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Economic evaluation of the application of intelligent metal processing technologies for reducing enterprise operating costs

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Summary. The relevance of the study is determined by the increasing requirements for the efficiency of industrial enterprises under conditions of resource constraints and external instability caused by Russia's aggression against Ukraine. In this context, the intellectualization of metal processing is considered a key direction for reducing operating costs and improving the controllability of production systems. At the same time, the lack of a coherent economic evaluation framework limits the scalability of such technologies.

The purpose of the article is to substantiate the theoretical and methodological foundations for the economic evaluation of the application of intelligent metal processing technologies in the context of reducing operating costs of industrial enterprises.

Methods. The study employs methods of system analysis, generalization and systematization of scientific approaches, comparative analysis, as well as analytical methods for assessing the economic efficiency of production processes.

Results. The economic essence of intelligent metal processing technologies and their role in transforming production management have been investigated. The mechanisms of influence of intellectualization on the structure of operating costs have been identified, including optimization of processing modes, reduction of defects, improved equipment utilization, and rationalization of energy consumption. Approaches to the economic evaluation of implementation efficiency have been generalized based on the integration of investment, cost, and performance indicators. It has been proven that the economic effect is systemic and delayed in nature, which requires a comprehensive evaluation approach. The main challenges have been identified, including variability of production conditions, data fragmentation, difficulties in measuring intangible effects, and the gap between operational and financial indicators.

Conclusions. It has been proven that improving the efficiency of intelligent technologies requires their phased integration into production processes, the formation of a unified digital environment, and the implementation of continuous monitoring systems for economic results.

Further research should focus on the development of quantitative models for evaluating delayed economic effects, improvement of methods for measuring intangible outcomes of intellectualization, and integration of operational and financial indicators into comprehensive analytical management systems.

Keywords: production efficiency, adaptive control, industrial digitalization, cost optimization, industrial data, technological processes, resource efficiency, predictive maintenance.

CURRENT ISSUES OF ECONOMIC SCIENCES

Економічна оцінка застосування інтелектуальних технологій обробки металів для зниження операційних витрат підприємства

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Анотація. Актуальність дослідження зумовлена зростанням вимог до ефективності функціонування промислових підприємств в умовах ресурсних обмежень і нестабільності зовнішнього середовища, що посилюються внаслідок агресії Росії проти України. У цих умовах інтелектуалізація процесів обробки металів розглядається як ключовий напрям зниження операційних витрат і підвищення керованості виробничих систем. Водночас відсутність узгодженого економічного інструментарію оцінювання її ефективності стримує масштабування відповідних технологій.

Метою статті є теоретико-методичне обґрунтування підходів до економічної оцінки застосування інтелектуальних технологій обробки металів у контексті зниження операційних витрат промислових підприємств.

Методи. У дослідженні використано методи системного аналізу, узагальнення і систематизації наукових підходів, порівняльного аналізу, а також аналітичні методи оцінювання економічної ефективності виробничих процесів.

Результати. Досліджено економічну сутність інтелектуальних технологій обробки металів та їх роль у трансформації виробничого управління. Виявлено механізми впливу інтелектуалізації на структуру

операційних витрат, зокрема через оптимізацію режимів обробки, зменшення браку, підвищення використання обладнання та раціоналізацію енергоспоживання. Узагальнено підходи до економічної оцінки ефективності впровадження інтелектуальних технологій на основі інтеграції інвестиційних, витратних і результативних показників. Доведено, що економічний ефект має системний і відкладений характер, що зумовлює необхідність комплексного оцінювання. Виявлено основні проблеми, пов'язані з варіативністю виробничих умов, фрагментованістю даних, складністю інтерпретації нематеріальних ефектів та розривом між операційними і фінансовими показниками.

Висновки. Доведено, що підвищення ефективності застосування інтелектуальних технологій забезпечується їх поетапною інтеграцією у виробничі процеси, формуванням єдиного цифрового середовища та впровадженням систем безперервного моніторингу економічних результатів.

Перспективи подальших досліджень пов'язані з розробленням кількісних моделей оцінювання відкладених економічних ефектів, удосконаленням методів вимірювання нематеріальних результатів інтелектуалізації та інтеграцією операційних і фінансових показників у комплексні аналітичні системи управління підприємством.

Ключові слова: виробнича ефективність, адаптивне керування, цифровізація виробництва, оптимізація витрат, промислові дані, технологічні процеси, ресурсна ефективність, прогнозне обслуговування.

Problem statement. Modern industrial enterprises, particularly in metallurgy and mechanical engineering, operate under conditions of rising costs, resource constraints, and increasing efficiency requirements, which are further intensified by the economic transformations caused by Russia's aggression against Ukraine. Under these conditions, traditional metal processing approaches, oriented toward fixed regimes and limited adaptability, fail to ensure an adequate level of competitiveness.

Intelligent processing technologies, based on data analysis and adaptive control, create opportunities to optimize technological parameters, reduce losses, and enhance resource efficiency.

At the same time, their implementation outpaces the development of appropriate economic justification. Existing approaches predominantly focus on technological advantages while neglecting a systemic assessment of their impact on operating costs. This complicates investment decision-making and hinders the scaling of innovations. In this regard, there is an increasing need to develop a coherent approach to the economic evaluation of the intellectualization of metal processing, capable of capturing both direct and indirect effects of their application within the enterprise cost structure.

Analysis of recent research and publications. A review of contemporary studies indicates that the economic evaluation of intelligent metal processing technologies aimed at reducing operating costs is formed at the intersection of managerial innovation, production digitalization, intelligent monitoring of technological processes, and financial-analytical substantiation of automation effects. P. Tkachenko examines the effectiveness of animated infographics as a tool for enhancing the comprehensibility of complex financial information, which has methodological significance for presenting the results of economic evaluation of technological solutions and improving managerial perception of cost parameters [1]. I. V. Kryvovyazyuk substantiates the principles of managerial innovation under conditions of information and communication technologization, emphasizing that digital solutions should be assessed not only as technical innovations but also as drivers of business process improvement, resource coordination, and overall enterprise excellence [2]. K. H. Kirkopulo and V. M. Tonkonohyi analyze the application of the Internet of Things (Internet of Things, IoT) and intelligent sensors in monitoring and managing technological processes, demonstrating that real-time detection of deviations and increased control accuracy create preconditions for reducing resource losses, downtime, and non-productive costs in production [3]. P.

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Mykytyuk and V. Flyn investigate mechanisms for managing the use of material resources at the enterprise level, emphasizing that operating cost reduction is directly linked to the rationalization of raw material consumption, optimization of flows, and minimization of overexpenditures, which constitutes an important economic basis for evaluating the intellectualization of metal processing [4].

A significant contribution to understanding industry-specific features is made by studies devoted to intelligent manufacturing in metallurgy and related industries. D. Zhou et al., in a comprehensive review of intelligent manufacturing technologies in China's steel industry, systematize digital tools of automation, industrial analytics, and intelligent control, demonstrating their impact on productivity, energy efficiency, and stability of technological regimes, which is directly related to the reduction of operating costs [5]. Y. Guo et al. extend this research by developing an intelligent production management system based on data mining, showing that analytical processing of production data enhances the validity of decisions regarding resource conservation and cost management [6]. Q. Liu et al. propose a new model of intelligent manufacturing based on human–cyber-physical interaction in non-ferrous metallurgy, where the integration of human control, digital systems, and physical equipment is considered a factor in increasing production adaptability and minimizing losses caused by technological inconsistency [7]. T. Fu et al. investigate intelligent control systems for smelting processes with the integration of large language models, emphasizing that improving the quality of managerial decisions in complex production environments contributes to more efficient resource utilization and reduction of coordination and control costs [8].

A separate group of studies directly traces the relationship between intelligent technologies, production parameters, and the financial performance of enterprises. Y. Gu and Y. Li substantiate the possibilities of financial optimization in precision engineering based on intelligent materials and thermal environment sensors, demonstrating that increased accuracy of technological condition control reduces costs associated with defects, energy consumption, and reprocessing [9]. T. Yang et

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al. conceptualize intelligent manufacturing for the process industry as a system driven by industrial artificial intelligence, where cost reduction is achieved through forecasting, optimization of operating modes, and flexible adjustment of production processes [10]. G. Wu and Y. Liu directly link production automation with financial cost control based on intelligent management technologies, emphasizing that the effect of automation should be measured not only by technical productivity but also by financial savings within a sustainable production system [11]. X. Liu considers the selection of heavy metal detection technologies and improvement of operational efficiency based on a full life-cycle cost approach, which is particularly valuable for developing methodologies for economic evaluation of metal processing technologies, taking into account not only current but also related operational costs [12]. M. Chen et al. examine an environmental cost control system for manufacturing enterprises using artificial intelligence within the value chain of a circular economy, demonstrating that the economic effect of intellectualization is also manifested through the reduction of environmentally driven costs and increased resource efficiency [13].

Studies focusing on energy efficiency and logistics of secondary metal resources are also relevant. S. S. Chaudhari et al., in a review of the current state of artificial intelligence application for improving energy efficiency in metallurgical operations, show that intelligent systems can significantly reduce energy consumption as one of the key components of operating costs in metal production [14]. T. D. Mastos et al. analyze an IoT-based solution for managing scrap metal supply chains within the context of Industry 4.0, substantiating that digital traceability, coordination of flows, and transparent resource management reduce logistical losses, improve supply stability, and indirectly lower operating costs of enterprises [15].

Important contributions also include studies highlighting the role of digital and financial-analytical tools in transforming economic processes and asset management. R. Sharafan et al. examine the tokenization of real-sector assets as a

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driver of transformation in global capital markets, substantiating that digitalization of financial instruments increases asset liquidity and creates conditions for more flexible resource management, which has an indirect impact on cost optimization at the enterprise level [16]. D. Lyushenko et al. investigate financial forecasting of the crypto-asset market through the integration of high-frequency and behavioral data, demonstrating that the application of econometric models combined with big data analytics enhances the accuracy of financial decision-making and can be adapted for evaluating the effectiveness of innovative technologies in production systems [17].

Within the framework of digitalization of asset management, D. Lyushenko, R. Sharafan, and O. Tuholukov emphasize the use of information technologies for creating "digital safes" that ensure the security and control of assets in a digital environment, highlighting the importance of information security and structured data as a basis for effective resource management [18]. At the same time, M. Fedash examines the formation of competency models for training specialists in sensory product evaluation, indirectly confirming the importance of developing human capital and analytical competencies for the effective use of digital and intelligent technologies in modern production and economic systems [19].

Identification of unresolved aspects of the general problem. Despite the expansion of research in the field of production process intellectualization, a comprehensive economic justification of its impact on enterprise operating costs remains lacking. The relationship between adaptive technological solutions and the transformation of cost structures has not been sufficiently disclosed, and there is no coherent approach to evaluating effects that are delayed and predominantly indirect in nature. This is due to the complexity of quantitative interpretation of results, variability of production conditions, and fragmentation of existing analytical approaches.

The uncertainty of these aspects limits the possibility of adequately assessing the economic feasibility of intellectualization and restrains its practical implementation. Therefore, their investigation is necessary for developing a

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comprehensive methodological approach to efficiency evaluation, enabling the substantiation of directions for improving the economic performance of production processes and achieving a reduction in enterprise operating costs.

Formulation of the Article's Objectives (Task Setting). The aim of the article is to substantiate the theoretical and methodological foundations for the economic evaluation of the application of intelligent metal processing technologies to reduce the operating costs of an industrial enterprise.

The objectives of the study are as follows:

1. To reveal the economic essence of the intellectualization of metal processing and its impact on the structure of operating costs.

2. To generalize approaches to efficiency evaluation and identify key challenges in its determination.

3. To substantiate recommendations for improving the efficiency of operating cost reduction.

Main material. Intelligent metal processing technologies form a new level of organization of production processes, within which management shifts from rigidly regulated regimes to adaptive models based on continuous data analysis and self-adjustment of processing parameters. Their economic essence lies in ensuring more rational use of material, energy, and labor resources through increased precision, reduction of defects, and optimization of technological regimes [2, p. 58]. Functionally, such technologies integrate monitoring, analytics, and control systems into a unified digital environment, enabling synchronization of production operations, reduction of time losses, and improvement of product quality stability. As a result, the intellectualization of metal processing acts not only as a technological tool but also as an economic factor transforming the enterprise cost structure (table 1).

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Table 1

Functional features of intelligent metal processing technologies in the system of production management

Functional component	Content of implementation	Economic significance
Adaptive process control	Automatic adjustment of processing modes based on sensor data	Reduction in material and tool costs
Real-time monitoring	Continuous collection of data on processing parameters	Prevention of deviations and reduction of defects
Production data analytics	Use of machine learning algorithms to identify patterns	Cost optimization and productivity enhancement
Equipment condition forecasting	Assessment of wear and probability of failure	Reduction in repair costs and downtime
Integration into the digital environment	Integration of production systems into a unified information platform	Improved controllability and lower operating costs

Source: compiled by the author based on [2, p. 58; 3, p. 49; 6, p. 4065; 7, p. 555; 10, p. 1226].

In the practice of metallurgical and machine-building enterprises, intelligent technologies are implemented as a closed-loop management system in which data from equipment are continuously transformed into control actions. For example, in machining processes, adaptive control systems modify cutting speed and feed rate depending on the actual wear of the tool and fluctuations in material hardness, which makes it possible to stabilize surface quality while simultaneously reducing tool costs and the costs of reworking defective products [6, p. 4065]. In heat treatment, the use of sensor arrays and forecasting models ensures more precise compliance with temperature regimes, thereby reducing energy consumption and the variability of metal properties, which directly contributes to lowering rework costs.

An important shift is the movement of the quality control function toward preventive management: analytical modules detect deviations at the stage of their

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emergence, making it possible to intervene before a defect occurs. This fundamentally changes the cost structure: the share of costs associated with defect correction decreases, while control costs do not rise proportionally due to automation. In the field of equipment operation, predictive models make it possible to determine the point at which components reach critical wear, thus enabling maintenance planning without disrupting the production schedule [10, p. 1226]. As a result, unproductive downtime and the associated revenue losses are reduced.

The intellectualization of technological processes changes the logic of operating cost formation, shifting from fixed standards to dynamic alignment with actual production conditions. This ensures lower cost variability, reduction of unproductive losses, and more accurate allocation of resources across operations, which directly affects their structure (table 2).

Table 2

Mechanisms of the influence of the intellectualization of technological processes on the structure of enterprise operating costs

Area of influence	**Nature of changes in costs**	**Source of economic effect**
Optimization of processing modes	Reduction in variable costs for materials and tools	Precise adjustment of process parameters to actual conditions
Reduction of defects	Lower rework costs and product loss	Early detection and correction of deviations
Increased equipment utilization	Reduction in specific fixed costs	Less downtime and higher workload utilization
Rationalization of energy consumption	Reduction in energy costs	Alignment of operating modes with actual load
Reduction of operational delays	Lower time-related costs and logistics losses	Synchronization of production processes

Source: compiled by the author based on [2, p. 63; 4, p. 241; 9, p. 5; 11, p. 3; 14, p. 1602].

The economic effect arises not from individual solutions but from their systemic interaction within the production cycle. In metal machining, intelligent control systems make it possible to promptly adjust cutting parameters depending on the actual tool load, the microstructure of the material, and thermal deformations.

As a result, both excessive tool consumption and the probability of hidden defects are reduced; under traditional approaches, such defects often become apparent only at the product operation stage and generate deferred costs. In rolling production, the use of forecasting models makes it possible to adjust speed and temperature regimes with due regard to fluctuations in billet characteristics, thereby reducing deviations in thickness and mechanical properties and, consequently, lowering the volume of returns and rework [14, p. 1602].

In modern conditions, defect reduction is achieved primarily through a change in the control point, from final inspection to process-embedded control. For example, machine vision systems detect surface microdefects at early stages of processing, allowing technological parameters to be corrected without losing the entire product. This reduces costs not only for rework but also for the logistics of internal flows of defective products [9, p. 5]. Increased equipment utilization is manifested in a more even loading of production capacities: planning algorithms take into account the actual technical condition of machines and optimize the sequence of operations, thereby avoiding both overloads and downtime. As a result, fixed costs are distributed over a larger volume of output without additional expansion of resources.

The energy component of costs also undergoes substantial changes. In heat treatment and smelting processes, adaptive control systems make it possible to maintain the required temperature regimes while accounting for heat losses and load fluctuations, thereby reducing excessive energy consumption. Conventionally, this means a transition from a “reserve” mode to a “precision provision” mode, in which each unit of energy is used with maximum technological effect [11, p. 3]. The reduction of operational delays, in turn, is achieved through synchronization of production flows, for example, by aligning the rate of billet processing with the capabilities of subsequent stages, which minimizes the accumulation of work in progress and reduces the associated costs.

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To summarize, under modern conditions, intellectualization not only reduces individual cost items but also changes the very mechanism of their emergence, shifting from response to deviations to their prevention. This forms a more predictable, controllable, and economically grounded structure of operating costs, in which losses no longer dominate and are replaced by investments in enhancing the efficiency of the production system.

The economic evaluation of the effectiveness of implementing intelligent technologies in metal processing requires a combination of investment-based and operational approaches, since the result is manifested not only in financial indicators but also in changes in the stability and controllability of production processes (Table 3).

Table 3

Approaches to the economic evaluation of the effectiveness of implementing intelligent metal processing technologies

Evaluation approach	Key analytical focus	Evaluation tools	Type of economic effect
Investment-based	Feasibility of investments in digital solutions	Net Present Value (NPV), Internal Rate of Return (IRR)	Direct financial result
Cost-based	Change in the structure of operating costs	Cost analysis, process costing	Cost reduction and resource optimization
Performance-based	Dynamics of production efficiency	Key Performance Indicators (KPI), Overall Equipment Effectiveness (OEE)	Increased productivity and stability
Comparative	Difference in results before and after implementation	Benchmarking, variance analysis	Identification of relative effect
Integrated	Alignment of financial and non-financial indicators	Balanced Scorecard, multicriteria analysis	Comprehensive effect of systemic changes

Source: compiled by the author based on [1; 2, p. 71; 6, p. 4068; 11, p. 4; 13].

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In the practice of evaluating intelligent technologies, a key role is played by the formalization of effects through basic analytical relationships that make it possible to compare investment expenditures with the results obtained. The investment-based approach is grounded in the determination of net present value:

$$NPV = \sum_{t=1}^{T} \frac{CF_t}{(1+r)^t} - I_o \quad (1)$$

which makes it possible to assess the feasibility of investments in digital solutions while taking into account the time factor. In production conditions, this indicator is used, for example, in the implementation of intelligent control systems for technological modes, where the effect accumulates gradually through the reduction of losses and the enhancement of process stability [11, p. 4].

The cost-based approach specifies the economic result through the change in operating costs:

$$\Delta C = C_{before} - C_{after} \quad (2)$$

which makes it possible to directly capture the effect of optimizing resource use. In practice, this is manifested in lower expenditures on tools, energy, and defect rework as a result of more precise adjustment of technological parameters and reduced deviations.

The evaluation of the performance of intellectualization is complemented by the indicator of overall equipment effectiveness:

$$OEE = A * P * Q \quad (3)$$

which reflects the integrated impact of changes on equipment availability, productivity, and product quality. In real production systems, an increase in this indicator captures not only growth in output volume but also a reduction in process variability, which has a long-term economic effect.

The practical application of these approaches demonstrates that their combination is the most informative. For example, in high-precision machining processes, the implementation of intelligent systems is first reflected in improvements in OEE due to quality stabilization and reduced downtime; these changes are then transformed into cost reductions captured through ΔC, and only at the final stage do they generate a positive NPV [13]. In metallurgical production, a similar logic is observed in heat treatment processes, where lower energy consumption and reduced variability of temperature regimes initially have a technological effect, but over time this effect is converted into a financial result through cost reduction and increased yield of conforming products.

Thus, under modern conditions, the evaluation of the effectiveness of intelligent technologies should be constructed as a multilevel system in which financial, cost-based, and operational indicators are considered in their interrelationship. This makes it possible to take into account both direct results and deferred effects arising from enhanced controllability and stability of production processes.

The evaluation of the economic effects of the intellectualization of metal processing processes is complicated by the dominance of indirect and deferred results, which are manifested through the stabilization of production parameters and reduced process variability and are not always adequately reflected in financial indicators. One of the key problems is the separation of the effect of intelligent technologies from related changes, such as equipment modernization, organizational transformations, and personnel upskilling, which together shape the aggregate result and complicate the establishment of causal relationships [1].

A significant limitation is the variability of production conditions: material properties, processing modes, technical condition of equipment, and the level of digital maturity of the enterprise generate unstable evaluation results that are difficult to unify. An additional problem is the fragmentation and heterogeneity of data, which reduces the accuracy of analytics and complicates the integration of information from different production and management systems. This is further aggravated by the gap between operational indicators and financial reporting, in which improvements at the process level are not always transformed into a measurable economic result.

Another challenge lies in the quantitative interpretation of intangible effects, such as lower technological risks, greater flexibility, and improved predictability of production, all of which have economic value but no direct monetary expression. The problem of temporal asynchrony is also important: investments are made once, whereas the effect is formed gradually and depends on data accumulation and system adaptation [13]. Under these conditions, the risk increases both of underestimating long-term effects and of overestimating them at the planning stage.

At the methodological level, the absence of a coherent approach integrating investment-based, cost-based, and performance-based aspects leads to fragmented evaluation. In practice, this is compounded by the limited integration of information systems and a shortage of competencies required for interpreting analytical results, which reduces the accuracy and applied value of economic assessments of the intellectualization of production processes.

Enhancing the effectiveness of intelligent metal processing technologies should be ensured through their phased integration into the production system with a focus on achieving measurable economic results. Practice shows that the most justified approach is implementation in critical production areas, namely operations with a high cost share or significant variability of parameters, where the optimization potential is greatest. Such an approach makes it possible to localize the effect, obtain reliable data on cost changes, and scale solutions without excessive investment burden.

It is also important to ensure the integration of intelligent solutions with the existing information and production systems of the enterprise, because without coordinated data flows and management loops, even effective technologies do not produce a systemic economic result. It is advisable to focus on creating a unified

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digital environment in which data from technological equipment, planning systems, and accounting systems are used to generate control decisions in a near-real-time mode. This ensures consistency between technological parameters and economic indicators.

Of practical significance is also the implementation of an effectiveness evaluation system that combines financial and operational indicators. It is advisable to use not only payback indicators but also process stability parameters, defect rates, equipment utilization, and energy consumption, which makes it possible to evaluate results comprehensively and to adjust managerial decisions in a timely manner. In this regard, the key transition is from one-time evaluations to continuous monitoring of the effect of intellectualization.

Particular attention should be paid to the quality and structuring of data, since the effectiveness of intelligent technologies directly depends on their reliability. It is advisable to implement procedures for data standardization, cleaning, and verification, which make it possible to improve analytical accuracy and reduce the risk of erroneous managerial decisions. At the same time, it is necessary to ensure the development of personnel competencies in the field of data interpretation and the use of analytical tools, since the human factor ultimately determines the level of practical realization of the potential of intellectualization.

The reduction of operating costs is also achieved through a focus on preventive process management, namely identifying and eliminating the causes of deviations before they are transformed into costs. In this context, it is advisable to use predictive models for maintenance planning, optimization of processing modes, and synchronization of production flows. Such an approach makes it possible to minimize downtime, reduce repair costs, and decrease losses caused by defects.

Under current conditions of instability in the external environment, it is also advisable to consider the flexibility of the production system as a separate efficiency criterion. Intelligent technologies should be used not only to optimize current costs but also to ensure adaptability to changes in demand, resource availability, and technological conditions. This allows an enterprise not only to reduce costs but also to maintain the stability of economic results in the long term.

Conclusions. The study has established that the intellectualization of metal processing transforms the mechanism of operating cost formation, shifting it from the reactive elimination of deviations to their preventive avoidance, thereby reducing process variability, stabilizing quality, and ensuring more efficient use of resources. It has been demonstrated that the economic effect is systemic and deferred in nature; therefore, its adequate evaluation is possible only on the basis of an integrated approach combining investment-based, cost-based, and performance-based indicators. It has been found that the key problems include the difficulty of separating the effect of intellectualization from related changes, the variability of production conditions, data fragmentation, and the gap between operational and financial indicators. Additional difficulties are associated with the evaluation of intangible effects and temporal asynchrony between investments and results. It has been substantiated that greater effectiveness is achieved through the phased implementation of technologies in critical areas, their integration into a unified digital environment, ensuring data quality, and the transition to continuous monitoring of effects with a focus on preventive cost management. Prospects for further research are associated with the development of quantitative models for evaluating deferred effects, the improvement of methods for measuring intangible results, and the integration of operational and financial indicators into comprehensive analytical systems.

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