



ENERGY EFFICIENCY AS A CRITERION OF QUALITY 5.0: MANAGEMENT THROUGH SUSTAINABLE INNOVATIONS

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ABSTRACT

This paper is devoted to the analysis of energy efficiency as a decisive criterion in the context of the Quality 5.0 concept in the conditions of implementing sustainable innovations. Modern transformation processes, which accompany Industry 5.0, predetermined the need for new approaches to quality management, in which an important role belongs to digital technologies, environmental responsibility, social inclusion, and human factors. In this context, energy efficiency is considered not only as a technical indicator but also as a multi-component strategic phenomenon, which is integrated into the general system of quality management and forms new vectors of sustainable development. It is offered to consider energy efficiency as one of the main ESG indicators, which is closely connected with the use of ISO 14001 and ISO 50001 standards, integration of digital technologies, development of the systems of forecasting and management, and implementation of the circular economy principles. The key role of sustainable innovations is emphasised; they ensure the reduction of energy consumption, an increase in companies' analytical ability, improvement of labour conditions, and involvement of employees in the processes of quality management.

The research methodology is based on the multidisciplinary approach, which combines the principles of physics, energy, economics, quality management, cybernetics, and social and humanitarian sciences, with the involvement of the concepts of sustainable development, technological modes, corporate social responsibility, circular economy, and Society 5.0. Synthesis of the provisions of the modern theory of quality management, digital transformations, human-centrism, and environmental safety is supported by analytical elaboration on ISO standards and scholarly sources. This research is of the descriptive and analytical character and uses general scientific and special methods of abstracting, analysis, synthesis, comparison, and graphic and monographic analysis.

The main value of this paper lies in the theoretical substantiation of energy efficiency as an integral criterion of quality in the conditions of Industry 5.0, which combines the concepts of sustainable development, digital technologies, and human-centric management. The research offers a comprehensive view of the synergy between eco-oriented management, digital transformation, and continuous improvement of quality, which is relevant for modern companies in the conditions of transition to Industry 5.0.



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1. INTRODUCTION

The modern period is a period of dynamic changes and large-scale transformation, which covers a wide range of socio-political and socioeconomic processes. Technological progress, which was realised in the context of the Fourth Industrial Revolution, led to large-scale changes, which allowed for a significant increase in labour productiveness and improvement in the tools of quality management at production through comprehensive automatization of operational and managerial processes. Such digital technologies as big data analytics, cloud computing, the Internet of Things, artificial intelligence, blockchain, and other tools of Industry 4.0 are used in practice in different spheres of production and management, which allowed expanding the limits of the use of this concept and led to the emergence of new terms, e.g., Logistics 4.0, Service 4.0, Quality 4.0, and others (Fiałkowska-Filipek & Dobrovowolska, 2024).

The COVID-19 pandemic became a factor in the acceleration of technological changes and, at the same time, led to reconsideration of the values of technological transformations. According to this, the treatment of the effectiveness of businesses is expanded through technocratic benchmarks, such as productiveness and effectiveness, the criteria of social importance, climate resilience, and inclusion. This understanding of economic processes goes beyond the limits of treatment Industry 4.0, forming a new paradigm, which received the name Industry 5.0 in the scientific community. This paradigm is based on the harmonious interaction between humans and leading technologies, aiming to combine the principles of high effectiveness and sustainable development of economic systems (Frick & Grudowski, 2023). Quality 5.0, which is treated in the context of Industry 5.0, includes all of the above characteristics, focusing not only on the elimination of defects and support of high consumer parameters of products but also on the resilience of value formation chains against environmental and socio-economic challenges, customer satisfaction, interactive cooperation with them, involvement of employees with corporate values, and social responsibility of business.

Within the outlined trends and established priorities of modern transformations, energy efficiency is one of the most important criteria for resilience and sustainable development. It lies in the dimension of active and harmonious interaction between humans, nature, and technologies, based on innovations, which conforms to the Industry 5.0 concept. Energy efficiency is disclosed through the multicriterial approach, which involves the achievement of high economic results, reduction of the negative impact on ecology, creation of new value for consumers and society, and care for the quality of products at each stage of their life cycle.

2. EXPERIMENTAL SECTION

The problem of treating energy efficiency as one of the criteria of quality in the conditions of Industry 5.0 is considered through the lens of rational management of sustainable innovations, which gives it a complex and interdisciplinary character. The methodological basis of this research is formed at the intersection of several spheres of scientific cognition, in particular, physics, energy, economics, quality management, cybernetics, and social and humanitarian sciences. An in-depth understanding of the topic is ensured by the inclusion of the concepts of sustainable development, the theory of technological modes and revolutions, corporate social responsibility, and the principles of the circular economy. A special methodological value in the work belongs to the concept of Society 5.0, which gave an impulse for the approaches of Industry 5.0 and the derivative notion of Quality 5.0. This allows forming a new methodological paradigm, which integrates technological, social, environmental, and managerial dimensions.

The research methodology is based on the synthesis of the provisions of the modern theory of quality management, digital transformations, principles of human-centrism, and environmental safety. The theoretical framework is supported by the results of scientific and expert studies, current regulatory and legal acts, and inter-governmental and international standards (in particular, of ISO series), which regulate the aspects of quality and energy efficiency. The focus of the research is on the parameters and elements of Industry 5.0 and Quality 5.0, which cover digital technologies integrated into production and managerial processes given the human factor, institutional maturity, and principles of sustainable development.

This research is of the descriptive and analytical character and is based on systematisation and generalisation of scientific approaches, solutions, and provisions, which determine the conceptual and applied foundations of energy efficiency in the context of Quality 5.0. The applied methodological framework includes general scientific and special methods, in particular, abstracting and generalisation – to form a theoretical model of the studied problem; analysis and synthesis – to structure inter-governmental relations; comparison – to reveal differences and similarities between the concepts of Industry 4.0 and 5.0 and connected aspects; graphical method – to visualise the mechanism of realisation of the principles of sustainable development within the concept of Quality 5.0; monographic method – to study the relevant cases of sustainable innovations management. The theoretical basis of the paper is formed by a set of scholarly and expert works, which dwell on the problems of implementation of the Industry 5.0 concept in the context of quality management, innovations, and energy efficiency. Fundamental provisions of the formation of the Industry 5.0 concepts are considered (Sachsenmeier, 2016), its specifics and components are determined

(Özdemir & Hekim, 2018), attention is paid to the ethical approach to technologies (Longo et al., 2020) and their political influence on sustainable transformation in Europe (Renda et al., 2022). The main features of Industry 5.0 are systematised, and the conceptual model of its implementation is offered (Kaswan et al., 2024), and a multicriterial system of assessing the influence of Industry 5.0 on public and economic processes is developed (Abdel-Basset et al., 2025). In the context of Quality 5.0, its ability to improve the system of company management is established (Fiałkowska-Filipek & Dobrowolska, 2024), and the focus is made on the proactive approach to quality management (Frick & Grudowski, 2023). Its human-centrism (Arıcı & Kitapci, 2021), a roadmap is offered for the transition from Quality 4.0 to Quality 5.0 (Stefanovic et al., 2024), a concept of socially-oriented quality is offered (Milunovic Koprivica et al., 2019), as well as the use of AI in innovations management (Konina, 2024). The issue of sustainability and ESG management, which emphasises the connection between quality and eco-friendliness of products, is disclosed (Popkova et al., 2024), the integration of the Sustainable Development Goals into the system of quality management is studied (Bogoviz et al., 2023), socio-technical specifics of quality management are considered (Ali & Johl, 2024), and the use of AI in managerial innovations is considered. Special attention is paid to energy efficiency and international standards (SGS, 2025; CCS, 2025), which are characterised by the position of improving productivity and environmental responsibility of business.

Theoretical substantiation of the problem does not have an integrated manifestation and requires additional research on the connection between energy efficiency and the processes of quality management in the conditions of the management of sustainable innovations and Industry 5.0. According to this, the goal of this paper is theoretical substantiation of the conditions and provisions of determining energy efficiency as a criterion of quality in the conditions of Industry 5.0. Achievement of this goal requires the resolution of a range of tasks, which include the establishment of the essence and features of Quality 5.0, the study of the mechanism of implementing the principles of sustainable development within the Quality 5.0 concept, description of the specifics of perception and the criteria of quality within the Industry 5.0 concept, determination of the main tools and components of Quality 5.0, assessment of energy efficiency as a criterion of quality in the conditions of Industry 5.0, description of the influence of ISO 14001 and ISO 50001 on the quality management system within

the Quality 5.0 concept, disclosure of the conditions of sustainable management of innovations in the context of the research problem, and disclosure of practical features and advantages offered by digital technologies to raise energy efficiency by the principles of Quality 5.0.

3. RESULTS

At present, the scientific discourse does not offer a unified generally accepted treatment of the definition of Industry 5.0 (I5.0) and the derivative concept of Quality 5.0 (Q5.0). It is believed that the initial understanding of I5.0 was formed by Sachsenmeier in 2016, who considered it a new stage of the industrial revolution based on bionic technologies, which combine biological and technological processes that can change society and economic systems (Sachsenmeier, 2016). Unlike this, Özdemir & Hekim supported the evolutionary nature of I5.0 and focused on the necessity to achieve balance in innovative ecosystems through an increase in the role of humans, avoidance of excessive automatization of production processes, and support of equal access to technologies (Özdemir & Hekim, 2018). This vision was developed through an increase in the factor of human-centrism in the conditions of I5.0 (Longo et al., 2020) and the focus on sustainable development, resilience of systems, environmental responsibility, social inclusion, and effectiveness of managerial processes (Renda et al., 2022). This approach conforms, on the whole, to the Japanese concept of Society 5.0, which is integrated with I4.0 and is based, at the same time, on the principles of total quality management (TQM). This allows considering quality in the context of achievement of high living standards and humanisation of technologies, which takes place due to the use of digital technologies, a high level of productiveness and effectiveness and product quality (Arıcı & Kitapci, 2021). Despite the efforts to unify the definitions of Industry 5.0, scientific thought still has pluralism regarding this notion. The main unifying factor for all approaches is the recognition of digital technologies as the main driving force of changes and dynamic development.

Quality 5.0 is a complex mechanism, which is characterised by a range of features that are manifested through the corresponding qualities and principles and involve the use of the designated list of components, which, in aggregate, allow ensuring substantial advantages and realising the concept of sustainable development (Fig. 1).

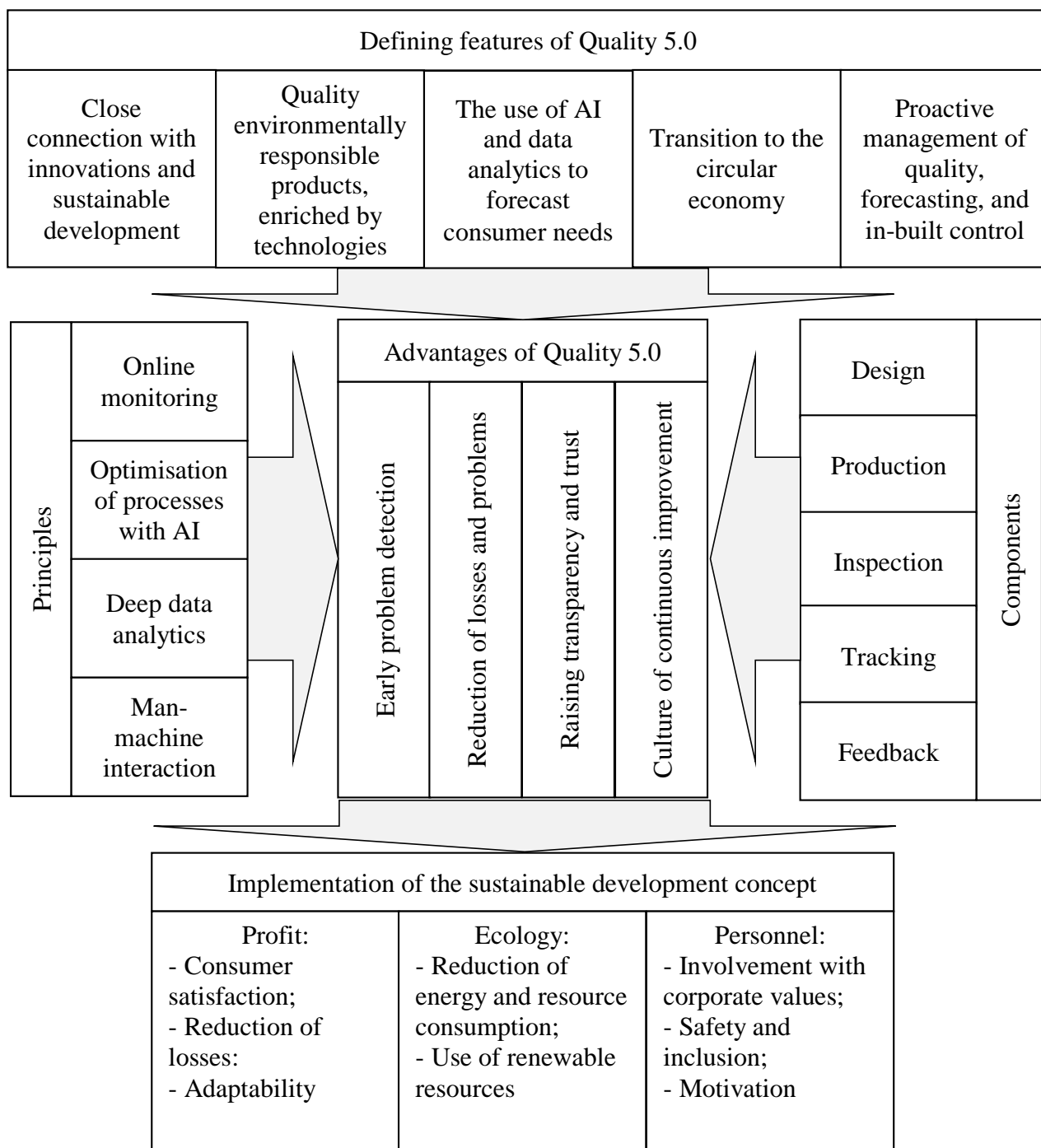


Figure 1. General mechanism of implementing the principles of sustainable development within the Quality 5.0 concept
 Source: Prepared by the authors based on (Ghobakhloo et al., 2024; Frick & Grudowski, 2023; Milunovic Koprivica et al., 2019)

The above mechanism is realised based on the designated list of principles, which characterise the use of digital technologies (online monitoring, optimisation of processes with the use of AI and data analytics), and support of harmonious cooperation of humans and technologies. The main components involved in support of Quality 5.0 are eco-design, production control, an inspection of quality in production processes, tracking the movement of the materials flow, and feedback with the corresponding correction of the production cycle and the cycle of product quality management. Components of

Quality 5.0 allow achieving significant advantages in company management, in particular, detecting problems with quality, reducing product defects and product losses, raising trust in manufacturers, ensuring the transparency of production processes, and forming a culture of continuous improvement of quality.

In the conditions of the I5.0 concept, quality is considered a complex phenomenon, which includes the system of management, production processes, technologies, and human factors. The management

system is based on the strategic perception of quality, within which correspondence to market demands and principles of sustainable development and social responsibility is declared. It is accompanied by a flexible structure of managerial decision-making based on the wide use of the capabilities of big data analytics, AI, and other digital technologies and is characterised by the ability to quickly adapt to the changing conditions of the environment (Kaswan et al., 2024). Thus, the criteria of quality management in the conditions of I5.0 are traditional indicators of resilience, effectiveness, and competitiveness of the company, supplemented by the indicators of correspondence to ESG parameters, including environmental norms and social metrics.

From the position of process approach, the basis of Quality 5.0 is determined by proactive management of production and quality support. According to this, an increase in the array of information through the use of sensors, meters, and data analytics, combined with the expansion of analytical tools through AI technologies and machine learning, allow for early detection of deviations in the production system, identification of product defects, and prevention of their emergence at early stages (Abdel-Basset et al., 2025). In total, such capabilities raise the parameters of product quality and the effectiveness of quality management systems at companies. A specific feature of this approach is the high level of flexibility and adaptability of processes, which allows for quick resetting of the operational and managerial systems according to the market demands. Apart from this, attention should be paid to the principle of continuous improvement, which is based on the use of the PDCA (Plan–Do–Check–Act) method and algorithmization of operations. Due to them, improvement of the quality level is mostly automatic, without direct human involvement.

The technological basis of Quality 5.0 is formed by cyber-physical systems, created on the basis of the integration of information technologies into production processes. They involve the wide application of AI and machine learning, the Internet of Things and digital twins. The IoT technologies allow creating networks of sensors that can perform uninterrupted monitoring of production and forming large arrays of big data, which are mostly inaccessible to human senses (Frick & Grudowski, 2023). AI significantly expands analytical tools due to the automatization of routine operations of monitoring and control (allows reducing the risk of human tiredness) and the use of the tools of computer vision, natural language processing, and predictive analytics. This creates conditions for tracking the parameters of product quality in real-time conditions and for early detection of possible failures in the work of equipment. Digital twins offer the possibility for the creation of a virtual copy of equipment or processes, which are synchronized with real objects. This technology expands opportunities for testing and

optimisation of processes without real interference in production.

Special attention in the context of ensuring quality based on I5.0 principles is paid to human factors. Given the principle of human-centrism, an important task is determining a clear place for humans in the system of production and quality management and its proper integration with information and production processes. According to this, distribution of roles between employees and algorithms is ensured (Frick & Grudowski, 2023), and constant training and advanced training are performed for rational interaction between humans and technologies (Ali & Johl, 2024). Large attention, according to the conditions of Society 5.0, is paid to employees' involvement and the level of their well-being at the workplace and outside it (Milunovic Koprivica et al., 2019). Additional measurements of quality, according to I5.0, are principles of sustainable development (resources saving and minimisation of anthropogenic influence on ecology), inclusion (involvement of different social groups in the determination of quality criteria and provision of equal access to quality products), and ethics (refusal of greenwashing, transparency of quality control algorithms, etc.).

The problem of energy efficiency has a dual nature. On the one hand, it was developed as a result of understanding of depletion of energy resources and initialisation of the search for reserves of energy saving with the simultaneous increase in the level of energy output or saving. On the other hand, it became directly connected to climate processes, which are assessed from the position of the influence of CO₂ emissions on global warming and related processes. At present, both of these aspects are set on the current processes of technological transformations and attention to social factors, which are also manifested within the Quality 5.0 concept.

Quality management in business structures is based on the active application of ISO 9000 standards. At present, when sustainable development ceases to be a simple business imperative but is often a tool for strategic competitive advantages, standards that regulate environmental and energy processes are actively integrated into the systems of corporate management, supplementing the tools of the Quality 5.0 concept. In these conditions, ISO 14001 (Environmental management systems) and ISO 50001 (Energy management systems) determine important directions for effective management of energy consumption, resources, and influence on ecology and ensure the influence on the quality management system. Each standard ensures individual effect on quality management, reducing the volume of waste and emissions, raising the level of trust and transparency or reducing the volumes of energy consumption and decreasing greenhouse gas emissions. At the same time, joint influence of the standards, together with the Quality 5.0 tools, form additional

effects, which raise the economic effectiveness of business, allow for effective management of waste,

contribute to a positive image, and ensure the level of predictability and analytics based on big data (Table 1).

Table 1. Characteristics of the influence of ISO 14001 and ISO 50001 on the quality management system within the Quality 5.0 concept

Standard code	Influence of the standards on quality management	Aggregate effects of quality management based on the principles of ISO 14001, ISO 50001 and Quality 5.0
ISO 14001	<ul style="list-style-type: none"> - Reduction of waste and emission and resource-saving; - Growth of trust from stakeholders; - Reduction of the risks of fines 	Increase in economic effectiveness, which is achieved by lower expenditures for waste management and energy supply. Systemic management of environmental and energy indicators connected with CO ₂ emissions; Formation of a positive climate-responsible brand; Decision-making based on data
ISO 50001	<ul style="list-style-type: none"> - Search for and use of reserves for reducing energy consumption; - Direct reduction of CO₂ emissions; - Adaptation to unstable energy markets; - Protection from regulatory pressure 	

Source: Prepared by the author based on (CCS, 2025; SGS, 2025)

Energy efficiency in the conditions of Quality 5.0 is viewed as one of the main ESG indicators. It belongs to the group of environmental criteria, which also includes greenhouse emissions, parameters of waste disposal, water consumption, the use of soils and atmosphere air, etc. Together with social and managerial criteria, environmental factors transform the very understanding of quality from the position of sustainable development. Thus, quality is no longer viewed as a limited set of product parameters from the position of its ability to satisfy consumer needs. It is a strategic category, which characterises products' ability to meet consumer needs in harmony with society's needs and according to general values in the long term.

The basis of energy efficiency in modern conditions is innovations. Within energy processes, their main influence is focused on the following directions:

- Growth of energy output;
- Reduction of energy consumption;
- Development of alternative energy;
- Improvement of insulation materials;
- Reduction of energy losses;
- Redistribution of energy flow and their rational management.

In the conditions of Industry 5.0, the development of innovations in the sphere of energy efficiency combines scientific R&D in the sphere of digital technologies with a special focus on the human factor's influence. Thus, the basis of energy-efficient innovations is formed not only by AI, big data analytics, and the Internet of Things but also by new materials that can effectively accumulate, retain, and release heat, new directions for using renewable energy sources, the search for reserves for optimisation of energy consumption, redistribution of energy flows, etc. Integration of digital technologies with modern ERP systems, which have the ability for self-training, allows setting the equipment's work in such a way as to minimise energy consumption without a decrease in its power and productivity. Automated production plants without employees but with sensors

can regulate lighting, ventilation, and material flows, ensuring a high level of energy efficiency.

In the sphere of energy efficiency, in the context of Quality 5.0, the main sustainable innovations are as follows:

- Systems of monitoring and processing of information based on the Internet of Things and AI;
- Elements of forecasting and testing of the models of quality management and energy efficiency, which function as digital twins or AI models;
- Systems of optimisation of energy flows and processes, which involve automatization and creation of smart management systems.

The advantages of the systems of monitoring production processes and quality control, based on the collection and processing of big data, lie in an increase in the analytical basis of quality management. Digital technologies allow revealing and tracking processes which were not previously taken into account or could not be identified. From the standpoint of Quality 5.0, there is a possibility to track a wider range of processes that concern the influence of the company's activities on ecology, social dynamics, and interaction with consumers. AI and digital twin technologies allow for a deeper disclosure of the character of this influence and modelling it according to the set values and goals of sustainable development. Smart management systems are integrated tools for the optimisation of the processes of quality management of the growth of energy efficiency and adherence to the principles of sustainable development. Thus, product quality management through sustainable innovations in the conditions of Industry 5.0 involves a complex use of digital tools to achieve the balance between economic effectiveness, environmental responsibility, and social orientation.

Quality 5.0 also allows revising the essence of energy efficiency, providing it with capabilities to reduce energy

consumption and raise energy output, as well as to improve the quality of life through long-term influence on labour conditions and environmental and climate perspectives. By implementing energy-efficient technologies, companies not only reduce operational costs but also contribute to the reduction of energy risks and energy burden on society on the whole. Due to the involvement of employees with the processes of energy effective management, the diffusion of the corresponding values in a social environment, an increase in the level of society's environmental awareness, and growth of the level of satisfaction with work and career take place.

As of now, the principles of Quality 5.0, combined with energy efficiency, are actively implemented in the activities of companies from different sectors of the economy. Thus, Toyota adopted the programme "Toyota Environmental Challenge 2050", which involves the management of energy consumption at factories. The programme combines the expert solutions of energy engineers of the company with the elements of smart forecasting of demand for energy. Such actions allow reducing energy consumption, ensuring the level of employee satisfaction given their involvement with the processes of decision-making within the programme (Toyota Motor Corporation, 2023). The Italian Prada Group also uses a platform for energy consumption management at production, which allows reducing the level of energy consumption through consideration of the specifics of materials and design demands, as well as the use of photovoltaic panels, LED lighting, and purchase of green energy, and raising product quality due to better synchronisation of technological operations (Prada Group, 2022).

Further perspectives of implementing energy-efficient technologies, adapted to Quality 5.0 systems, create large opportunities for expansion of the use of digital technologies, an increase in the level of product quality, reduction of production losses and waste, cyclical use of resources, and formation of transparent value chains. Full involvement of employees in the outlined processes ensures an increase in social long-term effects from the rational management of sustainable innovations, stimulates the development of a sustainable consumption culture, and offers the formation of the complex demand in society for new standards of product quality that are based on eco-friendliness and sustainability.

4. DISCUSSION

Given the complex character of the issue of Quality 5.0 in the context of energy efficiency and rational management of sustainable innovations, the study of all relevant directions for the research is a complex and important task. Apart from this, the high level of dynamics of the outlined scientific problems forms the need for supporting its constant relevance through the change in conditions and the emergence of new factors, demands, and challenges in the market. Thus, a large

share of research tasks and problems requires additional studies, search for, and reconsideration to bring the results and conclusions received in accordance with new conditions that are constantly changing.

One of the main aspects requiring a separate study from the position of the problems posed is the assessment of the level of digital technologies' energy consumption. This problem has an internal conflict, according to which an increase in the volume of the use of digital technologies cannot be viewed only as a factor in the increase in the level of energy efficiency and product quality. Energy consumption, which grows in these conditions, also must receive the proper critical evaluation with the determination of the volumes of energy consumption, the search for energy consumption, and the assessment of the general level of energy efficiency of the use of digital tools to ensure the needs of Quality 5.0.

Another important direction of the research requiring additional disclosure is the problem of ensuring cyber security in managerial information systems, which envisages the corresponding setting of information processes, protection of communication channels, and application of rational methods of search, generation, storing, and processing of data, as well as data protection from unsanctioned access. Given an increase in the volume of data in Quality 5.0 systems, this problem should be the basis of the strategic security of companies, especially in the context of industrial espionage and hybrid security threats of the modern world.

Additional attention should be also paid to the assessment of the influence of different digital tools on the effectiveness of product quality management in the interconnection with support of the high level of energy efficiency and innovativeness. This research will allow revealing the most effective tools of quality management and their connection with the Sustainable Development Goals and establishing additional reserves for application at modern companies.

5. CONCLUSION

Industry 5.0 is a new stage of industrial development which reflects the transition to a technocratic to human-centric approach in production systems management. Compared to Industry 4.0, the new concept combines digital technologies with the principles of environmental responsibility, social inclusion, and humanism. At that, Quality 5.0 is a complex phenomenon, which combines the features of product parameters with metrics of sustainable development, assigning the status of the strategic tool of well-balanced achievement of economic, environmental, and social goals to the process of quality management. In this regard, the notion of energy efficiency also acquires a new role, which goes beyond the limits of reduction of energy consumption or growth of energy output and is expanded to the long-term,

improvement of the quality of life, an increase in social importance, etc. Energy efficiency – as a criterion of Quality 5.0 – is integrated into the strategic framework of quality management and is viewed from the position of the company's ability to harmonise economic interests with environmental and social demands of sustainable development.

The management of sustainable innovations opens new horizons for raising energy efficiency and product quality. This is achieved due to precise forecasting and the formation of adaptive and proactive systems of management, which allow reducing the level of energy consumption without the reduction of productivity or power of production equipment. At the same time, this study puts emphasis on the increasing role of the human factor in the functioning of energy systems of the new

generation and systems of quality management. Integration of the standards of environmental and energy management with quality management systems forms a synergetic effect, which allows not only optimising costs and production processes but also improving the company's reputation and raising its flexibility in reaction to environmental, energy, and social challenges, as well as forming long-term perspective of effective activities. Thus, in the Industry 5.0 paradigm, energy efficiency is not just an operational goal but also a strategic value and advantage, which raises the level of the company's competitiveness and offers perspectives for building a new model of industry with a harmonious combination of economic, environmental, and social effectiveness based on the rational use of digital technologies' capabilities.

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