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Comprehensive Assessment Production Efficiency of Electric Rope Shovel through Operator Qualification Criteria

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A B S T R A C T

The article examines methods for assessing the efficiency of electric mining excavators, emphasizing the inseparability of operational efficiency from the operator-machine ergatic system. It reviews methods for evaluating operator skills via experimental data and proposes a comprehensive approach to assess the excavator's operational efficiency and the operator's skill level. This method includes analyzing the machine's operating time and energy efficiency using a simulator, thereby offering a novel perspective on the dynamic interaction between human operators and automated systems. With the working cycle's duration measured by the ratio of average to nominal cycle times, and energy efficiency assessed through the comparison of specific energy consumption to theoretical values. The findings suggest prioritizing reductions in operating cycle time for suboptimal machine control and focusing on improving bucket fill rates to enhance energy efficiency. Moreover, the study underscores the potential for utilizing these methodologies in real-world applications, aiming to optimize the utilization of mining equipment and thereby significantly contribute to the advancement of operational methodologies in the mining sector.

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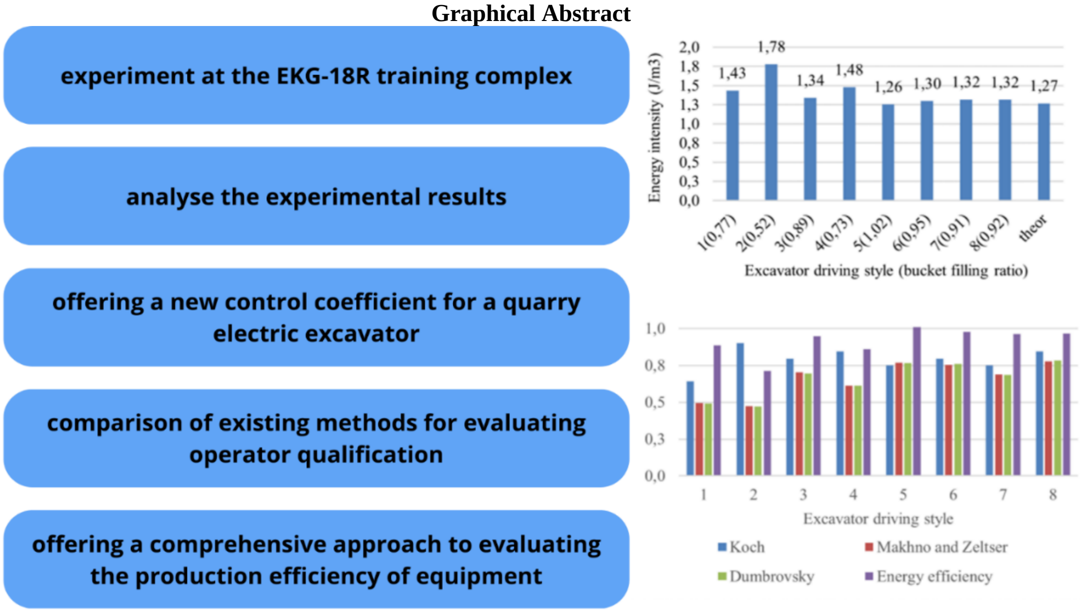
Graphical Abstract



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NOMENCLATURE

W_A	specific energy intensity for one cycle process (J/m^3)	m_{tt}	excavator turntable weight (kg)
N_Y	the total power of the excavator electric motors, (W)	m_s	soil weigh (kg)t
q_b	bucket capacity (m^3)	k_a	experimental positioning factor
$t_{a.c}$	average cycle time (s)	r	radius of the center of mass of rotation (m)
$k_{a.\,fill}$	average fill factor	ε	platform angular acceleration (1/s^2)
A_c	cycle work (J)	φ	rotation angle (rad)
A_d	work of digging resistance forces (J)	k_l	loosening factor
A_{lt}	lifting work (J)	K_k	Koch control factor
A_t	work on turning an excavator with soil (J)	t_{theor}	theoretic cycle time (s)
A_u	soil unloading work (J)	K_d	Dubrovsky control factor
$A_{e.t}$	empty bucket turning operation (J)	Q	excavator capacity (m^3/h)
A_{lw}	work to lower the bucket to the beginning of the face (J)	Q_{theor}	theoretical excavator capacity (m^3/h)
k_{sp}	specific resistance of soil to digging (N/m^2)	K_c	Makhno control factor
Y_s	soil volume weight (N/m^3)	$t_{sp.theor}$	specific theoretical cycle time (s/m^3)
g	gravitational acceleration (m/s^2)	$t_{sp.actual}$	specific actual cycle time (s/m^3)
H_{lift}	lifting height (m)	K_e	energy efficiency control factor
m_b	bucket weight (kg)	W_{theor}	theoretical specific energy intensity (J/m3)

1. INTRODUCTION

In the current trend of mining industry development, there is a constant desire to improve the efficiency and sustainability of production processes. Electric rope shovels, specifically the EKG-18R model, with their significant power capacity, aging machinery, and the varying skill levels of operators, stand at the forefront of this developmental push. These shovels are no exception. This equipment is being developed by an intensive method, on the basis of which new technological solutions do not appear on it. The increasing volume of excavated mass in one cycle of work is due to an increasing dimensions of the machine and the energy intensity of the excavation process. In turn, various operator assistance systems are added: cameras, devices that signal a possible collision of the bucket with the caterpillar, etc. Which leads to the conclusion that the main focus for equipment modernization is to help the operator and level out the lack of experience and skills (1, 2).

There are several parameters that characterize the production efficiency of the equipment. These include: productivity, specific energy consumption, specific material consumption, unit cost, etc. Production efficiency is primarily affected by the operating conditions of the equipment (3). Having divided them into the main categories, it can be represented as: mining-geological and mining engineering, the quality of preparation of the face and rock mass, the technical condition of the machine, the organization of mining operations, climatic conditions, ergatic system (4-6). The operating conditions of the equipment also affect the basic property of reliability, namely durability (7-9). As a consequence, it is necessary to select equipment and develop a technological scheme of development for its effective utilization under given operating conditions (10, 11). Additionally, advanced technologies play a crucial role in enhancing the production efficiency of equipment. Notably, intelligent control systems and methods based on artificial intelligence significantly impact not only the improvement of efficiency but also the enhancement of equipment reliability across various operational conditions (12, 13).

The ergatic system, or man-machine system, is the interaction of a person with equipment. The main criterion of this system is the qualification of the operator, which should reflect the experience and skills of managing this machine (14, 15). There are several methods for assessing the operator qualifications of scientists. These methods will be shown in the methodology section. However, these methods rely only on the average cycle time of the excavator or on its performance, which does not allow to fully evaluate the ergatic system (16, 17). There are also approaches to analyze the factors affecting the operator in an ergatic system, such as: temperature of the environment, fatigue, and well-being. This study deals directly with the evaluation of operator skill or machine control criteria (18-20).

Nowadays, in real production, the efficiency of equipment utilization is evaluated by the productivity of the machine. Such as the excavator's positioning, which directly impacts the machine's productivity. The qualification of the operator is evaluated in the same way. However, this assessment is not objective, because it is considered together with the work of dump trucks. I.e. it is impossible to assess the production efficiency of only a dredging machine when at least one more object participates in the production cycle, as a rule, there are more dump trucks working on one excavator. Moreover, if take into account the performance of the machine itself, without the participation of third-party equipment, the ergatic system remains. Other criteria affecting the production efficiency of the equipment, except for the ergatic system, can be taken into account in calculations or by having reference values of operating time under given operating conditions.

Furthermore, the mining methods employed, such as the single backup or double backup methods, along with the rock quality and conditions of blasting operations, significantly influence the digging time (power) and other components of the excavator's working cycle duration. Consequently, conclude that the production efficiency of the equipment is inextricably linked to the ergatic system. As a result, by evaluating the production efficiency of the equipment it is possible to evaluate the level of operator's qualification. In this paper we proposed a comprehensive approach to assess the skill level of the operator, and, the production efficiency of the equipment, based on the evaluation of performance and energy efficiency of the equipment during operation. While extensive research exists in the field, practical application at the production level remains limited or non-indicative of actual efficiency. This gap underlines the necessity for innovative methodologies that accurately assess and enhance the real-world performance of mining equipment. The authors contribute by addressing the core challenges and obstacles in measuring production efficiency and operator proficiency, presenting initial achievements in overcoming these difficulties. Through a novel lens, this study introduces a methodological framework that not only evaluates the equipment's operational efficiency but also lays the groundwork for future research aimed at predicting the operational lifespan of electric rope shovels, thereby marking a significant advancement in the domain of mining machinery management (21-23).

2. METHODOLOGY

This study considers an integrated approach to the assessment of production efficiency taking into account the level of operator's skills directly at the site of extraction. The main criterion for evaluation is proposed to use the specific energy intensity of the excavation process for one cycle of work. This criterion combines the parameters directly related to the operator's skill level: working cycle time and bucket filling factor. Further in the formulas will be used the average cycle time of the excavator and the average bucket filling factor, because in the calculations will be used directly these values based on the results of the experiment. Specific energy intensity of the excavation process for one working cycle as a ratio of the work performed to the bucket capacity given by Equation 1:

$$W_A = \frac{N_Y t_{a.c}}{q_{\mathrm{b}}} \tag{1}$$

To calculate the specific energy intensity of the process, will be used the average cycle time of the excavator to fill the dump truck. The data obtained for the calculations are presented in srction 3 experiment. Also the bucket capacity is considered taking into account the average filling factor. As a consequence, the formula of specific energy intensity of the excavation process will take by Equation 2:

$$W_A = \frac{N_Y t_{a.c}}{q_{\mathrm{b}} k_{a.\,fill}} \tag{2}$$

The total power of the excavator drives multiplied by the average cycle time represents the total work done during the excavation cycle. During the excavation process, various actions are performed, which can be represented as work done by: digging (4), lifting (5), turning (6), turning with empty bucket (7), lowering (8). Also, in this cycle there is unloading work, but due to the specifics of the equipment it was taken as 0. Nevertheless, in Equation 3 given for the total work it is taken into account.

$$A_c = A_d + A_{\mathrm{lt}} + A_{\mathrm{t}} + A_u + A_{\mathrm{e.t}} + A_{\mathrm{lw}} \tag{3}$$

$$A_d = k_{sp} \cdot q_{\mathrm{b}} \cdot k_{\mathrm{a.fill}} \cdot k_{\mathrm{l}} \tag{4}$$

$$A_{\mathrm{lt}} = \left(q_b \cdot Y_s + m_b \cdot g\right) \cdot H_{\mathrm{lift}} \tag{5}$$

$$A_t = k_a\left(m_{tt} + m_s + m_b\right) \cdot r^2 \cdot \varepsilon \cdot \varphi \tag{6}$$

$$A_{e.t} = k_a\left(m_{tt} + m_b\right) \cdot r^2 \cdot \varepsilon \cdot \varphi \tag{7}$$

$$A_{\mathrm{lw}} = m_b \cdot g \cdot H_{lift} \tag{8}$$

In the ground lifting formula Equation 5 the value of volumetric weight Y_s = 2000 N/m^3 is assumed for the third category of soils, g = 9,81 m/s^2. In the formula of rotation 6 angular acceleration of the rotary platform ε = 1 1/c^2, experimental positioning coefficient k_a = 1.1, rotation angle φ = 90º. The bucket mass in all calculations is taken m_b = 31000 kg, equal to the bucket mass of 18 m^3 for excavator EKG-18R. In the digging operation Equation 4, the volume of excavated rock mass is expressed through bucket capacity, average bucket fill factor and ground loosening factor. The factors of soil resistance to digging k_{sp} and loosening k_l were assumed to be 0.25 and 1.25 for ground category III, respectively.

A mathematical model of the fourth coordinate, or working cycle time, for the selection of the necessary equipment was suggested by Balovnev (24, 25). Considering the parameters of production efficiency and operational conditions, the determination of the working cycle time emerges as a pivotal element in the selection of equipment. This approach facilitates the computation of production efficiency by integrating all referenced operational factors. Additionally, it was introduced a methodology for evaluating an operator's proficiency, which hinges on the proportion of theoretical cycle time to actual cycle time, with the theoretical aspect either deduced or furnished by the equipment manufacturer (9).

However, the method of calculation based on the operating cycle time in isolation from the bucket filling ratio is not representative over the entire range of variations of operating parameters. Excluding this problem, another method presented by Dombrovsky (26) suggests using the ratio of actual productivity to theoretical productivity. There is also another method described by Makhno (27). This methods are similar to Dombrovsky method, but it uses the ratio of specific theoretical cycle time (12) to specific actual cycle time (13). These methods also use the ladle filling ratio to estimate, in addition to the working cycle time. This allows the production efficiency to be evaluated over a larger range of operating hours .

$$K_c = \frac{T_{\text{theor}}}{T_{\text{actual}}} \tag{9}$$

$$K_d = \frac{Q_{\text{actual}}}{Q_{\text{theor}}} \tag{10}$$

$$K_c = \frac{T_{\text{sp.theor}}}{T_{\text{sp.actual}}} \tag{11}$$

$$T_{\text{sp.theor}} = \frac{t_{\text{c.theor}}}{q_b} \tag{12}$$

$$T_{\text{sp.actual}} = \frac{t_{a.c}}{q_b \cdot k_{a.fill}} \tag{13}$$

In this study it is proposed to use the ratio of the energy intensity of the excavation process to the energy intensity of the excavation process nominal (14). That is, the energy intensity with which the operator works on the real machine to the energy intensity calculated on the basis of nominal values. This indicator will make it possible to evaluate how energy efficient the equipment is used at the production site. As a consequence, Ke will become one of the parts of a comprehensive approach to assessing the production efficiency of equipment and evaluating the skill level of the operator.

$$K_e = \frac{W_A}{W_{theor}} \tag{14}$$

By comparing and analyzing existing methods of operator qualification assessment, it is possible to understand their effectiveness and applicability in real production. It will also allow to define more precisely the vector of research, focusing on the problems not previously described.

3. EXPERIMENTAL

In the course of the study, an experiment was conducted to retrain the operator on a different type-size range of excavators. The experiment was conducted on the simulator complex designed to train operators working on the excavator EKG-18R. The range of simulator settings allows modeling various production conditions (type of minerals extracted, weighted average piece size, the share of oversize output and etc.). This complex fully simulates the work of the excavator, its main feature is the IDS system. This system displays in real time the load on the drives and displays instantaneous values of current and voltage of electric motors in time. IDS system allows to monitor the load on the lift, head, slewing and travel drives. In addition, it is possible to obtain data on the time of each equipment cycle, the number of cycles and the total volume of excavated material (28).

During the retraining process, the operator underwent a control exercise. Which consisted of filling a BELAZ-75304 with coal under normal operating conditions. Table 1 shows the results of these exercises. Since in this study was considered directly the evaluation of the operator's qualification and as a consequence the production efficiency of the equipment, the obtained data can not be considered in relation to the training time. Therefore, only an experimental database with different excavation rates under the same operating conditions is needed for further analysis (29). Thus, the results of the experiment are considered in relation to different operating styles of the equipment. The table also shows theoretical operating time parameters, i.e. calculated with respect to the data provided by the manufacturer. As the results of the experiment the main operating parameters necessary for further calculations are presented, they include productivity (Q), average bucket filling ratio ($k_{a.fill}$), number of cycles required to fill the BELAZ-75304, average cycle time ($t_{a.c}$) and radius of the center of mass of the rotating parts of the excavator (r).

TABLE 1. Experimantel results of equipment runtime

№	Q (J/m^3)	$k_{a.fill}$	Cycle number (e.g)	$t_{a.c}$ (s)	r (m)
1	1176	0,77	13	42	1,83
2	1131	0,52	18	30	1,58
3	1665	0,89	12	34	1,94
4	1469	0,73	14	32	1,80
5	1834	1,02	10	36	2,07
6	1825	0,95	11	34	2,00
7	1642	0,91	11	36	1,97
8	1879	0,92	11	32	1,97
theor	2400	1,00	10	27	2,05

4. RESULTS AND DISCUSSION

In the course of study, the work done by the excavator in one cycle was calculated. The results of calculations of digging work (9), lifting (5), turning (6), total work(3) and energy intensity of the excavation process for an average excavator cycle are shown in Table 2 with respect to different styles of equipment operation. The work on the return of the empty bucket (7) and its lowering (8) are equal for all styles of equipment operation. Accordingly, $A_{e.t}$ = 0,71 MJ and A_{lw} = 4,5 MJ. Figure 1 shows the energy intensity of the excavation process in relation to different styles of excavator control and bucket filling ratio. Based on the graph we can conclude that the higher the bucket filling ratio, the less energy is required to excavate one cubic meter of rock.

Table 3 shows the results of equipment control coefficients calculated by the methods of Koch, Dumbrovsky, Makhno , and enery efficiency (14). Based on this data, a graph was created to compare these techniques as shown in Figure 2.

Having considered and compared the different criteria for evaluating operator qualification and as a consequence the production efficiency of the equipment.

TABLE 2. Calculated work and energy intensity of equipment

№	A_d (MJ)	A_{lt} (MJ)	A_t (MJ)	A_c (MJ)	W_A (MJ/m^3)
1	3,47	8,72	2,43	19,90	1,43
2	2,36	7,40	1,79	16,83	1,78
3	3,99	9,35	2,76	21,38	1,34
4	3,27	8,49	2,31	19,35	1,48
5	4,61	10,10	3,19	23,17	1,26
6	4,28	9,69	2,96	22,20	1,30
7	4,13	9,51	2,86	21,77	1,32
8	4,15	9,54	2,87	21,84	1,32
theor	4,50	9,96	3,11	22,85	1,27

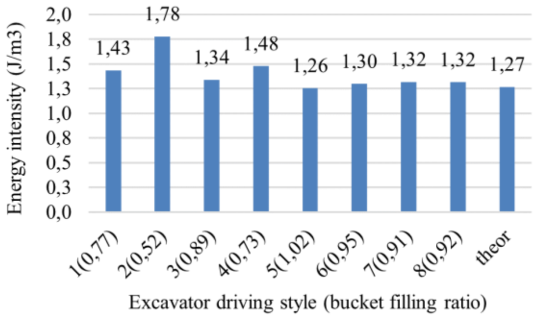

Figure 1. Dependence of energy intensity of excavation process on control style

TABLE 3. Estimated indicators of production efficiency of equipment

№	K_k	K_d	K_c	K_e
1	0,64	0,49	2,01	0,88
2	0,90	0,47	2,11	0,71
3	0,79	0,69	1,41	0,95
4	0,84	0,61	1,63	0,86
5	0,75	0,76	1,30	1,01
6	0,79	0,76	1,32	0,98
7	0,75	0,68	1,45	0,96
8	0,84	0,78	1,28	0,96

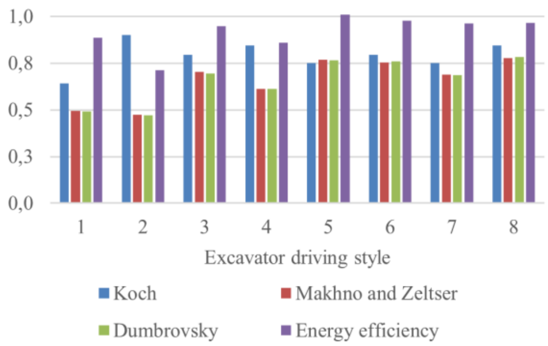

Figure 2. Dependence of production efficiency evaluation criteria on different excavator control styles

It can be seen that the approaches of Dumbrovsky, Makhno are similar in their results for different styles of equipment operation and differ slightly. Therefore, it can be concluded that these methods both are suitable for assessing operator qualification. However, in these approaches there is a problem of estimation of separate indicators of equipment operating time. It is fundamentally unclear which of the operating time indicators should be paid attention to in order to improve the production efficiency of the equipment.

Considering Koch's method, we can conclude that, as it was said earlier, the evaluation of cycle time does not cover all the parameters of equipment runtime. So in Figure 2, if we pay attention to the 2 styles of equipment operation, we can see that the performance and energy efficiency indicators are quite low relative to the others. However, the cycle time score is higher than the others. This is due to the fact that the bucket fill factor in this management style is low. Considering the other styles of equipment operation, we can say that this indicator correlates with Dumbrowski, Makhno indicators.

The energy efficiency of operation does not correlate with these parameters, as it is based mainly only on the bucket fill factor. At the same time, this parameter shows how efficiently the equipment is used in terms of energy consumed per cubic meter of production. Combining this approach together with Koch's method, it is possible to obtain a more indicative approach to assessing production efficiency.

Looking at Figure 2 in general, conclude that the most efficient control styles of the electric mining excavator are styles 3 and 5-8. The other control styles, in turn, have poor performance in terms of both productivity and energy efficiency.

Building on the foregoing discussion, particular emphasis should be placed on the energy efficiency criterion presented in this study. This criterion not only assesses the amount of energy expended per unit volume of extracted product but also, by integrating it with Koch's method, characterized by cycle time, will further allow for predicting the residual resource of the equipment. However, considering this research, combining these methods and delivering the results of these criteria directly during equipment operation, integrating them into the control system, this approach will enhance productivity by providing recommendations for equipment management. This includes advising on the necessity to reduce cycle times or increase the bucket fill factor, which will also enable the assessment of losses incurred by mining companies due to the use of unskilled labor.

5. CONCLUSION

This paper examined various techniques for assessing production efficiency and evaluating operator skill level based on different equipment control styles. The result of the study was comprehensive approach that includes the estimation of excavator cycle time based on Koch's method, as well as energy efficiency, considered as the ratio of production energy efficiency to theoretical evaluation of energy efficiency. Thanks to this approach, it is possible to assess the production efficiency of the equipment in operation from different aspects, and most importantly, to give recommendations for its improvement. Thus, if the Koch control criterion is low, it is possible to conclude that it is necessary to reduce the operating cycle time. If the energy efficiency is low, the focus should be on increasing the bucket filling ratio. The integration of energy efficiency evaluation with Koch's cycle time analysis highlights the importance of assessing equipment performance from multiple dimensions. This approach facilitates a targeted improvement strategy by identifying specific areas of inefficiency. Moreover, it allows for a deeper understanding of how operator skill influences machine productivity and energy consumption, enabling more precise adjustments in training or operational procedures. The findings contribute to a nuanced perspective on optimizing electric rope shovel operations, suggesting a pathway for more efficient and effective use of resources.

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Persian Abstract

چکیده

این مقاله تجزیه و تحلیل روش های ارزیابی عملکرد موثر یک حفاری معدن الکتریکی را مورد بحث قرار می دهد. نتیجه گیری می شود که کارایی عملیاتی را نمی توان به صورت جداگانه از سیستم اپراتور–ماشین ارگاتیک در نظر گرفت. تعدادی از روش های ارزیابی سطح مهارت اپراتورها بر اساس داده های تجربی در نظر گرفته شده است. این مطالعه یک رویکرد یکپارچه برای ارزیابی کارایی عملیاتی یک حفاری معدن الکتریکی و در نتیجه سطح مهارت اپراتور را پیشنهاد کرد. این شامل ارزیابی زمان کار دستگاه و بهره وری انرژی فرآیند با استفاده از شبیه ساز بیل مکانیکی بود. مدت زمان چرخه کار بیل مکانیکی به عنوان نسبت متوسط زمان چرخه به اسمی برای یک نوع خاص از تجهیزات تخمین زده شده است. بهره وری انرژی فرآیند ارزیابی شده با نسبت شدت انرژی خاص در طول چرخه کاری حفاری به ارزش نظری شدت انرژی محاسبه شده بر اساس پارامترهای اسمی. بنابراین ، اگر معیار کنترل ماشین کم باشد ، می توانیم نتیجه بگیریم که کاهش زمان چرخه کار ضروری است ؛ اگر بهره وری انرژی فرآیند کم باشد ، باید توجه اصلی به افزایش درجه پر کردن سطل بیل مکانیکی شود.