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INDUSTRIAL AND MANUFACTURING ENGINEERING AS THE BASIS OF QUALITY MANAGEMENT IN HIGH-TECH PRODUCTION WITH THE IMPLEMENTATION OF GREEN AND SOCIAL INNOVATIONS

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Abstract: *This paper examines the role of Industrial and Manufacturing Engineering (IME) as a methodological foundation for quality management in high-tech production environments, which is implemented within the context of digital transformation and the adoption of green and social innovations. The strategic value of high-tech manufacturing systems in forming the economy's innovative potential, generating technological spillovers, and supporting competitiveness is substantiated. The essence and restrictions of classical quality management systems with their application to complex cyber-physical production environments are disclosed, and the conceptual foundations of their transformation within the Quality 4.0 paradigm are characterised. Engineering approaches and the tools of IME are described from the position of ensuring product quality at the strategic, tactical, and operational levels of production systems management.*

The methodological basis of the research is formed by the system, interdisciplinary, and structural & functional approaches. Other methods employed include theoretical analysis of scholarly literature and materials of international organisations, comparative and content analysis, induction and deduction, and conceptual modelling of synergetic effects of integrated managerial systems.

The scientific value of this work lies in the comprehensive study of the interaction of engineering approaches, quality management systems, and principles of sustainable development in the environment of high-tech production. Conceptual outlines of the integrated system of quality management are offered. It combines the capabilities of IME, traditional QMS, and green and social innovations, ensuring the simultaneous achievement of operational, chain, environmental, and social quality of products based on a joint digital platform.

Keywords: *quality management, high-tech manufacturing, industrial and manufacturing engineering, industry 4.0, industry 5.0, green innovations, social innovations, digital transformation, sustainable development, quality 4.0.*

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1. Introduction

The global economy is currently in a state of dynamic transformations, which are combined with the gradual reorientation of manufacturing systems from resource-intensive technologies to knowledge-based models. In this context, high-tech manufacturing acquires the status of a strategic priority for individual companies and for national economies on the whole, because it ensures technological sovereignty, innovative dynamics, and competitiveness in the conditions of increasing uncertainty of the global environment. At the same time, traditional approaches to assessing the effectiveness and development of high-tech manufacturing need to be revised under the pressure of current trends of green transformation, sustainable development, and digitalisation.

Green transition, established in the regulatory initiatives of the European Green Deal, the Paris Agreement, and the UN Sustainable Development Goals, forms completely new requirements for manufacturing systems, which must take into account the environmental impact of production processes at all stages of the product life cycle (Burkhanov et al., 2025). The sustainable development concept expands the horizon of assessment of industrial systems beyond the limits of purely financial indicators, including the social and environmental dimensions. This changes the logic of strategic management of production. In turn, digitalisation not only transforms the technological architecture of manufacturing systems through Industry 4.0 but also creates completely new tools for managing production processes, ensuring product quality, and monitoring resource efficiency in real-time.

The technological component remains the decisive factor of competitiveness in the sphere of high-tech production. The complexity of modern cyber-physical manufacturing systems, which combine industrial Internet of Things, digital twins, artificial intelligence, and additive production, raises demands for the technological level of companies and, at the same time, expands their analytical and operational capabilities (Krishnaraj et al., 2026; Matevosyan et al., 2026).

The issue of quality management in the environment of high-tech manufacturing becomes especially relevant. Classical systems of quality management, formed in the conditions of mass production with stable technological parameters, demonstrate significant restrictions when applied to complex dynamic manufacturing systems with non-linear dependencies and constantly upgraded technological demands. The answer to these challenges requires not the partial improvement of the existing tools but systemic rethinking of the very nature of quality management, which, in the conditions of Industry 4.0 and Industry 5.0, is transformed from the controlling & measuring into analytical & design functions.

At present, production management, quality management systems, mechanisms of ensuring environmental resilience, and tools of social responsibility function primarily as individual managerial sub-systems with their goals, indicators, and methodological apparatus (Burkhanov et al., 2026). This fragmentation reduces the overall operational efficiency of companies and complicates the possibility of forming competitive advantages and synergetic effects, which are achieved at the intersection of technological, managerial, and socio-environmental approaches.

2. Methodology

The study of the problems of quality management in high-tech manufacturing in the conditions of implementing green and social innovations belongs to complex interdisciplinary scientific and practical tasks. Resolving these tasks allows forming a holistic engineering and managerial basis to ensure stable parameters of product quality in a dynamic technological environment. The methodological basis of this paper comprises general scientific and special methods, whose application conforms to the character of the analysed problem. The interdisciplinary approach is a necessary condition of the research, since the paper's subject is at the intersection of manufacturing engineering, quality management, digital technologies, and sustainable development concepts. The system approach ensures interpretation of quality as an integral property of production systems, which encompasses technological processes, organisational solutions, digital infrastructure, and environmental & social parameters of production. Comparative analysis allows comparing different methodologies, standards, and quality management systems from the position of their compliance with the requirements of high-tech production environments. The structural and logical analysis is used to reveal and systematise factors that determine product quality in the conditions of cyber-physical manufacturing systems and large-scale technological transformations.

The methods of induction and deduction are used to formulate generalised principles of the functioning of integrated quality management systems, while a structural and functional approach ensures analysis of interconnections between the strategic, tactical, and operational levels of management within Industrial and Manufacturing Engineering. Thus, the research methodology combines theoretical analysis, interdisciplinary synthesis, and conceptual modelling. This allows for the comprehensive study of the role of Industrial and Manufacturing Engineering in quality management of high-tech manufacturing in the conditions of digital transformation and transition to sustainable models of production.

To empirically verify the conceptual provisions of this research, we used correlation analysis. The information basis is statistical data from the World Bank Open Data database. The sample was formed by the principle of completeness of data: 184 countries for which there is an exhaustive set of values for all considered indicators. The resulting variable (y) is the share of high-tech exports in total industrial exports of the country. The factor variables encompass three groups: resource support of innovations — share of R&D expenditures (%) in GDP (x11) and number of researchers in R&D per 1 million people (x12); technological efficiency — payments for the use of intellectual property objects (x13), residents-to-nonresidents patent ratio (x21), revenues from the use of intellectual property objects (x22), and energy intensity of GDP (x23); macro-economic and social effect — share of ICT products exports (x31) and GDP per capita (x32). Given the significant right-hand asymmetry of the distribution of a range of indicators, caused by big inter-country differences in the level of technological development, all variables were standardised according to the formula LN(x + 1). This ensured proximity of distributions to normal and raised the reliability of the application of Pearson's correlation coefficient. Calculation of pair correlation coefficients allowed establishing the direction and strength of the connection between the studied variables, and the revealed regularities became the empirical basis for substantiating the conceptual provisions of the integrated system of quality management in high-tech production.

Relevance and methodological justification of the research are supported by the wide reference basis, which covers scientific works and expert materials on the key directions of the research. Modern studies demonstrate that quality management in high-tech manufacturing in the conditions of digital transformation and implementation of green and social innovations requires a complex interdisciplinary approach, which encompasses engineering design of manufacturing systems, adaptation of classical quality management systems to the requirements of cyber-physical environments, integration of Industry 4.0 and Industry 5.0 technologies, and harmonisation of operational, environmental, and social goals of production. Within these directions, scholarly and expert works devoted to the classification and characteristics of high-tech manufacturing systems, development of engineering approaches to design of production processes, transformation of quality management systems in the conditions of digitalisation, implementation of Industry 4.0 and Industry 5.0 technologies, integration of green and social innovations into production management systems, and formation of integrated approaches to quality management based on sustainable development principles were used.

Within these directions, the methodological foundations of classification of high-tech manufacturing were viewed, and the role in the formation of innovative potential of the economy was characterised (OECD, 2011; OECD, 2023; OECD, 2025; Eurostat, 2005; European Commission, 2009; UNIDO, 2021); the capabilities and limitations of classical quality management systems in their application to complex dynamic production environments were disclosed, and directions for their transformation within the Quality 4.0 concept was substantiated (Escobar et al., 2021; Antony et al., 2024; Fadilasari et al., 2024; Nguyen et al., 2023; Alkhatib et al., 2025; Klaput et al., 2024; Pongboonchai-Empl et al., 2026); engineering approaches and tools of Industrial and Manufacturing Engineering in the context of their influence on the design of production processes and parameters of product quality were systematised (Formentini et al., 2022; Juniani et al., 2022; Macias-Aguayo et al., 2022; Saeedi, 2024; Younus et al., 2025); the role of Industry 4.0 technologies and human-centric principles of Industry 5.0 in the transformation of the architecture of manufacturing systems and quality management systems were justified (Antony Jose et al., 2025; Achouch et al., 2022; Azamfirei et al., 2023; Bajic et al., 2023; Rydzi et al., 2024; Khan et al., 2025; Martín-Gómez et al., 2024; Turner & Oyekan, 2023); the potential of green innovations and principles of sustainable production to achieve synergy of the goals of quality, operational efficiency, and environmental resilience was studied (Ghasemibojd et al., 2025; Huang et al., 2023; Lario et al., 2025; Duong Thi Binh et al., 2024; Burkhanov et al., 2026); and the influence of social innovations, ESG-oriented management, and risk-oriented approaches on the expansion of the criteria of product quality of high-tech manufacturing was revealed (Fridkin et al., 2024; Kozminykh & Klochkov, 2025; Aichouni et al., 2024; Alimova et al., 2026).

The objective of this research was to disclose the role of Industrial and Manufacturing Engineering as a methodological basis of quality management in high-tech manufacturing in the conditions of digital transformation and implementation of green and social innovations, and to identify the conceptual contours of the integrated system of quality management, which combines engineering, managerial, and sustainable dimensions of manufacturing systems.

3. Results

High-tech manufacturing, as a separate scientific category, is characterised by a range of features that determine the character of its study in the context of quality management and sustainable innovative development. It should be noted that, at present, the scientific discourse lacks a unified interpretation of the definition of "high-tech manufacturing". This is due to its multidimensionality and dynamism. According to this, high rates of technological development require periodic revision of the characteristics of high-tech character, and different methodological approaches focus on different parameters of high-tech manufacturing, which diversifies their treatment in the expert and scientific field. At the same time, most researchers of these problems reach a consensus that the main features of high-tech character in the sphere of industrial manufacturing are high intensity of research work and a large share of research expenditures in the structure of companies or sectors' expenditures (OECD, 2011). The most recognised approach is the one by the OECD, which ranks industrial sectors based on the share of R&D expenditures in the total volume of production costs or value-added. There is another popular approach, which takes into account additional criteria, such as the share of scientists and skilled personnel in the total number of personnel, complexity of production technologies, patent activity, and connection between production and global innovative networks (OECD, 2025). On the whole, high-tech manufacturing is defined as manufacturing systems characterised by an organic combination of leading technologies, complex engineering, and mandatory strategic focus on innovative development. Apart from this, an important characteristic of high-tech manufacturing is adaptability, which is viewed through the lens of Industry 4.0 and companies' ability to use digital capabilities to form and strengthen competitive advantages (Escobar et al., 2021).

According to the OECD and Eurostat's classifications, the category of high-tech manufacturing includes four sectors: production of PCs, electronic and optical equipment; pharmaceutical industry, production of scientific and medical measuring instruments; and production of space and aviation equipment (European Commission, 2009; Eurostat, 2005). All these sectors are characterised by a high intensity of scientific and research work and have a range of features. Apart from the high share of R&D expenditures, they are notable for a large duration of the innovative cycle (pharmaceutical sector), very high rates of technological upgrade (computer equipment and electronics), very strict requirements for the reliability of products at all production stages (aerspace industry), and integration of achievements of different technological directions which cover microelectronics, software, material science, etc. These features set specific requirements for quality management systems, which take into account the long duration of technological chains, support of the stability of product parameters in the conditions of constant update of technological demands, and compliance with strict regulatory requirements for the quality and safety of products (Antony Jose et al., 2025).

It should be noted that, very often, certain medium-high technology sectors are included in high-tech manufacturing: car industry, chemical industry, electronic equipment, and machine-building (OECD, 2023). Even though these sectors do not conform to the previously mentioned criteria, they have a high level of intensity of research work. Also, they have an important effect on technological chains, consumer networks, and the general economic situation. They also actively participate in the global chains of value-added.

Assessment of the influence of high-tech manufacturing on the general situation in the economy or labour market does not reflect all advantages and effects. This sector is also the main generator of technology spillovers, which are manifested in different adjacent sectors and influence an increase in innovative potential of economic agents (Kozminykh & Klochkov, 2025; UNIDO, 2021). These spillovers are manifested through the labour market, supply chains, and regulatory institutions. Highly-skilled specialists, who acquired competencies in high-tech production, actively disseminate their knowledge in other sectors, high requirements for materials and components stimulate suppliers from adjacent sectors to modernise equipment and business processes, and regulatory requirements ensure the development of the standardisation and certification systems, which positively influence the formation of the institutional innovative infrastructure. High-tech manufacturing becomes the centre of formation and development of technological clusters. Research universities, start-up ecosystems, and specialised suppliers unite around them, and a special institutional support is formed (OECD, 2023).

The technological and organisational complexity of high-tech manufacturing in modern conditions is combined with the specifics of digital systems of management and analytical platforms of big data analytics. This symbiosis changes the environment of quality management. Special attention is paid to such aspects of Industry 4.0 as automation and robotisation, industrial Internet of Things, digital twins technology, artificial intelligence, etc. (Table 1).

Table 1. Digital characteristics of high-tech manufacturing systems in the context of quality management in the conditions of Industry 4.0

Digital characteristics of high-tech production	Technological basis	Value for quality management
Automation and robotisation of production processes	Industrial robots, adaptive management systems, and machine vision	High precision of operations, stability of parameters of the process, reduction of variability and defect rate of products
Digitalisation of production	Industrial Internet of Things, Industrial Big Data, sensor networks	Monitoring of processes in real-time, analytics of deviations, and reduction of defect rate
Digital twins of manufacturing systems	Digital twins, modelling of processes, and integrated data platforms	Forecasting of defects, testing alternative scenarios of production, and optimisation of product construction
Artificial intelligence in manufacturing systems	Machine learning, deep neural networks, and computer vision	Automatic detection of defects, forecasting of equipment failures, and optimisation of technological regimes
Additive production	3D print, digital design of products	New approaches to quality control of complex components, adaptation of certification systems

Source: Prepared by the authors based on (Antony Jose et al., 2025; Escobar et al., 2021; Saeedi, 2024)

In the conditions of high-tech manufacturing, automation and robotisation are not the tools for replacing manual labour. They are treated as an intelligent system that can adapt to changing conditions, set and optimise processes in real-time, and support a high level of production which cannot be achieved by manual labour and simple mechanisation of production (Maslennikov & Chernitsova, 2017). Digital monitoring of production processes determines a large potential of the sector in the sphere of collection, processing, and analysis of big data flows to reveal regularities and deviations in the functioning of equipment at all stages. From the position of quality management, digital twins offer completely new opportunities for the transition from predicted control of quality parameters to optimisation of production based on real data on production and exploitation (Saeedi, 2024). Similar possibilities and requirements are also peculiar to additive production, within which the problem of mass production of parts is resolved and the need for development of new systems of certification and quality control is formed (Antony Jose et al., 2025).

Combined with the specifics of the sectors of high-tech manufacturing, these characteristics determine unique features of the organisation of manufacturing systems and quality management systems at the sector's companies. This is manifested most fully from the position of technological complexity, strict requirements to precision and stability of production processes, the need to ensure flexible interfunctional cooperation, management of production environment, and the need for constant upgrade of technological processes and manufacturing systems with the stability of product quality parameters (Escobar et al., 2021).

Integration of manufacturing systems with quality management systems in high-tech manufacturing involves the application of a set of organisational mechanisms in the form of general economic standards of quality (ISO 9001, IATF 16949, AS9100, ISO 13485) and specific industry systems, such as Good Manufacturing Practice in pharmaceutical industry, Advanced Product Quality Planning in car industry, First Article Inspection in aerospace sector, etc. (UNIDO, 2021). The main essence of this integration is that quality management in high-tech manufacturing cannot be viewed as an additional option – it must be fully built into the manufacturing system at all stages, starting from design.

Thus, quality management in high-tech manufacturing is significantly different from similar processes in traditional sectors of industry. The main differences are manifested in the mandatory character of product quality management as an inherent function, at which final control of the product cannot be used as the sole tool for quality support. Thus, the task of quality management in the studied sphere is transformed from controlling & measuring to analytical & design function (Klaput et al., 2024; Nguyen et al., 2023), within which the transition to quality management of manufacturing systems takes place, where the management object is the totality of interacting processes, technologies, and competencies (Antony et al., 2024). Also, since modern high-tech companies are complex cyber-physical systems, the sphere of quality control is also expanding. Apart from physical and chemical parameters, the control objects are programme and organisational algorithms, information flows, digital solutions, and platforms (Escobar et al., 2021). In these conditions, a failure of the software module of the quality management system is equated in importance to a failure of the mechanical node of the production line.

The additional parameter of the quality management system at production is time. This is due to the acceleration of technological and operational processes and the natural reaction to the complexity of high-tech manufacturing. According to this, a delayed reaction to certain deviations leads to substantial losses. Therefore, quality management systems in cyber-physical systems are set in such a way that controlling procedures take place simultaneously with production operations in real-time (Antony et al., 2024).

On the whole, all determinants that have a special effect on product quality in high-tech manufacturing can be combined into four main groups, which include technological, information, organisational, and innovative factors (Figure 1).

Each group of the above factors has a different direction and contributes certain features to quality management in the environment of high-tech manufacturing. Thus, technological factors determine the basic level of attainable quality. Their influence can be mutually dependent, have a non-linear character, and have a multiplicative effect on other manufacturing processes. Information factors are manifested to the largest extent through the maximum capacity to reveal subtle signs of deviations in the production system’s functioning, which turned the function of quality management into predictive, aimed at forecasting possible deviations and losses. Organisational factors often have a limiting effect, because problems with quality take place most often not due to equipment failures but due to non-optimal decisions of the personnel, operators’ mistakes, bad coordination, etc. The main influence of innovative factors is connected with the need to coordinate the function of the quality management system with quick innovative transformations, which often require the revision of the key parameters and settings of the system.

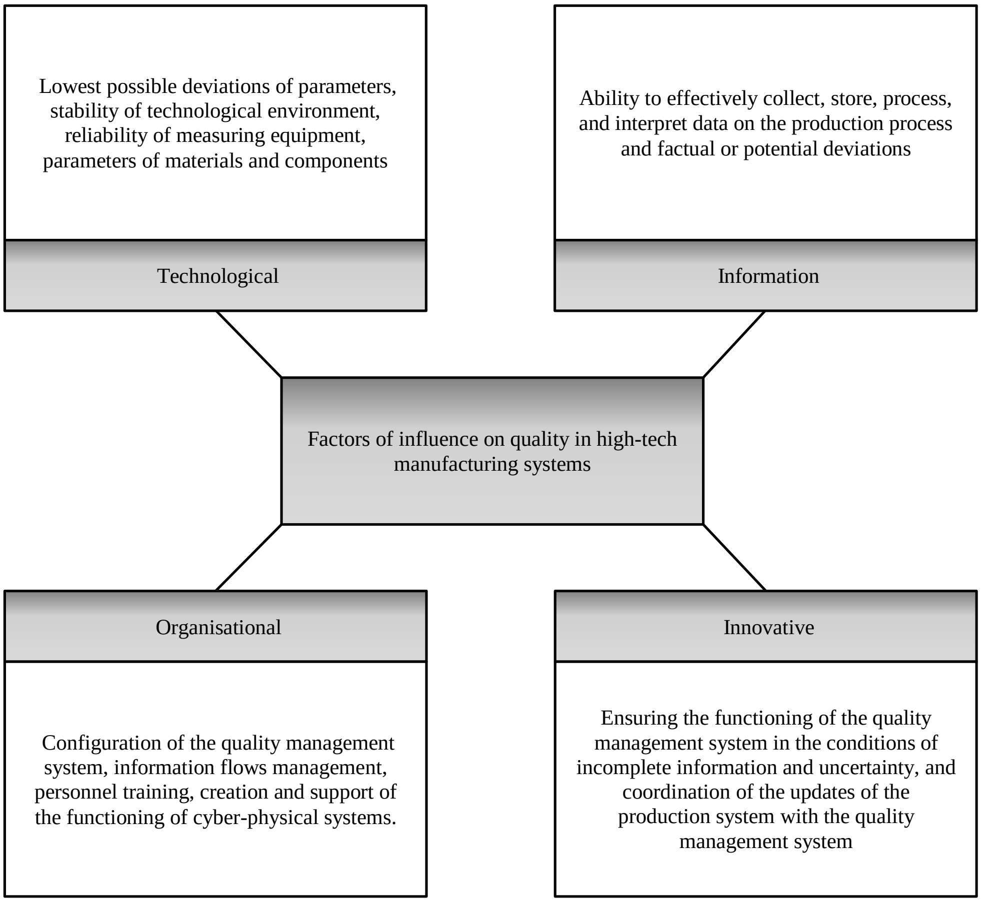

Figure 1. Characteristics of the factors of influence on product quality in the sphere of high-tech manufacturing
Source: Prepared by the authors based on (Alkhatib et al., 2025; Escobar et al., 2021; Fadilasari et al., 2024; Fridkin et al., 2024; Pochmara & Świetlicka, 2024; Pongboonchai-Empl et al., 2026)

The outlined characteristics of high-tech manufacturing form additional requirements for quality management systems. Classical systems, e.g., Total Quality Management (TQM), Six Sigma, Lean Quality, Statistical Process Control (SPC), have been formed in the conditions of mass production and are focused primarily on the reduction of deviations in production processes and avoidance of systemic defects in an environment with stable technological conditions. They barely take into account complex non-linear ties, are limited to several main criteria of quality, use statistical assumptions, and rarely consider the context of manufacturing processes (Alkhatib et al., 2025; Escobar et al., 2021; Pongboonchai-Empl et al., 2026). Thus, using these quality management systems in the sphere of high-tech manufacturing has limitations and requires the corresponding settings.

Thus, TQM sets correct principles and forms a holistic managerial philosophy of quality. Its tools are based on observation and analysis, which determine the basis to improve management (Antony et al., 2024; Fadilasari et al., 2024). An increase in the number of factors and criteria of influence on quality in high-tech manufacturing raises the load on the quality management system and reduces its operational efficiency. A similar effect on quality in complex technological conditions is also peculiar to the Six Sigma system. In this case, the limitation is based on the connection with statistical analysis of the designated parameters of quality. In the conditions of high-tech manufacturing, parameters have a dynamic character and require the application of complex algorithms for the correct and timely detection of defects. As for SPC, its drawbacks are manifested most fully through the use of statistical assumptions, which are not characteristic of the high-tech sector. Apart from this, an increase in the complexity of production, growth of the number of parameters, and multicriterial character of quality assessment lead to the need to supplement the tools of SPC (Alkhatib et al., 2025; Escobar et al., 2021). An equally important problem is scaling the successful practices of quality management, used within traditional systems, to production with thousands of mutually dependent operations, hundreds of units of complex equipment, a large number of suppliers, and a continuous flow of technological improvements.

Capabilities of Industry 4.0 allow dealing with most of the revealed restrictions of quality management systems within the Quality 4.0 concept. It involves integration of the existing systems with big data, machine learning, and AI technology, cyber-physical systems, cloud technologies, etc. (Escobar et al., 2021; Pongboonchai-Empl et al., 2026).

Industrial and Manufacturing Engineering (IME) determines the paradigm of design, analysis, and improvement of manufacturing systems. These processes combine the advantages of industrial and manufacturing engineering, which ensures a comprehensive optimisation of manufacturing systems and allows achieving a high level of technology-oriented interaction (Formentini et al., 2022). In the conditions of digitalisation, system- and technology-oriented tasks of ensuring product quality are successfully combined, creating a complex multi-level system, oriented towards constant improvement (Macias-Aguayo et al., 2022). IME is implemented at three hierarchical levels of the manufacturing system management. The strategic level features the general design of manufacturing systems, which encompasses the determination of production areas and capacities, the establishment of technological routes, and the formation of the structure of production centres. At the tactical level, manufacturing flows are optimised, production lines are balanced, and material and technical support is ensured. At the operational level, control of the quality of technological operations is performed, stabilisation of production parameters is ensured, and constant improvement of manufacturing systems is provided (Saeedi, 2024).

A special effect of IME on product quality is formed at the design stage. Decisions made at this stage set the technological and constructive parameters of product quality (Juniani et al., 2022). In the environment of high-tech manufacturing, their influence is especially important, since it allows avoiding expensive design changes at later stages of production. The main tools of implementing engineering approaches in the design of production processes and their positive effect on quality are the Design for Manufacturing and Assembly (DFMA) methodology, the Design for Six Sigma (DFSS) concept, computer-integrated manufacturing (CAD/CAM/CAE), analysis of failure modes and effects analysis (FMEA/PFMEA), the use of digital twins, etc. (Younus et al., 2025; Juniani et al., 2022; Khan et al., 2025; Macias-Aguayo et al., 2022).

The advantages that these tools give to IME systems at the design stage have a complex character and are largely reflected in product quality. The DFMA potential is disclosed through the possibility to assess technological elements' suitability for compliance with established tolerances, ensuring a sufficient level of variability, and compliance with the optimal sequence of operations from the position of accumulation of errors (Juniani et al., 2022). DFSS's capabilities allow setting technological processes before the first start (Rydzi et al., 2024). Computer-integrated manufacturing, combining a CAD model of the product with a CAM system for the formation of technological programmes and CAE systems of technological processes simulation, allows detecting potential problems with quality at the design stage. FMEA/PFMEA approaches in the aerospace and car industries, with the possibility of scaling in other sectors of high-tech production, offer clear algorithms for complex management of risks of failures and the development of preventive measures to avoid them (Juniani et al., 2022). Using digital twins of production processes allows building dynamic feedback between manufacturing and managerial sub-systems (Saeedi, 2024). In aggregate, all engineering approaches and tools of production processes design have a positive effect on the quality of products, create opportunities for predictive risk management, and allow avoiding losses at later production stages.

Optimisation of production flows and control of quality processes based on IME in high-tech manufacturing creates a comprehensive engineering basis for quality management. A unified focus is determined within it, which is aimed simultaneously at the quality and effectiveness of the system's functioning. According to the IME, philosophy, sources of losses and reduction of effectiveness in manufacturing systems often serve as the factors in the deterioration of product quality. To resolve these tasks, the corresponding tools and methodologies are used, in particular, Operations Research and Lean Manufacturing (Macias-Aguayo et al., 2022; Rydzi et al., 2024). Operations Research is a kind of analytical tool, which expands IME's capabilities and formalises quality as a parameter of manufacturing systems optimisation. Here, the methods of mathematical programming, the series and simulation theories are used; they allow for optimal decisions on the structure of production processes, placement of quality control points, and balancing resources from the position of requirements for product quality. According to this, the engineering design of processes at the systemic level also integrates the goals of quality support. The Lean Manufacturing methodology combines the management of flows and quality through the optimisation of processes, elimination of losses, reduction of errors, improvement of stability of processes, and an increase in the level of reproducibility of results. According to this, elimination of the possibility of overproduction, reduction of stock, decrease in equipment idle time, and avoidance of excessive processing, displacements, or actions ensure a decrease in variability of production operations, growth of controllability of processes, and formation of preconditions for the stable and predictable product quality.

Thus, in the context of the Industry 4.0 paradigm, quality control transforms into a holistic system of ensuring the reliability of the production architecture. At the same time, the Industry 5.0 concept expands this horizon. Unlike Industry 4.0, which is focused on effectiveness and automation, Industry 5.0 puts humans back in the centre of manufacturing systems and puts resilience and social responsibility at the same level as productivity (Bajic et al., 2023). Green and social innovations in these systems supplement methodological and instrumental principles of quality management in high-tech manufacturing through a harmonious combination of environmental, technological, and social factors within one system.

Operational implementation of green innovations in the format of green manufacturing ensures the achievement of a range of environmental advantages through the corresponding setting of manufacturing and quality management systems. These actions are manifested through optimisation of resource use, reduction of waste, and achievement of a closed character of material flows, which conforms, at the same time, to production goals, tasks of product quality management, and principles of sustainable development (Rydzi et al., 2024; Lario et al., 2025). Apart from the correspondence to product specifications, they take into account the indicators of the carbon footprint, chemical safety, and resource efficiency at all stages of development and manufacture of products during the entire life cycle (Juniani et al., 2022). In many cases, including environmental goals in quality criteria contributes to their better integration into manufacturing and technological processes, starting from the stage of high-tech product design.

Social innovations are manifested through the inclusion of human-centeredness, equality, and inclusion in the system of goals and values of production criteria. This vision conforms to the Industry 5.0 concept, within which quality is viewed as a result of the interaction of technological and social elements (Alimova et al., 2026; Azamfirei et al., 2023; Bajic et al., 2023). The influence of social innovations on product quality through the IME tools is implemented through the development of the appropriate competencies, personnel's involvement in management, development of organisational culture, etc. (Achouch et al., 2022). In aggregate, a combination of environmental and social innovations within quality management through industrial and manufacturing engineering allows forming an engineering-oriented model, in which environmental requirements, human capital, and digital technologies supplement effective operational systems and ensure compliance with sustainable parameters of high-tech manufacturing (Escobar et al., 2021). Expanding the notion of product quality by taking into account the four dimensions through an increase in regulatory pressure in the sphere of ESG regulation and control of supply chains, as well as the development of a human-centric concept of Industry 5.0, forms demands for quality management that cannot be met only through technology-oriented engineering measures (Ergasheva et al., 2023; Klaput et al., 2024). They require the development of an integrated system of quality management, which would combine the capabilities of IME, traditional quality management systems, and sustainable development principles.

An important task of the development and implementation of integrated quality management systems of high-tech manufacturing based on Industry 5.0 principles is addressing complex multiple criteria, predetermined by the complexity of the production environment and interaction (Martín-Gómez et al., 2024). According to this, apart from the criteria of operational quality, which reflects technical characteristics of products and production processes, it is necessary also to take into account the parameters of chain (compliance with criteria along the entire supply chain), social (compliance with labour and safety conditions, development of competencies), and environmental quality (compliance with environmental norms) (Bajic et al., 2023; Duong Thi Binh et al., 2024; Nguyen et al., 2023). These four dimensions form a unified system of quality criteria and require the development of the corresponding systems of indicators and their simultaneous tracing within complex manufacturing and economic systems.

Given the limitations of each approach to high-tech product quality management, it is necessary to outline the conceptual contours of an integrated system that can be formed by combining Industrial and Manufacturing Engineering (IME), quality management systems (QMS), and principles of sustainable development (Aichouni et al., 2024; Ghasemibojd et al., 2025). Within such integration, each element makes its contribution to general quality management, compensating for certain drawbacks and limitations from the position of simultaneous consideration of multiple criteria of high-tech production quality, social responsibility, and sustainable development.

Combining all the elements based on the system synthesis ensures the generation of completely new managerial capabilities, which is achieved due to the formation of the corresponding synergetic effects. These effects are formed primarily through the mutual strengthening of the goals of quality management and sustainable development. Due to Lean optimisation, which is implemented through the lens of environmental efficiency, there appears a possibility for simultaneous achievement of the goals of quality (reduction of the defect rate), operational efficiency (reduction of expenditures), and support of sustainability (reduction of the volumes of resources consumption) without any compromises (Aichouni et al., 2024; Huang et al., 2023).

Apart from this, mutual enrichment of analytical tools takes place. Methodological tools of quantitative measuring and optimisation of manufacturing systems, aimed for IME, are supplemented by analytical tools of sustainable development management, which include life cycle assessment (LCA), material flow analysis (MFA), and carbon budgets. This combination expands the angle of view of IME analysis, from operational efficiency to systemic resilience (Duong Thi Binh et al., 2024; Turner & Oyekan, 2023). On the other hand, analytical tools of IME provide the systems of sustainable development management with operational tools. As a result, instead of declarative environmental goals, there appears to be the possibility for their quantitative substantiation.

Another equally important synergetic effect is the formation of a joint digital basis for the management of the quality of high-tech manufacturing based on the implementation of social and environmental innovations (Ghasemibojd et al., 2025). Given the fact that digital tools, such as the IIoT, digital twins, and predictivt analytics platforms, are, at the same time, IME tools (for monitoring and optimisation of production processes), quality management systems (for quality control in real-time), and systems of sustainable development management (for monitoring of resource consumption and environmental impact), investments in the development of digital capabilities automatically strengthen the digital potential of all directions of product quality management, regardless of the motivation for their involvement (Aichouni et al., 2024; Bajic et al., 2023). Apart from this, the presence of a joint digital platform creates intersectional innovative impulses, due to which product quality analytics allows revealing regularities on resource saving, and monitoring of resource use contributes to the detection of deviations, which point to technological problems of quality. In the conditions of high-tech production, the influence of the above synergetic effects grows substantially, because the complexity of cyber-physical systems, high density of sensor data, and strict regulatory requirements simultaneously raise the value of integrated analytics and operational costs of its distributed support within isolated managerial subsystems.

Direct verification of the conclusions and provisions requires an in-depth study of the processes of industrial and manufacturing engineering in the context of quality management at companies that belong to the sphere of high-tech production. The complexity of the preparation of such a model lies in the need to form a substantial array of data connected with the functioning of an individual company or groups of companies in the environment, with the high level of commercial secrets protection and limited access to intellectual property objects due to the risks of information leaks on critical technologies and innovations. Given this, we present the results of the empirical verification of the research results based on a macro-model, which summarises the global connections between the factors of development of high-tech production sectors and indicators that characterise innovative potential, technological exchange, and the level of socioeconomic development (Table 2).

Table 2. Correlation matrix of the indicators of innovative potential and technological development of countries

	High-technology exports (% of manufactured exports)	Research and development expenditure (% of GDP)	Researchers in R&D (per million people)	Charges for the use of intellectual property, payments (BoP, current US$)	Residents-to-Nonresidents Patent Ratio	Charges for the use of intellectual property, receipts (BoP, current US$)	Energy intensity measured in terms of primary energy and GDP	ICT goods exports (% of total goods exports)	GDP per capita (current US$)
	y	x_{11}	x_{12}	x_{13}	x_{21}	x_{22}	x_{23}	x_{31}	x_{32}
y	1.000								
x_{11}	0.503	1.000							
x_{12}	0.377	0.728	1.000						
x_{13}	0.626	0.680	0.524	1.000					
x_{21}	0.284	0.591	0.626	0.369	1.000				
x_{22}	0.609	0.797	0.560	0.900	0.453	1.000			
x_{23}	-0.081	-0.026	0.009	-0.131	0.084	-0.093	1.000		
x_{31}	0.590	0.621	0.486	0.583	0.489	0.633	-0.068	1.000	
x_{32}	0.504	0.479	0.389	0.549	0.254	0.525	-0.053	0.408	1.000

Source: Prepared by the authors based on (World Bank, 2026a – World Bank, 2026j).

The presented indicators characterise three groups of variables, which potentially influence the level of success of high-tech production development, represented by the resulting indicator of their share in the structure of industrial product exports. These groups represent the following:

-Resource support, in particular x_{11} as the factor of financial capacity of innovations, x_{12} as the indicator of human capital development, x_{13} as the indicator of readiness to pay for “external” knowledge and ideas to improve the quality of own products.

-Technological performance, in particular x_{21} as the level of technological independence from patents (own/attracted patents ratio), x_{22} as the indicator of recognition of knowledge and ideas, and x_{23} as the factor of resources management efficiency in the context of environmental goals.

-Macro-economic and social effects, in particular x_{31} as the indicator characterising the level of economic digitalisation, x_{32} as the final indicator of public well-being and economic effectiveness at the country level.

As a result of calculating Pearson's correlation coefficients, it was established that, apart from the energy intensity of GDP (x_{23}), all other selected indicators demonstrated a statistically significant direct correlation with the endogenous variable. The highest value of the correlation coefficient ($r = 0.626$) was observed with the indicator of the volume of payments for intellectual property (x_{13}), as well as the indicator of revenues from the use of intellectual property objects and rights (x_{22}, $r = 0.609$). This shows that countries with a developed system of technology and knowledge transfer demonstrate a higher share of high-tech exports. The moderate direct correlation between the resulting indicator and share of ICT products exports (x_{31}) in the total commodity exports ($r = 0.590$), the share of R&D expenditure in GDP (x_{11}, $r = 0.503$), and GDP per capita (x_{32}, $r = 0.504$) points to the systemic character of technological development. According to this, the R&D basis, combined with digital infrastructure and the level of economic well-being, forms a totality of conditions that are favourable for the development of high-tech production.

The connection between the indicator of the number of researchers in R&D per 1 million people (x_{12}, $r = 0.377$) is lower compared to R&D expenditures, which can indicate the higher significance of quality and efficiency of research activities compared to its quantitative scale. Instead, the residents-to-nonresidents patent ratio (x_{21}, $r = 0.284$) demonstrates a weaker connection, which demonstrates that the structure of patent activity by itself has a lower effect on the share of high-tech exports than revenues from the use of intellectual rights. It should also be noted that the indicator of energy intensity of GDP (x_{23}, $r = -0.081$) hardly correlates with the share of high-tech exports, which reflects a contradictory impact: on the one hand, high-tech productions consume a lot of energy, and, on the other hand, they are leaders in the use of energy-efficient technologies. On the whole, the results obtained empirically confirm the conceptual model of the integrated system of quality management, in which the leading role is assigned to technological exchange, innovative resources, and ICT infrastructure. Their influence on the competitiveness of high-tech production conforms to the logic of combining IME, QMS, and sustainable development principles into one system of quality management.

4. Discussion

The problem of using Industrial and Manufacturing Engineering as the basis for quality management in high-tech manufacturing in the conditions of the implementation of green and social innovations has a complex nature and is characterised by considerable multidimensionality. However, it contains a range of provisions that require additional scientific substantiation and reflection. A large share of debatable aspects is caused by the transformation of the very nature of quality in the context of the transition from technology-oriented to integrated approaches, which organically combine operational efficiency, environmental responsibility, and human-centeredness. Therefore, any revision of the architecture of the quality management system in high-tech production requires a thorough analysis of mutual dependencies between its components.

Another debatable dimension is connected with the search for balance between the technological complexity of manufacturing systems and operational manageability of quality management processes. In particular, a relevant issue is how the expansion of the criterial space of quality through environmental and social parameters influences the effectiveness of the functioning of IME's traditional tools. It is important to study whether the integration of green and social innovations into manufacturing systems does not cause excessive complication of the processes of quality control and to determine the corresponding indicators and metrics, which allow for the balanced tracing of operational, chain, environmental, and social components of quality in the conditions of a dynamic technological environment without the loss of system’s controllability.

An equally important debatable issue is the problem of verification of synergetic effects, which emerge at the intersection of IME, quality management systems, and sustainable development principles. Despite the conceptual substantiation of these effects, their practical measurement in the environment of real manufacturing systems is a rather complex task due to the non-linear character of interconnections. In this context, a promising direction is the study of the possibilities to adapt the tools of assessing product life cycle, predictive analytics, and digital twins for the quantitative substantiation of synergy between operational goals of manufacturing systems and the Sustainable Development Goals.

It is necessary to consider and discuss the results of the conducted correlation analysis.

The revealed connections between the share of high-tech exports and indicators of innovative potential, technological exchange, and ICT infrastructure are statistically significant and conceptually substantiated, but the aggregate character of the data used does not allow differentiating the contribution of individual components of the quality management system to the formation of the corresponding results. In particular, there is an open question of the extent to which the recorded correlations reflect the influence of the architecture of production systems and practices of IME and the extent to which they reflect the wider institutional and macroeconomic context of countries. This confirms the need for a transition from the macro-model to micro-level studies focused on concrete companies of high-tech production, despite the objective limitations of access to the required data.

5. Conclusion

High-tech manufacturing, as an object of scientific research, is characterised by multidimensionality and dynamism, which causes the absence of a unified approach to its interpretation and classification. At the same time, there is consensus as to the acknowledgement of the intensity of research activities as the key criterion of technological nature, and the category of high-tech production continues to expand under the influence of digitalisation, globalisation of supply chains, and technological convergence.

In the environment of high-tech manufacturing systems, quality management differs from similar processes in the traditional sectors of industry. It acquires the character of the analytical and design function, where the management object is not a separate item but the entire totality of interacting processes, technologies, digital solutions, and competencies. Despite the large methodological potential, classical systems of quality management, such as TQM, Six Sigma, SPC, and Lean Quality, demonstrate significant limitations in the conditions of complex cyber-physical manufacturing systems, non-linear dependencies, and dynamic parameters of quality. It is possible to deal with these limitations within the Quality 4.0 concept, which involves the integration of available systems with big data, machine learning, artificial intelligence, and cloud computing. However, this transition leads to new challenges in the spheres of verification of hybrid systems, information saturation, and cybersecurity.

Industrial and Manufacturing Engineering forms an engineering paradigm of design, analysis, and improvement of manufacturing systems. It is implemented at the strategic, tactical, and operational levels of management. Application of the methodologies of DFMA, DFSS, FMEA/PFMEA, computer-integrated production, and digital twins allows setting parameters of quality at the stage of design, avoiding expensive design changes at later stages. Combining the Operations Research and Lean Manufacturing tools ensures an engineering basis for simultaneous management of quality and operational efficiency of manufacturing systems.

The Industry 5.0 concept transforms the very nature of quality in high-tech production, returning humans to the centre of manufacturing systems and equating the criteria of resilience and social responsibility to the indicators of productivity and effectiveness. In this context, quality can be viewed from the position of four dimensions: operational, chain, social, and environmental.

A systemic combination of Industrial and Manufacturing Engineering, traditional quality management systems, and principles of sustainable development forms completely new managerial possibilities, which go beyond a simple combination of approaches. Mutual strengthening of the goals of quality management and sustainable development, expansion of analytical tools through the combination of the LCA, MFA, and carbon budget method with the quantitative methods of IME, and formation of a joint digital platform based on the IIoT and predictive analytics form synergetic effects, whose value grows substantially in the conditions of high-tech production. As a result, the integrated system of quality management becomes a tool of not only technological perfection but also strategic resilience of companies in the conditions of the increasing complexity of the global manufacturing environment.

Correlation analysis, which was conducted based on a macro-model, provided an empirical basis for the formed conceptual provisions. Statistically significant direct correlation between the share of high-tech exports and the indicators of technological exchange ($r = 0.609–0.626$), ICT infrastructure ($r = 0.590$), and research basis ($r = 0.503$) confirms the systemic and interdependent character of the factors of high-tech production competitiveness. At the same time, the aggregated character of macro data outlines the boundaries of possible generalisations and determines the prospective direction for further research – transition from the micro-level analysis of quality management practices at high-tech production companies, given the industry specifics and institutional context.

Author Contributions

1st author formulated the idea and conceptual provisions of the study, offered a theoretical framework for the harmonious integration of Industrial and Manufacturing Engineering, product quality management systems in high-tech manufacturing, and the principles of sustainable development, and also led the process of preparing the manuscript.

2nd author provided systematisation of approaches to the definition and classification of high-tech industries, analysed the possibilities and limitations of classical quality management systems in the context of digital transformation, and contributed to the formulation of the literature review.

3rd author formulated scientific and methodological approaches to coordinating green and social innovations with production systems of high-tech enterprises, investigated the synergistic effects that arise when they are integrated with quality management systems, and made a final elaboration and generalisation of the methodological section

4th author analysed engineering approaches and tools of Industrial and Manufacturing Engineering at the strategic, tactical, and operational levels, characterised the role of Industry 4.0 and 5.0 technologies in the development of quality management systems, and made a major contribution to the formulation of the digital context of the study

5th author contributed to the results section, reviewed the final draft, and prepared the conclusion section.

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