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ВЪРХУ АНАЛИЗЪТ И ОПТИМИЗИРАНЕТО НА ЕКСПЛОАТАЦИОННИТЕ РАЗХОДИ ПРИ ИЗПОЛЗВАНЕ НА МАШИНИ ЗА ЗЕМНИ РАБОТИ НА СТРОИТЕЛНИ ОБЕКТИ

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ABOUT ANALYSIS AND OPTIMIZATION OF OPERATIONAL COSTS BY USING EARTH-MOVING MACHINERY AT CONSTRUCTION SITES

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Abstract:
Along with modern requirements for sustainable construction, there is also a need for optimization of all resources invested in construction. This requires a detailed assessment of the operational costs of machinery used on construction site. An essential point is the relationship between the level of technical ageing of machine (including worked machine hours) and the level of operational costs generated for its maintenance in workable technical condition (repair and maintenance costs). The current paper presents a structure of operational costs and repair and maintenance costs for construction machinery, as well as the different types of factors affecting the costs and level of technical ageing of earth-moving machinery. The relationship and model that express the interrelationship between the level of technical ageing and operational costs are examined. Particular attention is paid to the stage of machine's lifecycle (the point in time) at which it is recommended that additional engineering measures (preventive maintenance of machine or sale of machine to the secondary market) be taken by construction managers in order to optimize the further costs of repair and maintenance of the machinery park of construction company. On the basis of the analyses carried out, relevant conclusions related to the analysis and optimization of generated operational costs when using machines for earthworks on construction sites are formulated.

Keywords:
Construction machinery, Operational costs, Repair and maintenance, Level of technical ageing, Worked machine hours, Optimization

1. INTRODUCTION

The execution of construction processes involves the use of many and different types of resources – personnel, machines, materials, financial means, etc. Construction machinery costs represent a huge item (large share) of the total cost mix of construction companies. Adequate and

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correct management of the machinery park is a difficult task, which is of key importance for the successful realization of construction projects. In order for construction company as a whole, and in particular the construction implementation processes, to be economically justified, efficient and competitive, it is necessary to pay special attention to the processes of purchasing new (or second-hand) construction machinery and the processes of resale (discarding or disposal) of already used second-hand construction machinery. Making an economically sound decision as to when exactly preventive maintenance (before a failure occurs) of construction machine or replacement of used machine with a new one should be undertaken is a major challenge not only for the construction managers who are directly responsible for the management of the machinery park, but also for the companies supplying the equipment (in cases where these companies undertake the further maintenance and repair of the equipment supplied by them). In the case of heavy construction machines (for example: loaders, excavators, bulldozers), in order to make an adequate decision on this issue, it is very important to have a preliminary assessment of the costs for repair and maintenance of machines, as well as an adequate assessment of the level of technical ageing (residual life) of machines. The economic life of construction machine is the period of time during which it is economically justified (profitable) for construction company to use/exploit the machine in question, and this period is different from the physical life of the machine. According to the development [1], the repair and maintenance costs are the most important influencing factor on which duration of the economic life of machine will depend. In the paper [2], 11 construction companies in the USA were surveyed about which established management decision-making method for machinery park management they used. Eight of the asked construction companies (out of total 11) answered that they use the "method of analysing the model/graph of change in the machine operational costs over time (the so-called "Life cycle cost analysis" method, LCCA model)". This gives reason to pay special attention to the analysis of operational costs of construction machinery (in general), as well as the costs of repair and maintenance of machines (in particular).

2. STRUCTURE OF OPERATIONAL COSTS AND REPAIR AND MAINTENANCE COSTS WHEN WORKING WITH CONSTRUCTION EQUIPMENT

The maintenance costs of construction machine should start to be generated as soon as the machine is put into service. The concept of "machine maintenance activities" is defined in Geraerds (1983) [3] and represents: "all activities that support the maintenance (or restoration) of machine in the necessary working technical condition, which is necessary for the performance of prescribed operational functions of machine". The maintenance of heavy construction machinery includes several heterogeneous activities, such as: preventive maintenance activities, routine repairs, tire replacement, etc.

Peurifoy (2006) [4] in his study noted that machine repair costs usually comprise the largest share of total machine operational costs (in general, machine repair costs reach approximately 40% of total operational costs for the entire service life of machine).

According to the development [5] in the accounting database of construction company, the operational costs for repair and maintenance of construction machine can be divided into the following parts:

- Costs for repairing the undercarriage of machine (includes costs for replacing bearings, joints, shock absorbers, pads);
- Costs for replacing worn tires (running wheels) of machine;
- Costs for replacing worn working implements of machine (bucket, blade, etc.);
- Costs for preventive maintenance of machine (periodic lubrication of rubbing parts with oil and grease, specialized examination of the condition of machine, periodic visual inspections of the technical condition, periodic oil sampling every 500 engine (motor) hours to check the presence of chips, etc.;

- Costs for other ongoing repairs of machine (includes costs for: spare parts, staff labor, subcontractor costs, costs for transporting the machine to a garage and others).

According to the development [5], construction company managers perform periodic machine maintenance activities at specific time intervals (engine hour meter reading intervals), which are usually multiples of 500 engine hours or 1000 engine hours. According to Mitchell (1998) [6] periodic maintenance activities of construction machine and/or collection of data on the current technical condition of machine can be carried out at the following intervals: during individual seasons of the year, semi-annual intervals, annually or every 500, 1000, 1500, 2000, 2500, 5000, 7500 and 10000 worked machine hours.

In the Table 1 below, exemplary information on the frequency of replacement of main components of a hydraulic crawler 20-ton single-bucket excavator is presented by approximate data (exact data is prescribed by the manufacturer in the technical documentation for each specific model of construction machinery).

Table 1. Exemplary information on the frequency of replacement of main components of a 20-ton hydraulic crawler single-bucket excavator by approximate data.

№	Component	Approximate worked machine hours during which the component in question is recommended to be replaced	Note
1.	Excavator main diesel engine	About 15000 engine hours	----------
2.	Hydraulic cylinders	About 5000 engine hours	Every 500 engine hours, oil samples are also taken from each of the hydraulic cylinders and tested in a laboratory.
3.	Distribution valves, hydraulic components, oil lines	About 5000 engine hours	----------
4.	Hydraulic units (hydraulic pumps, hydromotors)	About 12500 engine hours	Every 500 engine hours, oil samples are taken from each hydraulic unit and tested in a laboratory.
5.	Sprockets and track chain links of crawler undercarriage (does not include chassis)	About 10000 engine hours	The technical ageing of the crawler undercarriage is measured and controlled, at the idler wheel tensioner.
6.	Support-rotating device of the excavator	About 50000 engine hours	The technical ageing of the support-rotating device of the excavator and the backlashes (clearances) between the stationary and rotating parts are measured (controlled) periodically.
7.	Excavator undercarriage chassis	It is not replaced	It is not replaced, but can only be repaired (restored).
8.	Excavator rotating platform (together with cab and supporting structure).	It is not replaced	It is not replaced, but can only be repaired (restored).
9.	Joints of the working equipment (boom, arm, bucket)	There is usually no set value for engine hours	The technical ageing (backlashes) in the joints of the working equipment (boom, arm, bucket) of the excavator is measured and controlled periodically.

3. FACTORS AFFECTING THE TECHNICAL AGEING LEVEL OF CONSTRUCTION MACHINERY

Based on statistical data, it has been established that the level of total hourly operational costs (and hence the price per machine-hour rental) of construction machine will depend most strongly on the level of technical ageing (residual resource) of the machine [5].

In the development [5], accumulated statistical data from the sale prices/values of construction equipment – dump trucks in North America (Canada, USA and Mexico) in the period 2011-2015 were analyzed. In a similar way, in the development [7], accumulated statistical data from the sale prices/values of bulldozers model D39PX-21 were analyzed. The analysis of results obtained in both studies clearly shows that the physical ageing and residual resource (and hence the sale price/value) of construction equipment will be influenced not only by the calendar age and the readings of the machine's engine hour meter (worked machine hours), but also and the general technical condition in which construction machine is at the time of evaluation, i.e. whether the machine has been properly operated to date and whether it has been properly and regularly serviced and repaired during this period.

The most easily accessible, fast and authoritative information about the level of technical ageing (so-called "real age" or just "age") of construction machine can be obtained on the basis of the following four technical parameters: volume of work produced to date (applicable only to certain types of construction machinery); number of worked machine hours by the engine of machine (engine hour meter readings); mileage of machine in kilometers/odometer readings (applicable only to some types of construction machinery) and the calendar age of machine (in years and months).

For the purposes of the present development, it is assumed that relatively reliable information about the level of technical ageing of construction machines in general can be obtained based on the worked machine hours to date (readings of the engine hour meter, service meter – SM). Although the data on worked machine hours may be considered authoritative for the level of machine ageing over a certain long period of time, it should still be taken into account that there may be some momentary fluctuations (more drastic changes) in the level of technical ageing due to other additional influencing factors, such as: when the machine has been under heavy load/mode for very short periods of time, which "sudden momentary changes" could actually "mask" the real/actual trend of change in the level of technical ageing and hence the trend of maintenance costs.

4. FACTORS INFLUENCING THE LEVEL OF REPAIR AND MAINTENANCE COSTS

According to the data presented in the development [2], the greatest influence on the way of change (the model) of total operational costs of machine over time (the so-called "Life cycle cost analysis" method, LCCA model) is exerted by the following factors: initial purchase price of machine [BGN]; degree of loading/occupancy/utilization of machine within the year [machine hours/year]; the total expected service life of machine [machine hours]; machine repair and maintenance costs [BGN/machine-hour]; salary costs of machine operator [BGN/machine-hour]; relative engine fuel consumption [liters/kWh]. To a lesser extent, the following factors influence: machine lubrication costs, oil change costs, oil change interval [machine hours], tire price, tire maintenance cost, expected tire life [machine hours or kilometers] etc. In the LCCA model in the development [2], the following stochastic (random, changing) quantities are used, which influence the total operational costs of machine: fuel price per liter, residual resource of machine, repair and maintenance costs, cost of tires, tire replacement cost, annual machine load (in machine hours), engine load rating at work, etc. On the other hand, the following are used as deterministic (fixed, non-changing) inputs in the LCCA model in the development [2]: initial purchase price of machine, annual depreciation charges for machine, design service life/term of machine [in "machine hours" and in "years"], specific engine fuel consumption [liters/kWh]. The level of organization of contractor company and its policy will also have an additional influence on the total operational costs of machine.

In the development [8], an analysis of various factors that influence the level of total absolute annual costs of repair and maintenance of machine, as well as their weighting factors (importance), was carried out. The following results were obtained: worked machine hours within the year – 60,3% influence on the level of total absolute annual costs for repair and maintenance of machine; calendar age (technical ageing level) of machine – 28,2% influence on the level of total absolute annual costs for repair and maintenance of machine; reliability and quality of production (manufacturer) of machine – 9,3% influence on the level of total absolute annual costs for repair and maintenance of machine; volume of preventive maintenance services performed on machine – 2,2% impact on the level of total absolute annual costs for repair and maintenance of machine. The obtained results show the significant influence (28,2%) of the calendar age (engine hour meter readings) of machine on the level of annual costs for repair and maintenance of machine. Research in the development [9] also confirms that the amount of operational costs and the costs of repair and maintenance of construction machinery are highly dependent on the age (engine hour meter readings) of machine.

The main part of the operational costs for repair and maintenance of machines (bearings, joints, shock absorbers, tires, working devices, lubricants) represent such components, which have a much shorter service life than the construction machine itself. They remain relatively constant (no sharp changes are observed) over time, with the increase in worked machine hours (engine hour meter readings) of machine, depending almost entirely on it [6]. The remaining operational costs for repair and maintenance (other spare parts, ongoing repairs) of machines are dependent not only on the age of machine, but also on many other influencing factors – working environment, operating conditions, mode of operation, way of using the machine and especially of the machine operator's skills. This means that the real relation (model) for the way of changing the total operational costs of machine over time with increasing worked machine hours (age) of a specific machine (the so-called "Life cycle cost analysis" method, LCCA model) is strictly individual for each machine separately, and therefore extremely difficult to predict with high accuracy. In the development [9], practical (real) data on market prices/values of front loaders are presented. From them it can be seen that four front loaders of the same brand and size (bucket capacity q=3,06 m^3 (4 yd^3)) with similar values of the engine hour meter readings (from 11093 machine hours to 13840 machine hours) could to be purchased from the secondary market at roughly the same price (about $127500), but at the same time have vastly different and widely varying (from $9,54/h to $47,14/h) hourly costs for repair and maintenance. This clearly shows that the level of costs for repair and maintenance of earth-moving construction equipment will be influenced not only by the age of machine (worked machine hours) from the engine hour meter readings, but also by the general technical condition in which the particular construction machine is at the moment of assessment (i.e. it also depends on whether the machine has been operated correctly up to now and whether it has been properly and regularly serviced and repaired). The level of costs for repair and maintenance of machine should always be evaluated and considered when carrying out operations with purchase and sale of earth-moving construction equipment, in which the maximum number of influencing factors should be taken into account if possible.

In the study [10], the specific fuel consumption for a single-bucket excavator at different digging depths is considered. It was found that at the greatest digging depth (highest engine load, highest engine power) the lowest relative fuel consumption [g/kWh] is obtained, i.e. least fuel [in grams or liters] is used to generate/obtain 1 kWh of energy (useful work).

5. DETERMINING THE RELATION/MODEL EXPRESSING INTERRELATIONSHIP BETWEEN THE LEVEL OF MACHINE AGEING AND THE LEVEL OF REPAIR AND MAINTENANCE COSTS

It is very important for the adequate management of machinery park to be able to correctly assess and pre-model the development trends of costs for repair and maintenance of machines (i.e. to develop an adequate model for evaluating the dynamics of development/change of costs), and based on this, the future costs for repair and maintenance of construction machine during the entire period of its operation can also be predicted. It is this developed "model for evaluating trends in the development of costs for repair and maintenance of construction machinery" that must be observed when decisions are made about the management of machinery park – the determination of exact moment in time (i.e. the stage of machine's lifecycle) in which preventive maintenance (before a failure occurs) of machine must be carried out or sale of used/depreciated machines on the secondary market and the purchase of new ones. In the development [5], the accumulated statistical data on repair and maintenance costs of heavy construction machinery were analyzed, and then based on this, regression mathematical models were simulated and predicted to calculate (prediction model development) the future repair and maintenance costs of this type of machine, in relation to the level of machine ageing, expressed in terms of worked machine hours. To determine the most appropriate point in time to make a reasoned decision as to when exactly the end of economic life of a used (obsolete) construction machine should be, Mitchell's second-order polynomial was used to express the model of total/cumulative machine costs – Mitchell (1998) [6]. In the research [5] it is emphasized that when calculating the level of repair and maintenance costs per 1 worked machine hour of construction machine (i.e. the ratio "engine hour meter readings vs. total/cumulative operational costs of machine") is very important in the analysis to eliminate in advance the costs of major repairs on construction machinery, so that one can then rely on a correct/adequate calculation of the value "hourly operational costs for repairs and maintenance falling on 1 worked machine hour".

Vorster, as early as 1980, proposed a "general model of machine costs", which gives a numerical and graphical solution to many questions and problems related to the management of machinery park [11]. The age of machine (expressed by the worked "machine hours") is plotted on the abscissa axis, and the "cumulative cost" is plotted on the ordinate axis – Figure 1.

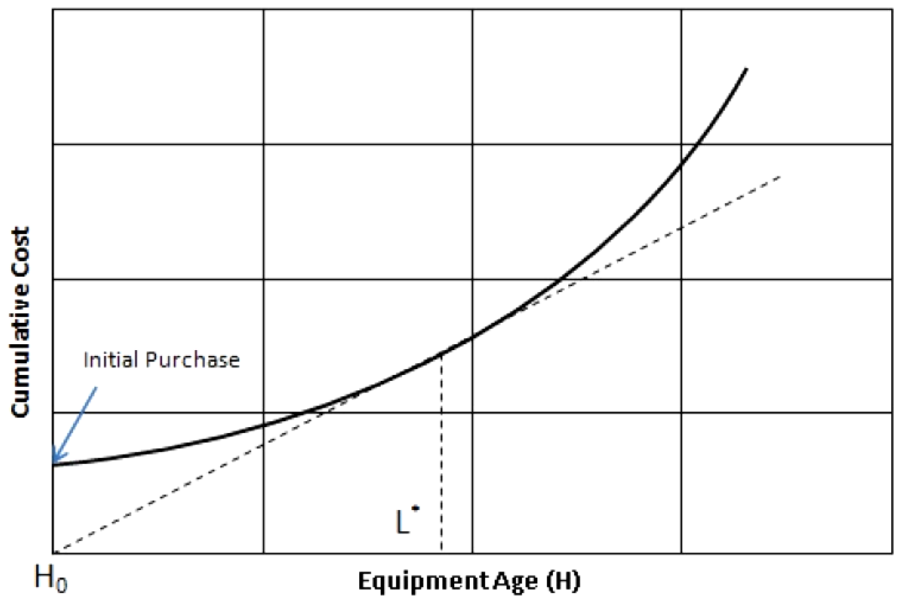

Figure 1. Cumulative cost model of Vorster [11].

The optimal point that shows the optimal economic life of machine – L* (i.e. the point at which it is recommended to replace the equipment with a new one) is the point of tangent to the curve that takes its origin from the zero point of coordinate system (as shown in Figure 1) [12]. It has been found that after this point, the operational costs of machine (mainly repair and maintenance costs) start to increase sharply at a very high rate. In the development [9], two main approaches are proposed for the analysis of relation/variation model of the total operational costs of machine over time in relation to the worked machine hours (LCCA model), namely: First approach – determination of the amount of operational machine costs up to a certain future period of time (life-to-date (LTD) cost analysis); Second approach – determining the amount of operational costs for machine separately for each separate period of the machine's service life (i.e. "step by step" or "period by period" – period cost based approach).

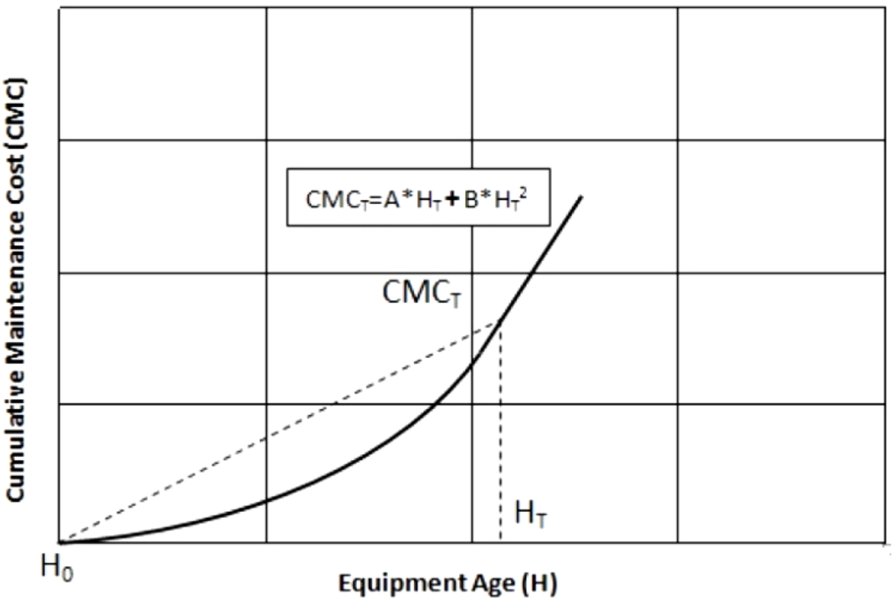

Figure 2. Cumulative cost model under the life-to-date (LTD) approach [9].

In the presence of a ready graph/model of repair and maintenance costs (Figure 2) for a relevant type of construction machine, it can easily be used to calculate expected/forecasted absolute repair and maintenance costs for a certain period of time (in worked machine hours – H_T [hours]), but the average expected/forecasted relative operational costs for 1 worked machine hour for the specified period (up to the moment H_T [hours]) can also be determined – see Fig. 2. To calculate the average expected/forecasted relative operational costs for 1 worked machine hour for the corresponding period (up to the moment H_T [hours]), a straight line must be built between the point of coordinate origin and the point of considered moment of time (see Fig. 2). The slope of the straight line drawn in this way will in practice represent the required value of expected/forecasted relative operational costs for 1 worked machine hour for the corresponding period. In the development [9], a large volume of experimental (empirical) data on the amount of operational costs of various construction machines for earthworks was collected at certain equal intervals of time (for example: 500 machine hours). The mathematical equation by which the built "curve" can be approximated is expressed by the following dependance (Fig. 2):

$$CMC_T = A * H_T + B * H_T^2 , \quad (1)$$

where:

H_T – the age of machine (i.e. worked machine hours) at time point T;

CMC_T – the level of cumulative maintenance costs at machine age (worked machine hours) equal to H_T .

Based on regression analysis of the built graph, the values of coefficients "A" and "B" are determined [9].

In the study [9], useful practical data on the estimated economic life of specific construction machines for earthworks were obtained. Some of these data are summarized, on the basis of which approximate values for the duration of economic life of machines are presented in Table 2 below.

Table 2. Summarized approximate values for the duration of economic life of construction machines based on the study [9].

№	Type and size of construction machine	Approximate duration of economic life
1.	Motor graders with engine power from 150 to 225 HP	About 9000 machine hours
2.	Double-drum vibratory rollers with own weight over 7 tons	About 8000 machine hours
3.	Wheel loaders with bucket capacities from 0,76 m^3 (1 yd^3) up to 1,53 m^3 (2 yd^3)	About 12000 machine hours
4.	Wheel loaders with bucket capacities from 3,43 m^3 (4,5 yd^3) up to 3,82 m^3 (5 yd^3)	About 15000 machine hours
5.	Self-propelled scrapers with elevator filling and bucket capacity greater than 6,87 m^3 (9 yd^3)	About 9000 machine hours

The study [2] presents data from the analysis of economic life of various types of construction machines operating in municipal construction companies in Minneapolis, USA, which economic life was determined (calculated) using different methods – deterministic and probabilistic methods. Special attention is paid to the critical/ultimate moment of time (trigger point), when it is recommended to start taking additional measures, in connection with the expected end of economic life of machines – sale/release from the used construction equipment or to be introduced additional preventive (anticipatory) measures for repair and maintenance of machine, which were obtained/calculated on the basis of "sensitivity analysis" of the economic life. This is necessary because the management decision to replace one construction machine with another (due to the end of its economic life) needs to be made with a certain amount of time in advance. In this case, again, the model/dependency of the change of total operational costs in relation to the worked machine hours over time (LCCA model) and the performance of a justified analysis/assessment for the end of economic life of machine are the main tools for performing the analysis. In the general case, it is characteristic that at the critical/ultimate moment of time (trigger point), the costs of repair and maintenance of machine start to become higher or commensurate with the residual market price/value of machine on the secondary market.

6. CONCLUSIONS AND RECOMMENDATIONS

Based on the research, summaries and analyzes carried out in the current paper, the following more important conclusions and recommendations can be made:

- If the specialists managing the machinery park of construction company have in advance a ready-made model/dependency of the change of total operational costs in relation to the worked machine hours over time (LCCA model) for a specific type of earth-moving machine, then based on it, the taking could be supported of the following more important decisions for the management of machinery park: 1. To make a timely decision to sell used machine on the secondary market; 2. To make a decision to carry out preventive maintenance or additional service of machine (before a failure occurs); 3. To decide to buy another new machine of the same type; 4. To forecast/anticipate the amount of future operational costs and repair and maintenance costs for machine, and based on this, make a preliminary decision to procure the necessary financing for the upcoming repairs in a timely manner;

- The greatest efficiency in terms of fuel consumed [g/kWh] for earth-moving machines will be when machine is loaded at nominal/maximum degree, and the least efficiency in terms of fuel consumed [g/kWh] will be there when the engine of machine is running at idle speed (no loading);
- Given the frequent and significant changes in the price of fuel, it is very important when setting as input data to the LCCA model the range of variation of stochastic (random) variable "price of 1 liter of fuel" that the most suitable/adequate period back in time, on the basis of which fuel prices assigned to the "LCCA model" and a range of variation/change in fuel prices for earth-moving construction equipment will be calculated/determined;
- An accurate prediction of the model/dependency of the change of future operational costs of machine over time (LCCA model) and an accurate determination of the economic life of machine, based only on "worked machine hours" could be achieved for those construction machines that work at relatively constant loads and in which there is less influence of quality indicators and subjective factors on the level of costs. These are, for example: concrete mixing machines, double-drum rollers, screening machines, etc. For earth-moving machines (single-bucket excavators, bulldozers, etc.), which work in variable (dynamic) working conditions and there are greater number of influencing factors (such as: mode of operation, etc.), the level of operational repair and maintenance costs and the economic life of machine will strongly depend not only on the age of machine (worked machine hours) but also on number of other factors, but above all on the skill of machine operator.

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