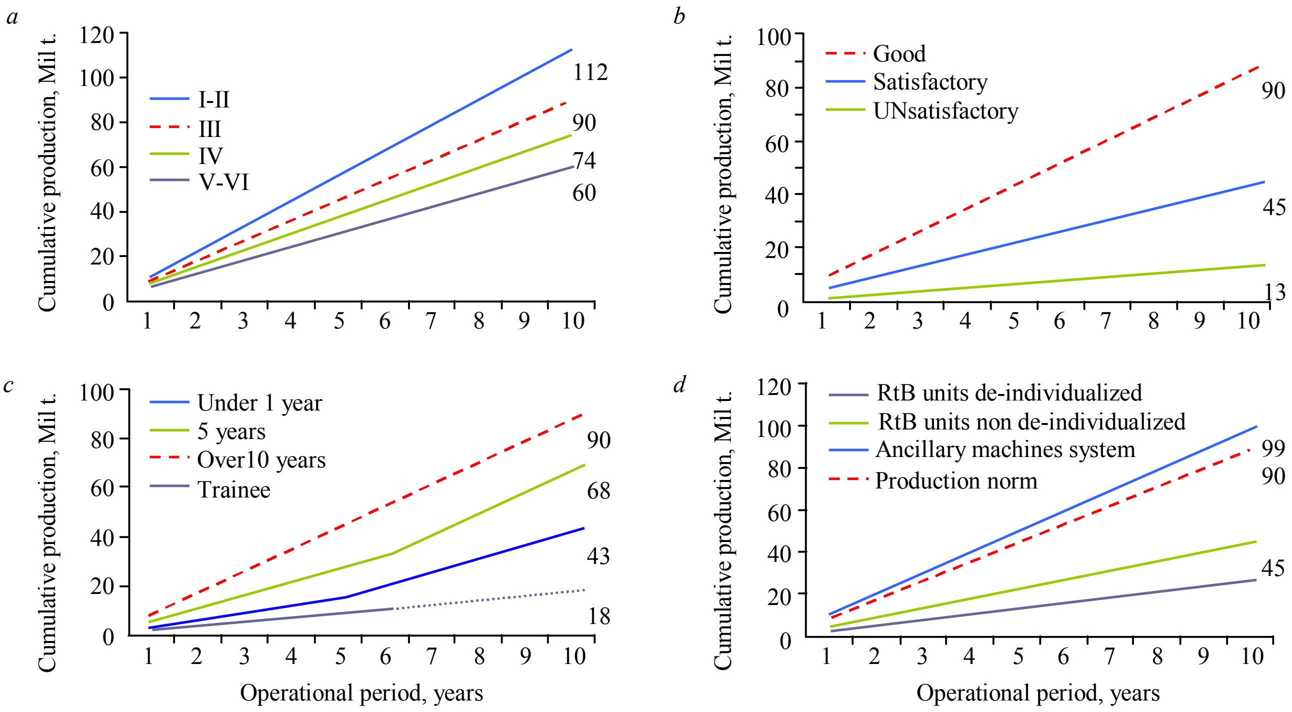

Fig. 4. Change of operating time to capital repairs for EKG-18R/20K excavators in dependence of external conditions (dotted line shows the operating time for basic conditions): *a* – mining geology and technology factors; *b* – quality of stall and rock mass preparation; *c* – excavator management; *d* – maintenance and repairs system

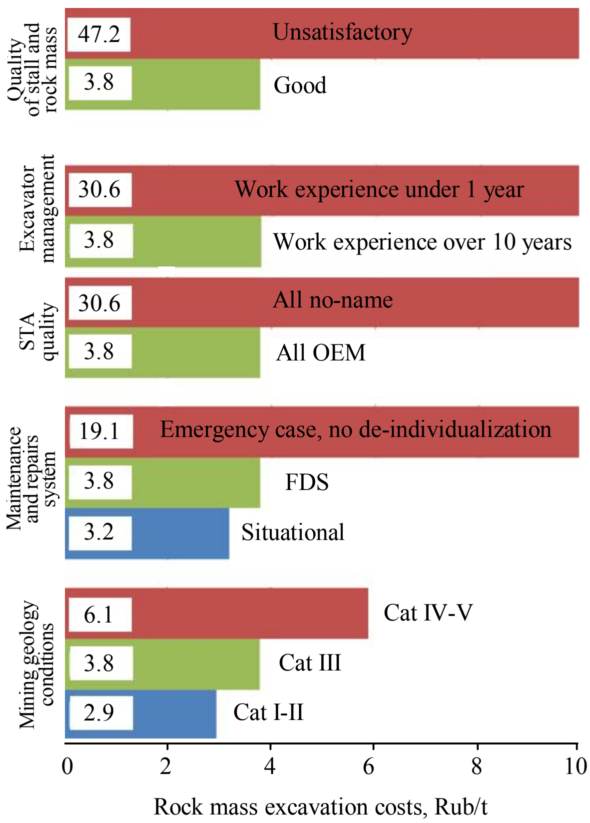

Fig.5. Rock mass excavation costs by EKG-18R/20K excavator for unit change in influencing factors

The effect of the factor «Organization of mining operations», hence the value of the indicator K_6 is defined by the value of deviation of the ratio of the actual factor of calendar time fund use to its basic value equal to 0.6.

Indicator K_7 that characterizes maintenance and repairs system is defined as a ratio of the annual operating time of opencast excavator for a maintenance and repairs system different from the basic one to operating time from the basic approach to technical maintenance and repairs of opencast excavators (regulation maintenance and repairs).

Changes in operating time to capital repairs were estimated for an EKG-18R/20K excavator when predetermined changes were introduced to each of the acting factors separately to identify the degree of such influence on changes in the operating time .

Changes in the cumulative operating time to capital repairs for the EKG-18R/20K excavator in dependence of the most influential factors are shown in Figs. 4 *a*, *b*, *c*, *d*. The value of operating time under normal conditions is indicated by the dotted line; it makes $90 \cdot 10^6$ t.

According to modeling results the degree of influence of separate factors affecting the operation of opencast excavators goes in the following order: stall and rock mass preparation quality (32 %), excavator management (29 %), technical state of the excavator (27 %) and mining geology and technology factors(12 %). Modeling results agree with expert assessment of the effect of these factors on excavators operating time.

Assessment of self-costs of excavating rock mas by EKG-18R/20K excavators after changing these influence factors by a unit is presented in Fig.5. The maximum increase in self-costs of excavation after deviating just a single factor from the normal (basic) conditions, namely the «Quality of stall and rock mass preparation» results in a growth of self-costs by a factor of 12.4.

Having linked external conditions and internal processes to changes in excavator operating time to capital repairs, we designed a technique to assess substantiated amount of spares and materials necessary for an opencast excavator over its service life, plus an algorithm for adjusting the timetable of opencast excavators service and maintenance jobs and repairs according to their actual state. Updating the rate of consumption of excavator resources is done employing the proposed measures of technical diagnostics within the scope of planned maintenance and expanding the capabilities of the standard information diagnostics system with functions of acoustic emission, vibrocoustics and vibro-monitoring.

Currently the task of assessing the technical state of complex systems requires using integral criteria that are capable of identifying the current technical state of the system and the residual resource of its machines, aggregates, etc., their failure bringing emergency situations that may be accompanied by considerable property damage. Form our point of view it is feasible to select some generalized indicator integrating the results of comprehensive assessment of the current technical state of the object, carried out in the course of diagnostic procedures which has the state of the item via expression (6) [12]

$$\Delta = 1 - Q, \qquad (6)$$

where Δ is the degree of object deterioration; Q is the integral indicator of object state.

In its turn, the integral indicator of the state of object is defined by the averaged value of unit diagnostic indicators reduced to the basic value of such integral indicator with the account of their weights

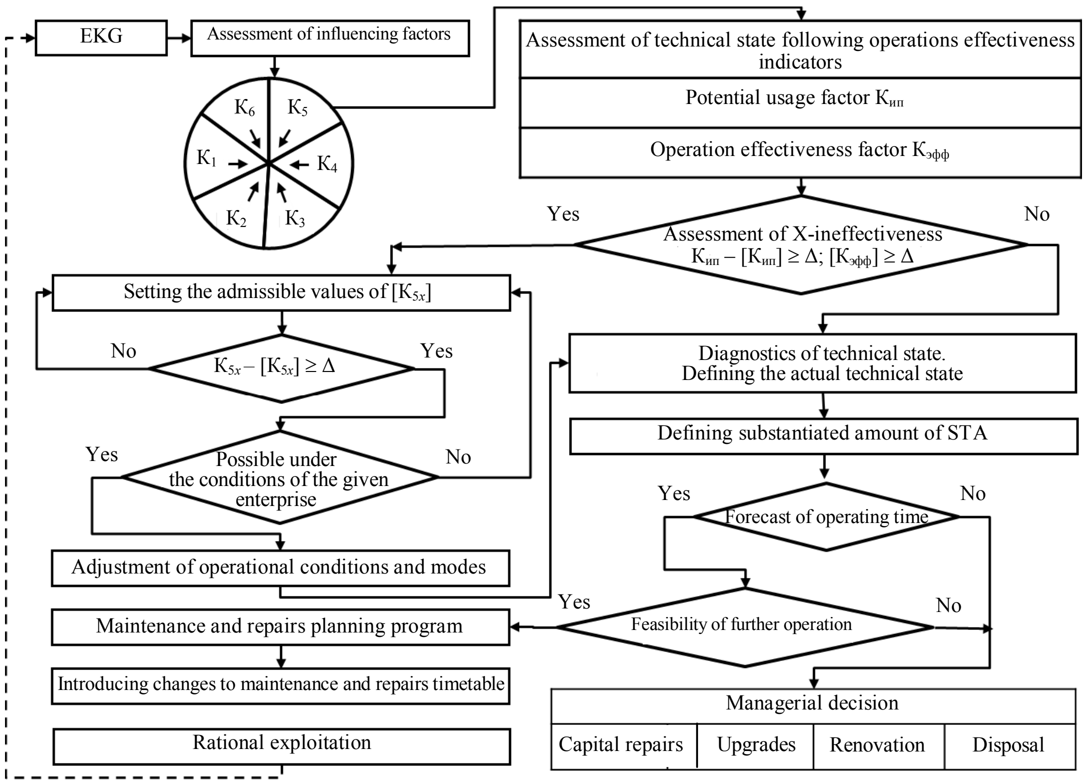

Fig. 6. Excavator functionality assessment algorithm

$$Q = N^{-1} \sum_{i=1}^{N} \frac{[q]_i}{q_i} \alpha_i , \qquad (7)$$

where q_i is the value of the i-th unit indicator, retrieved from diagnostic procedures; $[q]_i$ is the basic value of the i-th unit diagnostic indicator corresponding to the new object; N is the total number of diagnostic indicators; α_i is the weighting factor of the i-th indicator. Note that the sum of all the α_i is equal to unit. For unitary indicators one should take vibration and noise levels, temperature readings from the equipment, acoustic emission signals by the machinery, voltage and current characteristics of the driving electric motors, running time to full stop and some others.

The algorithm was developed for assessing excavator functionality (Fig.6), according to which factors are estimated from the list of K_{5x} plus the X-ineffectiveness factor during the excavator operation [14, 17]. Meanwhile limit values are prescribed for K_{5x} and the maximum acceptable value of X-ineffectiveness, which correspond to the actual operational conditions. Following the comparison of the actual values of these factors with those preset, organizational and technical decisions are adopted to adjust and correct excavator operation conditions and modes.

Thus the conditions are provided for rational excavator operations, after which the list of maintenance and repairs activities is drawn for the adjusted conditions of its operation. The set of activities on assessing and adjusting the operational conditions and modes is repeated upon a preset time interval . Upon the excavator reaching its limit state a decision is taken on capital repairs, upgrades, renovation or disposal of the machine.

Conclusions. Domestically produced opencast Excavators of the new product line by «P.G.Korobkov IZ-KARTEX» LLC meet modern ergonomic requirements and safety regulations in mining and compete with foreign made hydraulic excavators on a par basis. Moreover, the usage factor for domestic model is 2.7-3.3 times better than that for hydraulic excavators of similar capacity.

To improve reliability of assessing the effectiveness of operating opencast excavators is suggested to stop using non-standardized indicators, and employ the factors of effectiveness retention: $K_{ип}$ and $K_{эфф}$ which define the X-ineffectiveness of operating opencast excavators following the criterion of complete use of excavator potential. The suggested comprehensive indicators assess reliability and durability of the excavator as a system.

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Using experimental data on energy consumption, the factor of its potential use, $К_{ип}$ and operation effectiveness, $К_{эфф}$ for EKG-18R excavators under the production conditions of «UK «Kuzbassrazrezugol» OJSC the value of *X*-ineffectiveness was estimated, making 110 % on the average over the excavator pool, which characterizes the excavators operation as ineffective.

Comprehensive assessment of acting factors showed that the ones most influential for operating time of opencast EKG-18R excavators are: the quality of stall and rock mass preparation , excavator management, technical state of the excavator and mining geology and technology factors. The results obtained correlate with expert assessments while the effect of a single such factor may reduce the operating time of an EKG-18R excavator by 85 % increasing the cost of excavating rock mass 12.4 times.

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