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Impact of digital twins on the economic efficiency of quality management of metal products in industrial mechanical engineering

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Abstract. The relevance of the study is determined by the growing requirements for the quality of metal products under increasingly complex production conditions and the need to improve the economic efficiency of management in industrial mechanical engineering. Traditional quality control approaches do not ensure sufficient proactivity and economic justification of decisions, which necessitates the application of digital technologies.

The aim of the study is to examine the impact of digital twins on the economic efficiency of quality management of metal products in industrial mechanical engineering and to substantiate directions for improving the effectiveness of managerial decisions.

Methods. The research employs methods of system analysis, generalization, structural-functional approach, and logical-analytical modeling.

Results. The economic essence and functional capabilities of digital twins in the quality management system have been investigated. The mechanisms of their influence on the formation of economic results of production have been identified, including adaptive process control, prediction of deviations, and integration of analytical tools into decision-making. Approaches to integrating digital twins into quality control and assurance processes have been generalized, ensuring a transition to end-to-end quality management. It has been proven that the economic effect is formed through the coordination of “cost – time – quality” parameters within a unified digital environment. The main scientific and practical problems of evaluating efficiency have been identified, including the lack of unified methodologies, the difficulty of quantifying indirect effects, and the dependence on data quality.

Conclusions. Practical recommendations for improving the economic efficiency of quality management based on the phased implementation of digital twins, their integration into planning systems, and the establishment of feedback loops have been substantiated. It has been established that their application contributes to cost reduction, defect minimization, and improved stability of product quality.

Prospects for further research are associated with the development of quantitative models for evaluating the economic efficiency of digital twins, the formation of integrated “quality–economics” indicators, and the study of scaling mechanisms for digital solutions in complex production systems.

Keywords: industrial analytics, adaptive management, production processes, digital transformation, cost optimization, intelligent systems.

Вплив цифрових двійників на економічну результативність управління якістю металопродукції в галузевому машинобудуванні

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Анотація. Актуальність дослідження зумовлена зростанням вимог до якості металопродукції в умовах ускладнення виробничих процесів і необхідністю підвищення економічної результативності управління в галузевому машинобудуванні. Традиційні підходи до контролю якості не забезпечують належного рівня превентивності та економічної обґрунтованості рішень, що актуалізує використання цифрових технологій.

Метою дослідження визначено вивчення впливу цифрових двійників на економічну результативність управління якістю металопродукції в галузевому машинобудуванні та обґрунтування напрямів підвищення ефективності відповідних управлінських рішень.

Методи. У процесі дослідження використано методи системного аналізу, узагальнення, структурно-функціонального підходу та логіко-аналітичного моделювання.

Результати. Досліджено економічну сутність і функціональні можливості цифрових двійників у системі управління якістю. Виявлено механізми їх впливу на формування економічних результатів виробництва через адаптивне керування процесами, прогнозування відхилень та інтеграцію аналітичних інструментів у прийняття рішень. Узагальнено підходи до інтеграції цифрових двійників у процеси контролю та забезпечення якості, що забезпечують перехід до наскрізного управління якістю. Доведено, що економічний ефект формується як результат узгодження параметрів «витрати – час – якість» у межах єдиного цифрового контуру. Виявлено основні наукові та практичні проблеми оцінювання ефективності, зокрема відсутність уніфікованих підходів, складність кількісного виміру непрямих результатів і залежність від якості даних.

Висновки. Обґрунтовано практичні рекомендації щодо підвищення економічної ефективності управління якістю на основі поетапного впровадження цифрових двійників, інтеграції їх у системи планування та формування замкненого циклу зворотного зв'язку. Встановлено, що їх використання сприяє зниженню витрат, скороченню браку та підвищенню стабільності якості продукції.

Перспективи подальших досліджень пов'язані з розробленням кількісних моделей оцінювання економічної результативності цифрових двійників, формуванням інтегрованих систем показників та дослідженням механізмів масштабування цифрових рішень у складних виробничих системах.

Ключові слова: промислова аналітика, адаптивне управління, виробничі процеси, цифрова трансформація, оптимізація витрат, інтелектуальні системи.

Introduction

Relevance of the problem. The relevance of this study is driven by the increasing requirements for the quality of metal products in a highly competitive sectoral mechanical engineering environment and the need to enhance the economic performance of managerial

decision-making. Traditional quality control approaches based on ex post diagnostics and selective inspection are becoming less effective in complex production systems, where the role of dynamic factors, process parameter variability, and the integration of multiple technological stages is growing. This necessitates a transition to proactive management models capable of ensuring continuous monitoring, deviation forecasting, and prompt adjustment of production regimes.

In this context, digital twins, as a tool for synchronizing the physical and digital characteristics of products and processes, open up new opportunities for improving the accuracy of quality management. Their application enables the integration of data from various sources, simulation of product behavior across all stages of the life cycle, and evaluation of the economic consequences of managerial decisions prior to their implementation. At the same time, the issue of quantitatively measuring the impact of digital twins specifically on the economic performance of quality management in metal products remains insufficiently studied, which reduces the validity of investment decisions in relevant digital solutions. This determines the need for an in-depth scientific analysis of the outlined problem, taking into account the specifics of sectoral mechanical engineering.

Analysis of recent research and publications. A review of contemporary studies indicates the gradual formation of a coherent scientific approach to understanding the role of digital twins in improving the economic performance of quality management in metal products within sectoral mechanical engineering. V. S. Doroshenko substantiates the feasibility of applying digital twins in the topological optimization of cast structures in additive manufacturing, demonstrating that the integration of virtual modeling at early design stages reduces material consumption and costs, directly affecting economic quality indicators [1]. Expanding this direction, V. S. Doroshenko and co-authors emphasize the use of artificial intelligence methods in combination with digital twins to enhance the accuracy of designing casting technologies and metamaterials, thereby reducing defects and improving quality stability [2].

S. A. Mekhovych and co-authors investigate the impact of digitalization processes on design activities of enterprises, highlighting that the implementation of digital twins transforms approaches to quality management through the integration of product life cycle data [3]. In further studies, S. A. Mekhovych and Ye. V. Trush substantiate the concept of flexible intelligent design and manufacturing systems, where digital twins act as a key element of adaptive quality and cost management [4]. At the same time, O. I. Amosha and V. A. Nikiforova analyze global practices in the development of smart manufacturing in metallurgy, identifying digital twins as a fundamental technology for synchronizing production processes and improving resource efficiency [5]. K. M. Shcherbyna and N. P. Meshko complement these approaches by considering digitalization as a basis for forming innovative business models of metallurgical enterprise management, where product quality serves as a key competitiveness factor [6].

A significant contribution to the development of theoretical and applied aspects of digital twin usage in quality management systems has been made by foreign researchers. A. Ullah and co-authors substantiate the concept of cognitive digital twins as a tool for predictive quality management, enabling real-time process optimization and reduction of quality control costs [7]. B. De Ketelaere and co-authors consider digital twins as a key element of quality engineering that ensures the integration of physical and digital data to improve the accuracy of product parameter evaluation [8]. C. Zhuang and co-authors propose a digital twin-based quality management method using hybrid algorithms, which enhances the efficiency of controlling assembly processes in high-tech manufacturing [9].

M. Grieves develops the concept of certified digital twins, emphasizing their importance for virtual product testing and reducing costs associated with physical testing, which has a direct economic effect [10]. Z. Huang and Z. Yan substantiate the use of digital twin models employing deep learning methods for product quality management, enabling the automation of

decision-making processes [11]. D. R. Gunasegaram and co-authors demonstrate the effectiveness of digital twins in metal additive manufacturing, particularly in reducing defects and optimizing process parameters [12].

P. Catti and co-authors propose a hybrid approach to building digital twins for proactive quality control, which reduces defect correction costs and increases production efficiency [13]. L. Wu and co-authors generalize approaches to the application of digital twins in high-precision machining, emphasizing their role in ensuring parameter stability and reducing production losses [14]. K. Lu and co-authors explore the possibilities of surface quality monitoring during machining using digital twins, facilitating real-time adjustment of technological parameters and improving economic efficiency [15].

R. Sharafan co-authors examine the impact of digital transformation instruments on the functioning of the real sector, substantiating that the integration of innovative digital solutions contributes to the restructuring of economic processes and enhances the efficiency of capital utilization, which indirectly confirms the importance of data-driven approaches in improving the economic outcomes of production systems [16].

R. Bondarchuk and co-authors analyze financial and credit mechanisms for supporting innovation-oriented enterprises, emphasizing that the effectiveness of implementing advanced technological solutions, including digital models, depends on the availability of appropriate financial instruments and institutional support, which determines the scalability and economic feasibility of digital twin deployment in industrial production [17].

Identification of unresolved issues. Despite the active implementation of digital twins in production systems, their economic role in the context of quality management of metal products remains insufficiently defined – there is no consistent understanding of how changes in technological parameters are transformed into economic outcomes. Existing studies are predominantly focused on the technical capabilities of digital models, which leads to fragmentation in approaches to their integration into quality control and assurance processes.

A critically unresolved issue remains the quantitative assessment of economic performance, particularly regarding indirect effects and the impact of uncertainty, which limits the feasibility of informed application of such solutions in practice. In this regard, there is a need for a systematic study of the relationship between quality, costs, and managerial decisions, which determines the logic and direction of this research.

The purpose of the article is to investigate the impact of digital twins on the economic performance of quality management of metal products in sectoral mechanical engineering and to substantiate directions for improving the efficiency of relevant managerial decisions.

Objectives of the article:

1. To reveal the economic essence and generalize the functional capabilities of digital twins in the quality management system of metal products.
2. To characterize the mechanisms of their impact on production economic results and identify problems in performance evaluation.
3. To substantiate practical recommendations for improving the economic efficiency of quality management based on their implementation.

Scientific novelty. The scientific novelty of the study lies in the development of theoretical approaches to assessing the impact of digital twins on the economic performance of quality management of metal products through substantiating an integrated relationship of the parameters “quality – cost – time” and systematizing the mechanisms of their alignment within a unified digital management contour.

Practical significance. The practical significance lies in the possibility of applying the proposed approaches to improve the efficiency of quality management in mechanical engineering enterprises through the implementation of digital twins, ensuring cost reduction, defect minimization, and increased stability of production processes.

Methodology

Research methods. System analysis methods were used to identify relationships between technological and economic parameters; generalization was applied to develop approaches to digital twin integration; structural and functional analysis was employed to determine their role in quality management systems; logical-analytical modeling was used to substantiate mechanisms influencing economic outcomes.

Data sources. The information base includes results of scientific research in the field of digital twins and quality management, analytical materials on industrial digitalization, and generalized data from the practice of sectoral mechanical engineering enterprises.

Analysis tools. Analytical models for assessing the “quality – cost – time” relationship, elements of process modeling of production systems, and tools for comparative analysis of alternative managerial decisions were applied.

Research limitations. The study has a generalizing character and is focused on typical operating conditions of sectoral mechanical engineering enterprises, which opens opportunities for further refinement of the results considering the specifics of individual production systems.

Results

Digital twins form a new paradigm of quality management of metal products by integrating physical production objects with their virtual models operating in real time based on sensor data and production analytics. Their economic essence lies in reducing transaction costs of control, increasing decision-making accuracy, and minimizing losses from defects through the transition from reactive to preventive quality management. Functionally, digital twins ensure continuous monitoring of technological process parameters, identification of deviations, forecasting of final product quality, and optimization of production regimes considering economic efficiency criteria (table 1).

Table 1

Functional capabilities of digital twins in the quality management system of metal products

Function	Implementation content	Economic effect
Real-time monitoring	Collection and processing of data on technological parameters (temperature, pressure, alloy composition)	Reduction in quality control costs — prompt detection of deviations
Process simulation	Reproduction of production processes in a digital environment	Reduction in the costs of experiments and testing
Quality forecasting	Evaluation of product characteristics before the completion of production	Reduction in defects and rework costs
Optimization of operating modes	Selection of optimal production parameters based on models	Increased productivity and resource efficiency
Data integration	Consolidation of information from different production systems	Improved validity of managerial decisions

Source: compiled by the author based on [1, p. 55; 2, p. 78; 7; 8, p. 405; 10; 12].

The systematic use of the above functional capabilities of digital twins in modern mechanical engineering demonstrates a transition from fragmented control to integrated quality management, where the key issue is no longer merely the detection of a defect, but the ability to prevent its occurrence at the stage of metal property formation, namely during melting, casting, or heat treatment processes. In particular, in the production of high-strength steels, digital twins of technological units make it possible to correlate cooling temperature–

rate parameters in real time with the predicted mechanical properties, thereby preventing internal stresses and microcracks without additional costs for post-production inspection [1, p. 55]. In rolling production, their application ensures dynamic adjustment of deformation modes depending on variations in the chemical composition of billets, thus minimizing geometric deviations and reducing the share of products requiring additional finishing [7].

The economic effect is manifested not only in the direct reduction of defects, but also in a change in the cost structure: the share of expenditures on preventive management increases, whereas the costs of defect correction and equipment downtime decrease. The practice of heavy mechanical engineering enterprises shows that the integration of digital twins with resource planning systems and technical diagnostics makes it possible to synchronize quality parameters with production constraints. For example, in the manufacture of large-sized metal structures, such models allow the impact of deviations in welding modes on the long-term reliability of a product to be assessed, thereby reducing the risks of warranty costs [10]. At the same time, the effect of reducing experimental cycles is also significant, since instead of a series of physical tests, variable digital simulation is used, which accelerates the introduction of new steel grades or processing technologies without loss of quality.

Thus, the digital twin acts not only as a control tool, but also as an economically oriented mechanism for aligning the technological and financial parameters of production. It makes it possible to quantitatively relate the quality characteristics of metal products to resource consumption, production cycle duration, and deviation risks, thereby forming the basis for more substantiated and timely managerial decisions under real production conditions.

The formation of the economic results of production in sectoral mechanical engineering under the influence of digital twins occurs through the transformation of production process management mechanisms, from statically predetermined parameters to adaptive operating modes that change according to the actual condition of equipment, materials, and the production environment. In this context, the digital twin performs not only a representational function, but also serves as a tool for the preliminary selection of managerial decisions, making it possible to evaluate their production-related and economic consequences before physical implementation. This fundamentally changes the logic of result formation: the economic effect is generated as an integrated consequence of controlled changes in process parameters rather than as an ex post assessment of deviations (table 2).

Table 2

Mechanisms of the influence of digital twins on the formation of economic production results in mechanical engineering

Mechanism of influence	Essence of action	Key production parameters of influence	Economic interpretation of the result
Adaptive process control	Dynamic adjustment of production parameters based on current data	Energy intensity of processes, material consumption, stability of operating modes	Reduction in unit costs — increase in resource efficiency
Virtual validation of decisions	Testing of scenarios in a digital environment before implementation	Duration of production preparation, volume of experimental operations	Reduction in implementation costs — lower risk of inefficient investments
Predictive assessment of deviations	Identification of potential problems at early stages	Defect rate, quality stability, repeatability of processes	Minimization of losses from defects — reduction in rework costs
Alignment of production flows	Synchronization of quality, time, and volume parameters	Equipment utilization, cycle duration, volume of work in progress	Acceleration of resource turnover — reduction in downtime

Intelligent decision-making	Use of analytical models to support management	Forecast accuracy, response speed, variability of scenarios	Improved validity of decisions — stability of economic results
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Source: compiled by the author based on [3, p. 72; 4, p. 50; 7; 9; 13; 15, p. 2042].

The outlined mechanisms in sectoral mechanical engineering are systemic in nature and are based on the integration of digital twins into the contours of operational and strategic production management. Adaptive process control ensures that technological modes are maintained within economically optimal ranges even under variability of input raw materials – in particular, in casting and heat treatment processes, deviations in temperature curves or cooling rates are promptly corrected with due regard to their impact on cost and stability of metal properties [4, p. 50]. This makes it possible to avoid excessive energy and material consumption, which under traditional conditions is compensated for by excessive safety margins or repeated processing.

Virtual validation of managerial and technological decisions effectively changes the structure of preparatory and production costs – part of experimental operations is transferred to a digital environment, where the impact of changes in processing parameters, alloy composition, or product configuration on cycle duration and resource load is assessed. In the production of complex mechanical engineering components, this makes it possible to reduce the number of pilot runs and decrease the likelihood of technological errors that lead to losses of time and materials [15, p. 2042].

Predictive assessment of deviations ensures early identification of trends that may potentially lead to defects, while the key factor is not the forecasting itself, but the ability to quantitatively relate the risk of defects to the cost of their prevention. In rolling production or machining processes, this is manifested in the timely adjustment of equipment loads or modification of cutting parameters – preventing the formation of latent defects and reducing the share of products requiring additional inspection or rework.

The alignment of production flows based on digital twins ensures synchronization of operational stages not only in terms of time parameters, but also in terms of quality requirements – this reduces the accumulation of work in progress and balances the utilization of production capacities. This is particularly important for enterprises with multi-stage technological cycles, where gaps between operations form a significant share of indirect costs. Intelligent decision-making, in turn, shifts management into the domain of scenario-based analysis – each decision is evaluated through a system of indicators reflecting its impact on costs, production duration, and product quality [13]. This logic makes it possible to form economic results as a controllable parameter of the production system rather than as a final indicator that merely records the consequences of already implemented decisions.

The integration of digital twins into quality control and assurance processes of metal products is formed as a multi-level system combining technological, informational, and managerial contours. Unlike the isolated implementation of individual digital tools, the digital twin acts as a core element that ensures consistency of data, control procedures, and quality criteria across all stages of the production cycle. This enables a transition from fragmented inspection operations to a comprehensive quality assurance model – where control is embedded directly into the process of value creation, and managerial actions are carried out based on a holistic understanding of the state of the object and its operating environment (table 3).

Table 3

Approaches to the integration of digital twins into quality control and assurance processes of metal products

Integration approach	Implementation principle	Process coverage level	Expected result
Embedded integration	Integration of the digital twin directly into technological operations	Individual production stages	Increased accuracy of parameter control during processing
Platform integration	Use of a unified digital platform to integrate data and models	Production unit or line	Consistency of data and control procedures
End-to-end integration	Integration of all product life cycle stages into a single digital model	Full production cycle	Ensuring continuous quality control
Analytics-oriented integration	Use of models to support decision-making in the field of quality	Management level	Improved validity of quality-related decisions
Ecosystem integration	Inclusion of suppliers and customers in the digital contour	Inter-organizational level	Increased transparency and stability of quality

Source: compiled by the author based on [5, p. 90; 6, p. 165; 8, p. 406; 11; 14].

The practical value of these approaches is manifested in their combined application depending on the structure of production and quality requirements – none of the approaches operates in isolation, and their combination forms a controllable quality loop with varying degrees of integration depth. Embedded integration, in particular, becomes critical in high-precision machining – the digital twin of a machine tool allows real cutting modes to be correlated with model-based constraints during operation, taking into account tool wear, thermal deformations, and vibrations. As a result, decisions on parameter adjustment are made before deviations evolve into defects – which significantly differs from traditional post-process inspection [6, p. 165].

Platform integration provides a different level of impact – it eliminates the gap between local control systems and production management. In practice, this means that measurement results obtained, for example, at non-destructive testing stages immediately influence the settings of preceding or subsequent operations – forming a closed information loop where each deviation generates a controlled feedback response [14]. This is particularly important for multi-stage metal processing, where quality is formed progressively and the accumulation of even minor errors may lead to product rejection at final stages.

End-to-end integration enables a transition from controlling individual parameters to managing cause-and-effect relationships in quality formation – for instance, in the production of critical components for energy or transport engineering, a digital twin makes it possible to trace how variations in raw material composition affect material behavior during processing and, consequently, operational characteristics. This creates the basis for shifting part of the control from final stages to earlier ones, where corrective actions are less costly.

Analytics-oriented integration changes the approach to quality-related decision-making – instead of strict adherence to standards, a range of acceptable decisions is formed, within which the option with the best ratio of cost and product characteristics is selected. This logic is applied, in particular, when balancing machining accuracy and productivity, where excessive quality improvement may not be economically justified [11]. Ecosystem integration

complements internal processes through external interactions – in practice, this means that material suppliers operate with digital specifications synchronized with the manufacturer's production models, while operational data from product usage can be fed back to adjust quality parameters at the production stage.

In summary, the integration of digital twins transforms the very architecture of quality management – control ceases to be a separate function and becomes embedded in the value creation process, where each technological decision has a directly measurable impact on the final result.

Enhancing the economic efficiency of quality management of metal products through the implementation of digital twins should be carried out via the phased formation of an integrated management contour, in which the digital model is directly linked to key economic performance indicators. First, it is necessary to identify critical quality parameters that have the greatest impact on costs and outcomes – these should be prioritized for integration into the digital twin. Next, consistency of data sources and their linkage to specific technological operations should be ensured, eliminating gaps between measurement and decision-making. It is also essential to implement forecasting models focused not only on technical deviations but also on their economic consequences – enabling the selection of management options considering costs, cycle duration, and quality levels. Particular attention should be paid to integrating the digital twin into production planning systems, ensuring synchronization of quality indicators with resource constraints. At the same time, feedback mechanisms must be established so that control results are used to adjust process parameters rather than merely record deviations. A key condition is also the training of personnel to work with analytical tools and the institutionalization of procedures for using digital models in managerial decision-making.

The implementation of these recommendations involves the gradual deployment of the digital twin as an element of the quality management system, with a clear definition of transition stages from local solutions to an integrated model of production system operation (fig. 1).

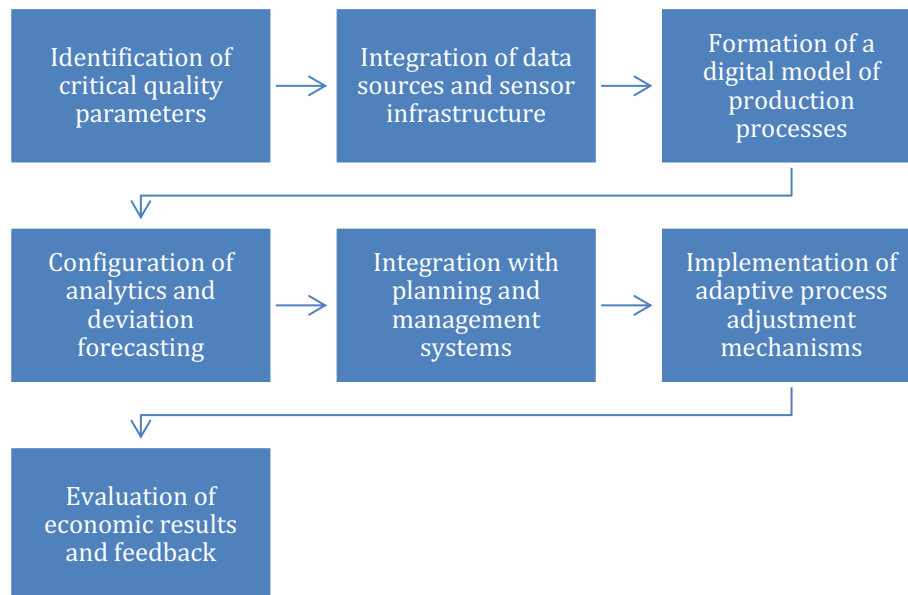


Fig. 1.1. Scheme for implementing digital twins in the quality management system of metal products

Source: developed by the author

The use of such an algorithm implies a gradual reduction of uncertainty in production processes through the transition to controllable quality parameters. At the initial stage, the enterprise gains the ability to locally control critical product characteristics; however, already at the stage of data integration, an informational basis for comprehensive analysis is formed.

The subsequent implementation of a digital model makes it possible not only to monitor the current state, but also to evaluate the consequences of changes in technological modes prior to their implementation – which reduces the likelihood of costly errors.

As integration with planning systems progresses, the effect extends to the level of production organization – quality parameters begin to be taken into account in resource allocation and production scheduling, making it possible to avoid equipment overload and the growth of indirect costs. The introduction of adaptive adjustment ensures prompt response to deviations without interrupting the process, while the use of feedback creates a cumulative effect – the system gradually improves forecasting accuracy and result stability.

Under modern conditions, this implies a transition to a model in which the economic efficiency of quality management is formed as a result of continuous optimization of interrelated parameters “cost – time – quality”. The expected effect is manifested in a reduction in the defect rate, lower rework costs, increased productivity, and stabilization of product quality, which collectively ensures enhanced competitiveness of the enterprise.

Discussion

Interpretation of results. The obtained results confirm that digital twins form a qualitatively new logic of quality management of metal products, within which economic performance is ensured not through the elimination of defect consequences, but through their prevention based on predictive analytics and adaptive process parameter control. It has been established that the key shift lies in moving from a control function to an integrated management function, where quality, costs, and production cycle duration are considered as interrelated variables of a single system. In this context, the digital twin acts as a tool for synchronizing technological and economic parameters – enabling minimization of process variability, improvement of product characteristic stability, and more rational use of resources. At the same time, the results indicate that the economic effect is cumulative in nature and is formed through a set of local optimizations – reduction of defects, decrease in experimental operations, improvement of forecasting accuracy, and alignment of production flows.

Comparison with other studies. The obtained findings are consistent with studies in which digital twins are considered as a tool for improving the accuracy of quality management and optimizing production processes [8, p. 405; 10; 12]. In particular, the thesis regarding their ability to enable virtual testing and reduce the costs of physical experiments is confirmed [10], as well as their role in integrating data to increase the reliability of quality parameter evaluation [8, p. 406]. In addition, the results correlate with approaches to predictive quality management, where the use of analytical models makes it possible to minimize deviations even before the completion of the production cycle [7; 9]. At the same time, in contrast to existing studies that primarily focus on technical aspects of digital twin functioning, the present work deepens the economic interpretation of their impact through the categories of costs, productivity, and resource efficiency. Furthermore, provisions concerning the integration of digital twins into flexible production systems [4, p. 50] and their role in transforming business models of industrial enterprises [6, p. 165] have been further developed, allowing them to be considered as a system-forming element of quality management.

Scientific novelty. The scientific novelty of the obtained results lies in the development of theoretical and methodological foundations for assessing the impact of digital twins on the economic performance of quality management of metal products. For the first time, an integrated model of the relationship “quality – cost – time” has been substantiated as a fundamental basis for the formation of economic effects from the use of digital twins in sectoral mechanical engineering. Approaches to defining the functional capabilities of digital twins have been improved through their systematization not only according to technological, but also economic criteria, which makes it possible to evaluate their impact through changes in cost structure and production efficiency parameters. The substantiation of mechanisms for the

formation of economic results has been further developed, in particular through adaptive control, predictive analytics, and integration of production processes – ensuring a transition from a reactive to a proactive quality management model. A conceptual approach to integrating digital twins into management contours has also been proposed, involving the phased formation of a closed feedback loop between technological parameters and economic outcomes.

Practical significance. The practical significance of the study lies in the possibility of applying the obtained results to improve the efficiency of quality management of metal products at sectoral mechanical engineering enterprises. The proposed approaches enable enterprises to transition to more substantiated decision-making based on data and models, contributing to reduced quality control costs, lower defect rates, and optimized resource utilization. Practical implementation involves introducing digital twins as a tool for integrating technological and economic indicators into a unified management system – ensuring consistency of production processes and increasing their stability. The use of predictive models allows enterprises to minimize the risks of inefficient decisions and reduce the duration of preparatory and production cycles. In addition, the results can be applied in developing enterprise digital transformation strategies, forming performance evaluation systems, and improving production planning processes. The implementation of the proposed solutions contributes to increasing enterprise competitiveness through achieving stable product quality and reducing production costs.

Conclusions

The study establishes that digital twins transform the economic logic of quality management of metal products – the effect is formed not as a consequence of defect elimination, but as a result of preventive control of process parameters based on data and modeling. It is demonstrated that economic performance is determined by the alignment of cost, time, and quality, while key factors include adaptability of operating modes, deviation forecasting, and integration of control into the production process.

It has been identified that the main challenges include the lack of unified approaches to effect assessment, the complexity of quantitatively measuring indirect results, uncertainty regarding the contribution of digital twins to overall economic outcomes, as well as data quality limitations and difficulties in integration into management processes. An additional constraint is the time lag between investment and the realization of effects.

It is substantiated that efficiency improvement is possible under conditions of systematic integration of digital twins into management contours with a focus on critical quality parameters, the use of economically oriented analytics, and the implementation of a closed feedback loop. Prospects for further research are related to the development of quantitative evaluation models, integrated “quality–economics” indicator systems, and approaches to scaling digital solutions in complex production systems.

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