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Evaluation of the efficiency of maintenance and repairs to metallurgical equipment

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Abstract. Metallurgical enterprises are among the most capital-intensive industries, with high maintenance and repair costs for equipment. The proper management and efficient operation of equipment directly affect product output, safety, and economic performance indicators. The current study aimed to develop key performance indicators for engineering services, emphasising the systematisation of indicators into technical, organisational, and economic groups. This enabled the authors to address the primary challenge of evaluating the efficiency of maintenance and repairs in metallurgical enterprises using the developed key performance indicators. The study analysed and classified thirty-six performance assessment indicators. Using the Delphi expert assessment method and the subsequent step-by-step analysis of weight assessment coefficients via the fuzzy Step-Wise Weight Assessment Ratio Analysis method, the key factors for the operational control of the maintenance and repair efficiency of metallurgical equipment were identified. These factors were categorised into three groups. The first group included five technical indicators; the second, six organisational indicators; and the third, three economic indicators of the efficiency of technical maintenance and repairs of metallurgical equipment. Analysis of the obtained rating of key performance indicators showed that the most significant indicators were complex (generalising) indicators in each group. The key indicators in each group were determined to be: the technical readiness coefficient of equipment; the overall efficiency indicator of equipment; and the cost intensity of technical maintenance and repairs of equipment. Based on the indicator ratings, recommendations were developed for compiling a compliance matrix and priority measures in the event of negative dynamics in each group of indicators. The practical significance of this work lies in providing technical maintenance and repair specialists at metallurgical enterprises with criteria for objectively assessing the current state of equipment management, thereby enabling improvements to be made to the repair system

Keywords: organisational structure; rating; expert assessments; technical readiness coefficient; engineering services; Delphi method

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Introduction

Evaluation of the effectiveness of maintenance and repair services plays a key role in ensuring smooth operation of equipment, reducing downtime, and optimising operating costs. Evaluation and management of processes within the framework of the chosen and implemented maintenance and repair strategy at the enterprise is an important task of objective assessment of the current condition of equipment and planning for improving the repair system.

N. Gavrylenko (2022) developed recommendations for differentiating repairs, improvements, and maintenance. The study also noted that the decision on the nature and signs of repairs performed is made by the head of the enterprise, considering the analysis of the current situation and the materiality of costs. Such a decision should be made based on a technical report on the direction of planned activities, which is provided to the manager by a specialist of the appropriate profile, for example, a mechanic. Z. Zhuang *et al*. (2022), S. Singh *et al*. (2022) noted that improving the efficiency of equipment maintenance and repair management is one of the key areas of activity. The correct organisation of this process depends not only on the quality and functionality of the equipment, but also on the correctness of determining financial costs, which, as a result, affects the financial performance of the company. V. Florea & G. Pragorgescu (2018), J. Das *et al*. (2023) concluded that the particularly active implementation of various maintenance and repair strategies at metallurgical enterprises is associated with a significant material consumption of metallurgical industries and, accordingly, a significant impact of equipment maintenance and repair on all areas of production activity.

According to M. Huber *et al*. (2023) for the classification of factors that ensure the effective implementation of a set of technological and organisational measures to maintain the operability or serviceability of equipment, and to restore the operability, serviceability, and resource of equipment and its components, it is advisable to allocate an industry direction and take into account the specifics and scale of enterprises. R. Banelienė (2021) recommended that the factors that provide an assessment of production efficiency are divided into three groups: technical, organisational, and economic. Each of these groups can include exactly the indicators inherent in this group. According to L. Zhang *et al*. (2019), M. Krynke *et al*. (2022), the group of technical efficiency factors of maintenance and repair services focus on issues of reliability and safety of equipment, the group of organisational factors focus on issues of organisation of the process of maintenance and repair services and logistics support (spare parts, tools, documentation), the group of economic factors consider the costs of production and maintenance and repair services.

Considering the available publications that apply to the use of various systems of maintenance and repair of equipment in various industries, there is no systematisation of factors for evaluating the effectiveness of maintenance and repair services at metallurgical enterprises. It is also of considerable interest to identify key (dominant) factors that affect the effectiveness of implementing maintenance and repair activities. The purpose of the study was to analyse the factors that allow assessing the effectiveness of the implementation of the process of maintenance and repair of equipment at enterprises of the metallurgical sector, and based on the analysis of these factors, to propose measures for timely identification of shortcomings in the maintenance and repair system and their elimination.

To achieve this goal, the following research tasks were implemented. Systematisation and analysis of factors for evaluating the effective use of the maintenance and repair system at metallurgical enterprises was carried out. The dominant factors (key performance indicators) that have the greatest impact on the efficiency of maintenance and repairs at metallurgical enterprises were identified. The main measures (corrective actions) to improve the maintenance and repair services system were formulated, based on the developed key performance indicators.

Materials and Methods

To assess the effectiveness of production processes, it is customary to use the following methods: benchmarking and comparative analysis methods; equipment life cycle analysis method; cost-benefit analysis method; total cost of ownership estimation method; return on investment (ROI) calculation method; key performance evaluation method (Layard & Glaister, 1994; Phillips *et al*., 2011; Da Costa, 2024). The equipment life cycle analysis method is a systematic approach to assessing the economic, environmental or technical aspects of equipment throughout its entire life cycle: from design and production to operation, maintenance, and disposal. These approaches mainly relate to the methods of assessing the economic efficiency and risks of activities, through economic indicators indirectly show the effectiveness of implemented organisational, technical, personnel, and qualification measures. Among the listed methods, it is recommended to use the method of evaluating key performance indicators to assess the effectiveness of maintenance and repair implementation in enterprises. To determine relative performance indicators, it is necessary to note the key factors that are their components. It is the use of relative indicators that allows making comparisons not only within an individual enterprise, but also within an industry.

It is possible to determine the key factors of influence using one of the existing scientific methods listed below. An expert method that involves attracting professionals (engineers, technologists, economists) to evaluate and select the most relevant indicators. This method is most often used in the absence of accurate data and at the stage of developing and implementing performance indicators (Peniwati, 2017; Zhong *et al.*, 2019). Business process analysis, which consists in studying the production process as a chain of operations. Key factors are determined based on "bottlenecks" and control points (Hammer & Champy, 1993). Historical data analysis, which consists of examining accumulated production data and determining the relationship between indicators and results (Smith & Mobley, 2008).

Analysis of the described methods shows that there are certain restrictions when using them. Thus, the method of analysing historical data can be implemented with a sufficiently long study and the presence of fixing the necessary data in production. The method of analysing business processes requires a long and detailed study of technological processes and the impact of production units on them. The expert method also has its drawbacks related to the bias of experts and subjectivity of opinion. However, these shortcomings can be minimised by adhering to the established rules for selecting expert groups. Therefore, the use of the expert method allows determining the key (dominant) factors for evaluating the effectiveness of maintenance and repairs. As a basic expert method, it is customary to use the Delphi method. The advantages of this method of expert assessments are multi-level, anonymous and absentee examination.

Thus, the current study, based on the determination of key factors by the expert method, included the following stages. The goal was determined and the evaluation objects were selected. At the second stage, expert groups were formed, which included: heads of departments, technical specialists, economists, analysts, representatives of quality services. At the third stage, expert responses were collected and ranked. Among the possible methods of collecting information, a multi-stage survey with feedback was chosen. At the fourth stage, scores were processed and aggregated using a point scale. As a result of the implementation of the fourth stage, a rating list of factors was compiled, sorted by significance. At the fifth stage, the final list of indicators was verified and adjusted, and the methodology for calculating each key indicator was clarified.

The result of the implementation of the first (preparatory) stage was selected and classified into three groups of factors based on the analysis and systematisation of the results of the review of scientific literature, international standards (ISO) and standards of the American Petroleum Institute (API). Factors are organised into technological, organisational, and economic groups. Technological factors that were included in the survey: T_1 – mean time between failures (MTBF); T_2 – number of cases of damage to personnel related to maintenance and repair work during the calendar period; T_3 – meat time to recovery (MTTR), T_4 – coefficient of technical readiness or availability of equipment (CTR); T_5 – mean downtime; T_6 – failure rate; T_7 – number of failures that caused environmental damage in the calendar period; T_8 – total time of disability due to maintenance and repair; T_9 – coefficient of technical utilisation (CTU); T_{10} – annual amount of waste or harmful impacts associated with maintenance and repair; T_{11} – total time spent on planning maintenance and repair services; T_{12} – residual resource, based on data obtained from the following papers (Moubray, 1997; ISO/DIS 22400-2, 2014; Goriveau *et al.*, 2016).

Organisational factors that were included in the survey: O_1 – coefficient of planned maintenance work; O_2 – coefficient of unscheduled repairs; O_3 – total number of working hours of production equipment operators to perform inspections and maintenance; O_4 – number of hours spent on continuous improvement of the maintenance and maintenance system; O_5 – coefficient of performance of routine maintenance work; O_6 – compliance with repair deadlines; O_7 – overall equipment efficiency (OEE); O_8 – coefficient of shift work of personnel (personnel engaged in maintenance and repair and working in shifts to the total number of personnel performing maintenance and repair); O_9 – number of delivered spare parts to the total number of spare parts required for maintenance and repair; O_{10} – number of personnel using diagnostic tools to the total number of personnel engaged in maintenance and repair; O_{11} – personnel qualification coefficient (the number of employees engaged in maintenance and repair and who have completed advanced training to the total number of personnel performing maintenance and repair services for the period); O_{12} – number of hours for professional development of maintenance and repair personnel to the total duration of maintenance and repair for the period, based on data obtained from the following papers: R.K. Mobley (2002), ISO/DIS 22400-2 (2014), API RP 581, (2025).

Economic factors that were included in the survey: E_1 – total costs of maintenance and repair; E_2 – mean replacement cost of equipment; E_3 – cost intensity for maintenance and repair (maintenance and repair costs divided by the actual volume of production); E_4 – share of material costs in total maintenance and repair costs; E_5 – expenses for professional development in the field of maintenance and repair; E_6 – coefficient of compliance of maintenance and repair costs aimed at modernisation with total maintenance and repair costs; E_7 – economic effect of preventing downtime; E_8 – share of direct labour costs for maintenance and repair in total maintenance and repair costs; E_9 – specific weight of maintenance and repair costs per unit of equipment; E_{10} – mean inventory cost of materials for maintenance and repair to the replacement cost of the corresponding object of maintenance and repair; E_{11} – total outsourcing costs for maintenance and repair services; E_{12} – total energy consumption for maintenance and repair, based on data obtained from the following papers: R.K. Mobley (2002), T. Wireman (2004), M.T. Howell & F.S. Alshakhshir (2016). In addition, individual indicators were taken from the studies of the following researchers: A. Tesini & A. Rolfe (2009), C.L. Cooper (2015), S. Li *et al.* (2023).

At the stage of creating expert groups (the second stage), the recommendations of specialised enterprises were taken into consideration. Each candidate was sent an individual invitation explaining the research objectives, Delphi methodology, participation requirements, and confidentiality conditions. All participants gave informed consent. The survey was conducted in Q4 2024. The survey was conducted online, through a questionnaire (in several rounds), partially supplemented with electronic comments from experts. The Google Forms service was used for the survey, and Zoom and email were used for feedback. The survey was conducted anonymously. Experts did not know each other's personalities, which made it possible to reduce social pressure and avoid the influence of authorities. The expert groups included representatives of metallurgical enterprises of the Zaporizhzhia Oblast: PJSC "Zaporizhstal", PJSC "Dniprospetsstal", JSC "Zaporizhia Ferroalloy Plant", PrJSC "Zaporizhcoks", PrJSC "Zaporizhogneupor". Studies involving people were conducted in compliance with ethical standards and requirements established by institutional, national, and international regulatory authorities. The authors adhered to the principles set out in The Declaration of Helsinki (2013), which regulates the ethical principles of research involving people. During the study, all ethical requirements were met in accordance with Regulation of the European Parliament and of the Council No. 695 (2021). All participants provided informed consent, and the data was processed in compliance with confidentiality and personal data protection in accordance with the provisions of the Law of Ukraine No. 2297-VI (2010).

The experts' attention was focused on paragraph 6.5 of the Resolution of the General Assembly of the NAS of Ukraine No. 2 (2009), on compliance with the principles of equality, factual validity and reliability in discussions, polemics and critical comments. The principle of equality guarantees equal rights to all participants in a discussion or controversy, regardless of academic degrees and titles. The principle of factual validity excludes biased criticism. The principle of credibility prohibits any misrepresentation with the aim of humiliating or discrediting.

Further stages of the study included experts evaluating the importance of each factor on a five-point Likert scale. The importance of factors was converted to points on the following scale: very low importance – "1" points, low importance – "2" points, average importance – "3" points, high importance – "4" points, very high importance – "5" points. That is, "1" – a factor that does not affect the effectiveness of maintenance and repair, "5" – a factor that has the greatest impact. It is worth noting the specificity of the implementation of the fourth stage, related to the lack of consensus among experts on most of the dominant factors. In this case, it became necessary to conduct a second round of questionnaires using the Stepwise Weighted Assessment Ratio Analysis (SWARA) method. This method was presented by V. Kersuliene *et al.* (2010). This method helped to determine the weight coefficients of the dominant factors. The process of determining the weights of criteria using the Fuzzy SWARA method is similar to the process of the usual SWARA method.

The algorithm for implementing the Fuzzy SWARA method was as follows. At the first stage, the criteria were arranged in descending order according to the level of their expected significance, i.e., the most significant criterion was assigned first, and the least significant criterion was assigned last. The process of implementing this method was described in detail in many papers (Petrovic *et al.*, 2019; Adshirinpour *et al.*, 2021; Pidchenko *et al.*, 2024). In the second step, each person who made the decision (a total of "*K*" experts), expressed their view on the relative importance of the criterion j regarding the previous one j-1 for all the criteria considered. This ratio was called the comparative importance of the average value s_j. For this purpose, the fuzzy comparison scale shown in Table 1 was used.

Table 1. Fuzzy comparison scale for evaluating criteria

Expert opinion	Evaluation scale
Equally important	(1, 1, 1)
Moderately less important	(2/3, 1, 3/2)
Less important	(2/5, 1/2, 2/3)
Much less important	(2/7, 1/3, 2/5)
Significantly less important	(2/9, 1/4, 2/7)

Source: G. Petrovic *et al.* (2019)

In the third step, the concept of geometric mean, arithmetic mean, or other ideas that helped to determine aggregate estimates of the weights of criteria and alternatives based on criteria was used to aggregate expert estimates. Thus, D. Kacprzak (2019) identified four approaches to determining the aggregate opinion of experts, namely: arithmetic mean, modified arithmetic mean, geometric mean, and modified geometric mean. In the current study, the Fuzzy SWARA method used a modified arithmetic mean calculated using the following equation:

$$\tilde{s}_j = \left(min(\tilde{a}_{ijk}), \frac{1}{K}\sum_{k=1}^{K} b_{ijk}, max(\tilde{c}_{ijk})\right). \quad (1)$$

Calculating coefficient values $\tilde{k}_j$, fuzzy weights $\tilde{q}_j$ and final weights of the criteria $\tilde{w}_j$ performed using the following equations.

Value of the coefficient $\tilde{k}_j$:

$$\tilde{k}_j = \begin{cases} \tilde{1}, if\ j = 1 \\ \tilde{s}_j(+)\tilde{1}, if\ j > 1. \end{cases} \quad (2)$$

Fuzzy listed weights $\tilde{q}_j$:

$$\tilde{q}_j = \begin{cases} \tilde{1}, if\ j = 1 \\ \frac{\tilde{q}_{j-1}}{\tilde{k}_j}, if\ j > 1. \end{cases} \quad (3)$$

Final relative weights of criteria $\tilde{w}_j$:

$$\tilde{w}_j = \tilde{q}_j / \sum_{k=1}^{n} \tilde{q}_k, \quad (4)$$

where $\tilde{w}_j = (\tilde{w}_{jl}, \tilde{w}_{jm}, \tilde{w}_{ju})$ denotes the fuzzy weight of the relative importance of the j-th criterion.

At the final stage, the dephasised weights of the criteria were determined as the arithmetic mean of the relative weights of the criteria.

Results and Discussion

In accordance with the methodology described in the previous section, at the previous stage, a list of questions was formulated regarding factors affecting the efficiency of maintenance at the enterprise. A clearly defined list of research issues that require professional assessments in the form of a collective expert forecast allowed outlining the necessary characteristics of future participants (experts). Experts who met the following criteria were invited to participate: education in mechanical engineering; higher education level – master's degree, specialist degree or scientific degree; professional qualifications – at least 5 years of experience as a department head; 10 or more years of experience in the metallurgical industry; willingness to participate in several rounds of surveys; objectivity and independence of assessment. The results of the point expert assessment are shown in Figure 1.

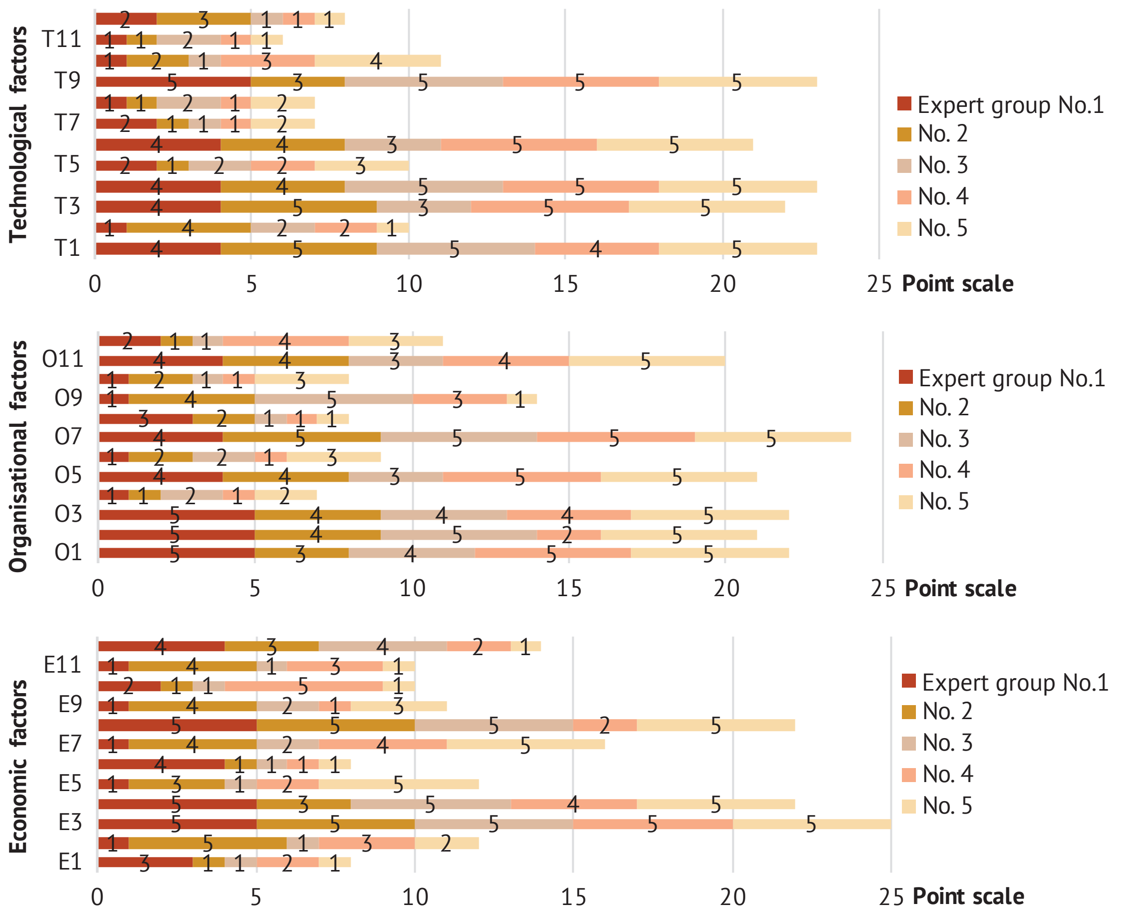

Figure 1. Comparative graphs of the relative importance of factors affecting the efficiency of maintenance and repairs according to expert estimates were obtained in the first round of the survey

Source: compiled by the authors

According to the estimates shown in the graphs, the fuzzy value of each question is treated as a triangular fuzzy number (H, C, B) so that the lower limit value of this triangular fuzzy number for each question is equal to the minimum value assigned by experts on the Likert scale; the middle of this fuzzy number is the calculation of the geometric mean of all expert opinions on the questions, and the upper limit of this triangular fuzzy number is the maximum value assigned by experts on the Likert scale. The fuzzy value of each criterion is shown in Table 2. Experts selected five factors from the first group, six factors from the second group, and three factors from the third group as dominant factors (key performance indicators) that affect the efficiency of maintenance and repairs. Thus, after the first stage, the experts chose the following factors: in the group of technical indicators: T_1, T_3, T_4, T_6, T_9; in the group of organisational indicators: O_1, O_2, O_3, O_5, O_7, O_{11}; in the group of economic indicators: E_3, E_4.

Table 2. Results of the first stage of the survey to determine the dominant factors

Parameter	Main factors of influence											
	Technological factors											
	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}	T_{11}	T_{12}
H	4	1	3	4	1	3	1	1	3	1	1	1
C	4.573	1.741	4.317	4.573	1.888	4.129	1.320	1.320	4.514	1.888	1.149	1.431
B	5	4	5	5	2	4	2	2	5	2	2	3
Dominant factors	+	-	+	+	-	+	-	-	+	-	-	-
Consensus level	60%	40%	60%	60%	60%	40%	60%	60%	80%	40%	80%	60%
	Organisational factors											
	O_1	O_2	O_3	O_4	O_5	O_6	O_7	O_8	O_9	O_{10}	O_{11}	O_{12}
H	3	2	4	1	3	1	4	1	1	1	3	1
C	4.317	3.981	4.373	1.320	4.129	1.644	4.782	1.431	2.268	1.431	3.949	1.888
B	5	5	5	2	4	2	5	3	5	2	4	2
Dominant factors	+	+	+	-	+	-	+	-	-	-	+	-
Consensus level	60%	60%	60%	60%	40%	40%	80%	60%	40%	60%	60%	40%
	Economic factors											
	E_1	E_2	E_3	E_4	E_5	E_6	E_7	E_8	E_9	E_{10}	E_{11}	E_{12}
H	1	1	5	3	1	1	1	2	1	1	1	1
C	1.431	1.974	5.000	4.317	1.974	1.320	2.759	4.163	1.888	1.585	1.644	2.491
B	3	5	5	5	3	4	4	5	4	2	4	4
Dominant factors	-	-	+	+	-	-	-	+	-	-	-	-
Consensus level	60%	40%	100%	60%	40%	80%	40%	80%	40%	60%	60%	40%

Notes: dominant factors are highlighted
Source: developed by the authors based on G. Petrovic *et al.* (2019), H. Adshirinpour *et al.* (2021), S. Pidchenko *et al.* (2024)

Due to the lack of expert consensus in most of the dominant factors (the presence of identical responses in more than 90% of experts), the next stage of expert assessments was carried out using the Fuzzy SWARA method. According to the first step, the criteria were arranged in descending order relative to their expected significance:

in the group of technical indicators:
$T_4 \rightarrow T_1 \rightarrow T_9 \rightarrow T_3 \rightarrow T_6$;

in the group of organisational indicators:
$O_7 \rightarrow O_3 \rightarrow O_1 \rightarrow O_5 \rightarrow O_2 \rightarrow O_{11}$;

in the group of economic indicators:
$E_3 \rightarrow E_4 \rightarrow E_8$.

As a result of the second step, a survey was conducted on a fuzzy comparison scale (Table 1) to determine the relative comparative importance between the two factors. The results are entered in the comparison matrix (Table 3).

Table 3. Matrix of comparative relative importance of performance indicators determined by experts on the evaluation scale from Table 1

Expert groups (EG)	Technological factors											
	T_1 to T_4			T_9 to T_1			T_3 to T_9			T_6 to T_3		
1	0.667	1.000	1.500	1.000	1.000	1.000	0.667	1.000	1.500	0.667	1.000	1.500
2	0.400	0.500	0.667	0.667	1.000	1.500	1.000	1.000	1.000	0.667	1.000	1.500
3	0.400	0.500	0.667	1.000	1.000	1.000	0.667	1.000	1.500	0.400	0.500	0.667

Table 3. Continued

Expert groups (EG)	Technological factors											
	T_1 to T_4			T_9 to T_1			T_3 to T_9			T_6 to T_3		
4	0.400	0.500	0.667	1.000	1.000	1.000	1.000	1.000	1.000	0.667	1.000	1.500
5	0.400	0.500	0.667	1.000	1.000	1.000	0.667	1.000	1.500	0.400	0.500	0.667

EG	Organisational factors														
	O_3 to O_7			O_1 to O_3			O_5 to O_1			O_2 to O_5			O_{11} to O_2		
1	0.667	1.000	1.500	0.400	0.500	0.667	0.667	1.000	1.500	0.667	1.000	1.500	0.400	0.500	0.667
2	1.000	1.000	1.000	0.667	1.000	1.500	0.667	1.000	1.500	0.400	0.500	0.667	0.286	0.334	0.400
3	0.667	1.000	1.500	0.400	0.500	0.667	0.400	0.500	0.667	0.400	0.500	0.667	0.400	0.500	0.667
4	0.667	1.000	1.500	0.667	1.000	1.500	0.667	1.000	1.500	0.400	0.500	0.667	0.400	0.500	0.667
5	1.000	1.000	1.000	0.286	0.334	0.400	0.667	1.000	1.500	0.400	0.500	0.667	0.286	0.334	0.400

EG	Economic factors					
	E_4 to E_3			E_8 to E_4		
1	1.000	1.000	1.000	0.667	1.000	1.500
2	1.000	1.000	1.000	0.667	1.000	1.500
3	1.000	1.000	1.000	1.000	1.000	1.000
4	1.000	1.000	1.000	0.667	1.000	1.500
5	0.667	1.000	1.500	0.667	1.000	1.500

Source: developed by the authors based on G. Petrovic *et al.* (2019), H. Adshirinpour *et al.* (2021), S. Pidchenko *et al.* (2024)

The next steps of the Fuzzy SWARA method are shown in Table 4. Final results – dephasised weights of the criteria show relative weight (significance) of each T factor (TF), O factor (OF), and E factor (EF).

Table 4. Matrix of comparative relative weight of each factor

TF	$\tilde{s}_j$			$\tilde{k}_j$			$\tilde{q}_j$			$\tilde{w}_j$			defuzz $\tilde{w}_j$
T_4	-	-	-	1.000	1.000	1.000	1.000	1.000	1.000	0.387	0.459	0.606	0.484
T_1	0.400	0.600	1.500	1.667	2.000	2.500	0.400	0.500	0.600	0.276	0.287	0.242	0.269
T_9	0.667	1.000	1.500	1.667	2.000	2.500	0.160	0.250	0.360	0.166	0.143	0.097	0.135
T_3	0.667	1.000	1.500	1.400	1.800	2.500	0.064	0.139	0.257	0.099	0.072	0.039	0.070
T_6	0.400	0.800	1.500	1.400	1.600	2.500	0.026	0.087	0.184	0.071	0.040	0.016	0.042
OF	$\tilde{s}_j$			$\tilde{k}_j$			$\tilde{q}_j$			$\tilde{w}_j$			**defuzz** $\tilde{w}_j$
O_7	-	-	-	1.000	1.000	1.000	1.000	1.000	1.000	0.359	0.479	0.601	0.480
O_3	0.667	1.000	1.500	1.667	2.000	2.500	0.400	0.500	0.600	0.215	0.239	0.240	0.232
O_1	0.400	0.900	1.500	1.400	1.900	2.500	0.160	0.263	0.428	0.154	0.126	0.096	0.125
O_5	0.286	0.667	1.500	1.286	1.667	2.500	0.064	0.158	0.333	0.120	0.076	0.038	0.078
O_2	0.400	0.600	1.500	1.400	1.600	2.500	0.026	0.099	0.238	0.085	0.047	0.015	0.049
O_{11}	0.286	0.434	0.667	1.286	1.434	1.667	0.015	0.069	0.185	0.066	0.033	0.009	0.036
EF	$\tilde{s}_j$			$\tilde{k}_j$			$\tilde{q}_j$			$\tilde{w}_j$			**defuzz** $\tilde{w}_j$
E_3	-	-	-	1.000	1.000	1.000	1.000	1.000	1.000	0.510	0.571	0.641	0.574
E_4	0.667	1.000	1.500	1.667	2.000	2.500	0.400	0.500	0.600	0.306	0.286	0.256	0.283
E_8	0.667	1.000	1.500	1.667	2.000	2.500	0.160	0.250	0.360	0.184	0.143	0.103	0.143

Source: compiled by the authors

Thus, the gradation of key performance indicators of maintenance and repair for metallurgical enterprises by importance (in the first place the most important indicator of the group, in the last place – the least important): in the group of technical indicators: T_4, T_1, T_9, T_3, T_6; in the group of organisational indicators: O_7 – overall equipment efficiency (OEE) = Availability × Productivity × Quality (where: Availability = Actual operating time / Scheduled time; Productivity = Actual output / Standard output; Quality = Usable products / Total output); O_3 – compliance with repair deadlines, O_1 – coefficient of unscheduled repairs, O_5 – coefficient of planned maintenance work, O_2 – coefficient of routine maintenance; O_{11} – coefficient of personnel qualification; in the group of economic indicators: E_3 – expenses for maintenance and repair; E_4 – share of material costs in total maintenance and repair costs; E_8 – share of direct labour costs for maintenance and repair in total maintenance and repair costs. The results obtained are systematised in the form of a rating (Table 5).

Table 5. Rating of key performance indicators (KPIs) for maintenance and repair of metallurgical equipment

Name of the KPI group	**Technical indicators**				
KPI rating	1	2	3	4	5
Name of the KPI	Coefficient of technical readiness or availability of equipment (CTR)	Mean time between failures (MTBF)	Coefficient of technical utilisation (CTU)	Mean time to recover (MTTR)	Failure rate
Definition (calculation equation)	= MTBF / (MTBF + MTTR)	= Total uptime / number of failures	= MTBF / Ttot, where Ttot – total usage time	= Total repair time / Number of repairs	= (Number of failures / total number of pieces of equipment) × 100%

Name of the KPI group	**Organisational indicators**					
KPI rating	1	2	3	4	5	6
Name of the KPI	Overall equipment efficiency (OEE)	Meeting repair deadlines	Coefficient of unscheduled repairs	Coefficient of planned maintenance works	Coefficient of routine maintenance works	Staff qualification ratio
Definition (calculation equation)	= Availability × Performance × Quality	-	= (Number of unscheduled repairs / Total number of repairs) × 100%	= (Number of planned maintenance / Total maintenance) × 100%	= (Actually completed routine maintenance / Planned routine maintenance) × 100%	= Number of maintenance and repair employees who have completed advanced training / Total number of maintenance and repair employees for the period

Name of the KPI group	**Economic indicators**		
KPI rating	1	2	3
Name of the KPI	Resource intensity of maintenance and repair	Share of material costs in total maintenance and repair costs	Share of direct labour costs for maintenance and repair in total maintenance and repair costs
Definition (calculation equation)	= Expenses for maintenance and repair / Actual production volume	= (Total material costs for maintenance and repair / Total maintenance and repair costs) × 100%	(Total personnel costs of the enterprise spent on maintenance and repair / Total maintenance and repair costs) × 100%

Source: developed by the authors based on the materials presented in the current study

Analysis of the obtained rating of key performance indicators showed that the most significant indicators include complex (generalising) indicators in each group. Thus, among the technical indicators, this is the coefficient of technical readiness, among organisational indicators – the overall efficiency of equipment, among economic indicators – the cost intensity for maintenance and repair. The analysis of a complex indicator in each group allowed for operational monitoring of the state of the maintenance and repair system. If their negative dynamics are detected during the application of key performance indicators for maintenance and repairs of metallurgical equipment, the analytical services of the enterprise should draw up a compliance matrix. Indicators that have positive dynamics are included in the green sector of the matrix, indicators that have negative dynamics during one period are included in the yellow sector of the matrix, and indicators that have negative dynamics over several periods are included in the red sector of the matrix.

Accordingly, to eliminate the negative impact on technical indicators, it is necessary first of all to focus on assessing the condition of equipment and the quality of spare parts. Perform control checks on the implementation of the recommendations of the equipment diagnostics departments. To eliminate the negative impact on organisational indicators, it is necessary first of all to analyse the structure of the maintenance and repair service, the qualifications and number of personnel involved in routine maintenance work, and in case of inconsistencies, to carry out measures to improve the skills of employees. The structure of an enterprise's repair services may undergo changes in the company's maintenance and repair system.

Economic factors should be analysed in conjunction with factors affecting the volume of production, both external and internal. For this purpose, the company develops a map of the technological process with recording of working hours, planned, and unscheduled downtime. Based on this data, both the possibility of increasing hardware performance and the causes of downtime are determined. The effectiveness of the functioning of departments and services responsible for effective maintenance and repair is directly affected by the implementation of timely corrective actions to improve its work. Maintenance and repair work is the result of technical and administrative measures, including operational ones, to maintain or restore the operability of equipment during operation, including its testing, adjustment, and regulation, which provides for the maintenance and restoration of equipment, maintaining it in a state in which it is able to perform the necessary functions.

That is, maintenance and repair work is the result of complex actions that can be evaluated by applying appropriate indicators (key performance indicators of the maintenance and repair system), which, in turn, measure the results obtained and expected. This approach can be recommended for inclusion as a component of the operational stage, when using the method of analysing the equipment life cycle. Comparisons of the current study with studies by other researchers showed comparability of the results. The research methodology in terms of fuzzy multi-criteria decision-making for determining dominant factors, which was described in the paper by S. Pidchenko *et al.* (2024), corresponds to the step-by-step stages of the current study. The difference lies in the additional use of the Fuzzy TOPSIS method in the paper by the researchers due to the presence of additional groups of factors that influence the final choice of experts.

The methodology of the current study and conclusions correlate with the methodology of the study conducted to assess the effectiveness of physical asset management in oil and gas companies by H. Adshirinpour *et al.* (2021). The researchers showed the possibility of applying the method of expert assessments. For this purpose, the paper obtained 15 criteria based on a review of the literature and research literature to evaluate the effectiveness of physical asset management in oil and gas companies. The eight most important evaluation criteria were then determined based on expert opinions and the Delphi fuzzy method, and in the next step, these criteria were weighted using the Fuzzy SWARA method. The conclusions were comparable to the results of current research and indicated that the most important criterion for the operation of equipment is the cost of maintenance.

The study by A. Parida (2007) proposed seven groups of criteria for measuring the effectiveness of maintenance implementation. Groups of performance evaluation indicators included the following indicators: equipment-related indicators; cost/funding indicators; maintenance-related indicators; customer satisfaction indicators; training and growth-related indicators; health, safety, and environment indicators; employee satisfaction indicators. Similarly to the current study, indicators related to equipment performance at the first level include the overall equipment effectiveness indicator (OEE).

K. Peng (2018), the importance of using indicators for any business was emphasised, as they showed the effectiveness and status of operations. Proper use of indicators can trigger the actions needed to improve the business, and they serve as a means of measuring the success of such actions. Maintenance is no exception. The purpose of performance indicators is to provide an overall vision of the company's goals, business strategy, and specific goals.

M. Stefanovic *et al.* (2016) proposed an approach to evaluating and ranking maintenance process indicators, and maintenance cost indicators and maintenance equipment indicators using the fuzzy set approach. The weight values of these indicators were determined using the experience of decision makers from the analysed small and medium-sized enterprises and calculated using the fuzzy set approach. The paper also presented a model for ranking and optimising service efficiency indicators at small and medium-sized enterprises. The presented approach allowed for multi-purpose optimisation of selected key performance indicators as part of optimising maintenance productivity.

The results of the current study were also consistent with the research by C. Murad *et al.* (2022), in which key service performance indicators differ depending on the organisation, goals, strategy, and action plan. The study proposed a method for ranking key performance indicators of energy organisations, and identified six indicators related to operational performance indicators of maintenance. Experts identified the failure rate and serviceability of equipment as the most important indicators.

C. Stenstrom *et al.* (2012) systematised performance indicators for railway infrastructure maintenance. The paper analysed about 130 performance indicators. Such indicators were considered as a single indicator. The indicators listed in this paper were the basis for building a system for measuring the performance of railway infrastructure maintenance. However, the paper did not highlight and rank key indicators.

For hydropower facilities, R. Silva *et al.* (2020) proposed a method for determining maintenance efficiency indicators for asset management based on international standards ISO 55000 and the balanced scorecard (BSC). The results were obtained using a sequential method by which organisations can determine the effectiveness of maintenance. In this paper, the first level of assessment of maintenance efficiency was proposed to be made based on the asset condition index, which showed the share of a controlled physical asset in working condition (%). This indicator correlates with the technical performance indicator – the technical utilisation rate, which was presented in the current study.

The study by R. Pieretti *et al.* (2020) submitted indicators that can be used in the daily life of the company when it comes to ensuring the reliability of equipment. The study also highlighted an important point related to information collection. Information is collected even before a decision is made on a specific indicator, so it is necessary that the databases from which information is obtained are well coordinated. As indicators related to maintenance efficiency, the study recommends using reliability indicators: MTTR, MTBF, MTBR. The current conclusion is fully consistent with the technical performance indicators presented in the current study. Thus, the above-described studies show the feasibility of using key performance indicators to assess the effectiveness of engineering services.

Conclusions

The paper analysed and systematised factors for evaluating the effective use of the maintenance and repair system at metallurgical enterprises. In total, 36 factors were identified, which were described in the relevant literature and relate to industrial enterprises. All performance factors are divided into three groups: technological, organisational, and economic. To identify the dominant factors (key performance indicators) inherent in the system of maintenance and repair of metallurgical enterprises, an expert assessment of factors was carried out using the Delphi method. As a result, five key indicators were identified in the group of technological factors, six key indicators in the group of organisational factors, and three key indicators in the group of economic factors. Further determination of the weighting factors of each key indicator was carried out using the Fuzzy SWARA method based on expert estimates on the fuzzy comparison scale.

Thus, a system of key performance indicators for maintenance and repairs for metallurgical enterprises has been created by their importance (the most important indicator of the group is in the first place, and the least important indicator is in the last place). In the group of technical indicators: technical readiness or availability of equipment; average time between failures; technical utilisation rate; average recovery time; failure rate. In the group of organisational indicators: overall efficiency of equipment; compliance with repair deadlines; coefficient of unscheduled repairs; coefficient of scheduled maintenance work, coefficient of routine maintenance; coefficient of personnel qualification. In the group of economic indicators: cost of maintenance and repair; share of material costs in the total cost of maintenance and repair; share of direct labour costs for maintenance and repairs in the total cost of maintenance and repair.

A set of measures for each group of key performance indicators was proposed, which contribute to a more thorough and professional creation and implementation of an optimal system for managing equipment maintenance and repair activities at a metallurgical enterprise. In case of negative values of technical indicators, it is necessary to focus on assessing the condition of equipment and the quality of spare parts. In case of negative values of organisational indicators, it is necessary to analyse the structure of the maintenance and repair service, the qualifications and number of personnel involved in routine maintenance work, and carry out measures to improve the skills of employees. If economic indicators are negative, it is necessary to analyse maintenance and repair costs and their impact on equipment performance and the causes of downtime. Thus, the use of key performance indicators during the operation of equipment allows focusing on the key shortcomings of engineering services and take corrective actions in advance. It is advisable to focus further development of the system for evaluating the effectiveness of maintenance and repairs on determining their recommendation range, depending on the company's maintenance and repair strategies.

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Conflict of Interest

None.

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Оцінка технічного обслуговування та ремонтів металургійного обладнанняза критеріями ефективності

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Анотація. Підприємства металургійної промисловості відносяться до найбільш капіталомістких виробництв, з високими витратами на технічне обслуговування та ремонт обладнання. Належне управління та ефективна робота обладнання безпосередньо впливає на випуск продукції, безпеку та економічні показники. Мета поточного дослідження полягала у розробці ключових показників ефективності роботи інжинірингових служб, з акцентом на систематизацію показників по технічним, організаційним та економічним групам. Це дозволило вирішити головне питання оперативної оцінки ефективності технічного обслуговування та ремонтів обладнання металургійних підприємств, з використанням розроблених ключових показників. В роботі проаналізовано та класифіковано тридцять шість показників оцінки ефективності. Використовуючи метод експертних оцінок Дельфі, з подальшим поетапним аналізом коефіцієнтів оцінки ваги за допомогою нечіткого методу поетапного аналізу коефіцієнта оцінки ваги, були встановлені ключові фактори оперативного контролю ефективності технічного обслуговування та ремонтів металургійного обладнання. Зазначені фактори систематизовано у три групи. До першої групи увійшли п'ять технічних показників, до другої групи увійшло шість організаційних показників, до третьої групи – три економічні показники ефективності технічного обслуговування та ремонтів металургійного обладнання. Аналіз отриманого рейтингу ключових показників ефективності показав, що до найбільш значущих показників відносяться комплексні (узагальнюючі) показники у кожній групі. Ключовими показниками у кожні групі визначено: коефіцієнт технічної готовності обладнання, показник загальної ефективність обладнання, витратоємність технічного обслуговування та ремонтів обладнання. На підставі рейтингу показників розроблено рекомендації по складанню матриці відповідності та першочерговим заходам у разі негативної динаміки кожної групи показників. Практична значимість роботи полягає у наданні фахівцям служб технічного обслуговування та ремонтів металургійних підприємств критеріїв об'єктивної оцінки поточний стан управління обладнанням, що дозволяє покращувати систему ремонтів

Ключові слова: організаційна структура; рейтинг; експертні оцінки; коефіцієнт технічної готовності; інжинірингові служби; метод Дельфі