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Quality 4.0 in the Context of Industry 4.0: Theoretical Aspects and Research Results

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Abstract:

Purpose: *The aim of this article is to present the essence and significance of Quality 4.0 in the context of Industry 4.0, based on both a review of theoretical and empirical studies published in the literature and the authors' own research.*
Desing/Methodology/Approach: *The research concept includes a review of selected, significant studies that indicate the current state and directions of research, along with their justification in the context of the Fourth Industrial Revolution. The authors' own research was conducted in Polish companies with a strong focus on quality and management systems indicating the need for the integration within the framework of Industry 4.0. The research was carried out using the diagnostic survey method, with an original online questionnaire as the primary tool. Both quantitative and qualitative (interviews) methods were employed.*
Findings: *The understanding of Quality 4.0 and Industry 4.0 by representatives of quality-oriented companies was highlighted, and the relationships between Quality 4.0 and Industry 4.0 solutions were presented.*
Practical implications: *The results obtained from one hundred companies were subjected to statistical analysis, showing the status and directions of development of the concepts of Quality 4.0, TQM 4.0, and Quality Management 4.0, as well as their place and significance in organizations operating in the conditions of the Industry 4.0. They indicate areas requiring adaptation to the changing solutions of the Industry 4.0 and areas requiring improvement in terms of employee skills, knowledge, IT solutions, and real-time decision-making.*
Originality/value: *Contribution of research to shaping the definition of Quality 4.0, identification of areas in which Industry 4.0 creates opportunities for improving Quality 4.0 management (linking Quality 4.0 with processes), identification of the role of knowledge in Quality 4.0 improvement processes.*

Keywords: *Quality, Quality 4.0, Quality Management 4.0, Fourth Industrial Revolution, Industry 4.0.*

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1. Introduction

Quality 4.0 draws on the concept of Industry 4.0. This concept combines the use of technical, IT, communication, and material models with traditional management models related to quality and closely connected categories of excellence. Quality 4.0 is linked to and dependent on the exponential digitisation of entire societies, affecting production methods and processes.

It requires extensive organizational knowledge, access to the latest data and information, and a commitment to keeping up to date with new developments and acquiring new skills, often distinctive ones, that enable the implementation, application, and improvement of technical and organizational solutions.

The effective application of acquired knowledge is a prerequisite for improving the quality of products and services and for implementing projects that lead to improvement, maturity, and competitiveness of an organization operating in conditions of change, risk, uncertainty, and discontinuity of operations. Knowledge transfer and sharing are essential as they contribute to the optimization of the communication process (Gomes, Oliveira, and Chaves, 2016).

Technology, linking an increasing number of industries to society, influences the volume and quality of production and the functionality of products. The present day is characterized by the following trends: VUCA, the Fourth Industrial Revolution and DEMIST. VUCA (volatility, uncertainty, complexity and ambiguity). VUCA elements are used to describe the business environment, the environment in which people live and work, the reality of the world, and the era in which they exist.

The Fourth Industrial Revolution brings far-reaching changes in all areas of human and business life. These changes are of a social, industrial, and technological nature, and are driven by the digital transformation of industry, which aims to define how technology and society can coexist (Schwab, 2018). In the context of the ongoing Fourth Industrial Revolution (Industry 4.0), the need to adapt existing quality solutions to the concept of Quality 4.0 is being discussed more and more often.

The Fourth Industrial Revolution is transforming all aspects of human life, including the culture of quality and quality management (QM) in industry. DEMIST (digital economy, management, innovation, society and technology) refers to the domination of the modern world by new means of communication and information processing. Digital transformation is the mass computerization and digitization of human activities, expressed individually or in any organizational arrangement (The Future...2018; Davenport, Guha, Grewal, and Bressgott, 2020).

Quality 4.0 is becoming a tool for improvement throughout the entire value chain of organizations, corporations, and countries. The category of quality must be broadened to include references to the globalisation of innovation. The modern

world, where digitization, digitalization, networking, and social media are becoming part of everyday life, requires a broader view of quality and its applications, which must undergo changes understood not as threats but rather as opportunities for creating a better world.

Quality 4.0 aims to strengthen existing approaches to quality, expand the scale of application of new technologies, and seek ways to improve management, basic, and support processes (Armani, Oliveira, Munhoz, and Akkari, 2021).

Quality 4.0 is the digitisation of quality management to integrate technological structures, processes and people (Jakobs, 2017). The concept of Quality 4.0 encompasses the cyber world and the physical world, ICT and operational technologies, and digitalization (automation, IT, software, telecommunications, big data, AI, industrial internet) as well as quality systems, quality management, quality engineering, machines, interfaces, and tools (Jong Lim, 2019).

Quality 4.0 is a tool that enables the improvement of product and service quality through the use of smart manufacturing technologies, robots, and 3D printing in Industry 4.0. Quality management methods, techniques, and tools must be adapted to the requirements of the digital revolution and linked and integrated with IT systems.

This will enable real-time quality management and reduce the time between the discovery of a technical problem and its resolution (Sisodia, Villegas, Forero 2020). Strong integration, ongoing data collection and processing, developed future skills including digital skills, the development of multidisciplinary teams, and the support and development of innovation are key to the development of Quality 4.0 (Radziwill, 2018).

Open quality is a new quality strategy in Industry 4.0 that encompasses design, production, marketing, and sales. An open quality system combines speed, creativity, data analysis, and artificial intelligence to improve product quality and safety. It includes approaches to implementing multidirectional flow (QM) in real-world applications. This approach uses big data, artificial intelligence (AI), and the Internet of Things (IoT).

It takes into account team creativity, total control and new valuation, and assumes the need to bring together quality experts and data analysts in order to prepare for the solutions offered by the fourth industrial revolution (Hyun Park, Seon Shin, Hyun Park, Y. Lee, 2017).

The concept of Quality 4.0 is in its formative stages. The growing number of studies worldwide testifies to the fact that quality is being reshaped to meet the requirements of Industry 4.0. Quality management 4.0 is an indispensable element of the pursuit of organizational excellence, and its effectiveness will depend on the ability to engage in critical self-reflection, flexibility, and readiness to implement innovative

and contextually appropriate solutions (Fundin, Lilja, Lagrosen, and Bergquist, 2025; Ali, 2025).

TQM 4.0 is a concept aimed at achieving business excellence through comprehensive quality management, including raising its level (Sallek and Salaiman, 2021; Susmila, 2021). Research conducted in this area aims to determine the potential impact of TQM on adapting quality management to the realities of Industry 4.0 and identifies research areas (Souza, Corsi, Balbinotti, and Kovaleski, 2022) related to:

- technology: exploring ways of managing quality through the digitalization and automation of processes while ensuring security, privacy, and data protection,
- quality: exploring ways of assessing the maturity of an organization's adaptation to TQM 4.0,
- human resource management: exploring ways of training quality management professionals to develop skills needed to address Industry 4.0 challenges, helping quality management staff adapt to change using real-time online platforms.

TQM 4.0 aims to create and design analog and digital systems for measurement, recording data for analysis and improvement of production processes (Sader, Husti, and Daroczi, 2019).

The Fourth Industrial Revolution emerged at the beginning of the 2020s and is associated with the use of the Internet of Things and cyber-physical systems for real-time monitoring and decision-making (Parhi, Joshi, Wuest, and Akarte, 2022). Three stages of the Fourth Industrial Revolution have been identified, the algorithm stage, the expansion stage, and the autonomy stage (Gusc and Jarka, 2020).

The goal of Industry 4.0 is to increase the efficiency and autonomy of production processes. Industry 4.0 is a collective term for the integration of intelligent machines and systems, the introduction of changes in production processes aimed at increasing manufacturing efficiency and introducing the possibility of flexible changes in product ranges, innovation requiring changes in the structure of the workplace, job satisfaction and employee engagement (Nardo, Forino, and Murino, 2020), a model for the functioning of the enterprise of the future, a digital business ecosystem, the unification of the world and machines, and the virtual world of the Internet and information technology (Skrzypek, 2020).

Benefits of Industry 4.0, include increased productivity through optimization and automation, operational reliability, improved quality, better customer service, improved communication, increased efficiency, better control of production processes, faster response to market and customer needs, greater transparency of supply chains, transition from a chain to a network of value creation, reduction of

production and logistics costs, avoidance of downtime, increased production flexibility, maximum utilization of the potential of collected data, raising production automation to a new advanced level, development of new business models, products and services, organizational management systems, demand for new skills, efficient supply chain management, the emergence of a digital value chain (the smart factory effect), the integration of cyber-physical systems, the Internet of Things, big data and cloud computing, which has contributed to increased productivity of production systems and the virtualization of organizations (Skrzypek, 2020).

Technologies driving the Fourth Industrial Revolution: cloud technology, virtual reality, distributed technologies, system integration, the Internet of Things, big data, cybersecurity, additive manufacturing (additive printing), artificial intelligence, machine learning, deep learning, data analytics, production optimization, process simulations, mobile robots, autonomous vehicles, RFID (radio-frequency identification), mobile interfaces, geolocation, and blockchain.

The implementation of tasks in Industry 4.0 requires broad and in-depth knowledge from all employees, including managers. Managerial competencies are the range of skills, knowledge, characteristics, experience, behaviours, and attitudes that contribute to effective and efficient management. They are characterized by complexity, operationality, purposefulness, situationality, variability, and measurability.

A Manager 4.0 must ensure that conditions are created for employees to acquire and develop knowledge in the areas of Quality 4.0 and Quality Management 4.0. In Society 4.0, an essential skill is the digital mindset — a set of beliefs and attitudes that enable individuals to understand technology, navigate a rapidly changing world, adapt quickly, and maintain a focus on innovation. They concern interacting with the digital world and using all available digital tools to improve the company's processes (Damborg, 2022).

2. Materials and Methods

Analysis of available results of selected studies and results of own research conducted on one hundred Polish companies that are quality-oriented and recognize the need for integration of management systems. Critical analysis of the available literature and a systematic literature review to ensure methodological rigour. The research was conducted in 2020 and 2021.

2.1 Research Objective

To identify the attitudes of Polish enterprises toward the issues of Industry 4.0 and Quality 4.0, and to gain insights into how these terms are understood by quality-oriented enterprises that are making decisions aimed at integrating existing systems. This integration is considered the basis for the introduction of Quality 4.0 solutions

within Industry 4.0. The study was qualitative in nature. The research tool used was an online questionnaire sent to three hundred Polish companies with an implemented quality management system. One hundred completely filled out questionnaires were used for statistical analysis.

3. Results

Based on an analysis of respondents' answers using a tag cloud, it was concluded that Quality 4.0 is understood as a new concept of quality management and an opportunity for the comprehensive improvement of an organization, enabling its growth. It is a new way of using technology and tools to improve products and services.

Popular definitions of Quality 4.0 were identified: comprehensive understanding of quality (43% of respondents), technology and a new approach to quality management (42%), a management tool for IT-supported organizations, and an opportunity for productivity growth (30% each).

A connection was identified between Quality 4.0 and cost reduction (80% of respondents), business support through rapid response, anticipation, and effective action with reduced employee involvement (66%), as well as the universal nature of quality (66%). It was emphasized that Quality 4.0 is technically linked to the correlation of current data from various sensors (5G), the Internet of Things (60%) and Industry 4.0 advances.

Links were identified between Quality 4.0 and processes in enterprises and their impact on the functioning of enterprises, including: the ability to conduct analyses to predict quality issues in individual processes and maintenance needs (64.7%), monitoring processes, collecting data, and making decisions in real time (73.5%), optimizing processes throughout the entire product life cycle, from research and development, through procurement, production, logistics, to sales, after-sales services, administration, and management (74.5%), incorporating new digital technologies accompanied by improvements in practices and procedures that enhance quality (75.5%), optimizing business processes, as digital tools enable work to be performed faster, better, and more efficiently at lower costs (76.5%).

The impact of the links between Quality 4.0 and processes on management improvement was investigated. The following were identified: faster data analysis, development of remote working systems, more efficient communication, individualization of customer needs, improvement of the quality and flexibility of the production process, increase in the share of partially or fully automated work, the need to develop competencies, wider application of artificial intelligence solutions, comprehensive analysis of process quality costs using IT tools, full integration of the supply chain, the possibility of increasing the scale of automation of quality control

processes, the elimination of accumulated mental barriers and resistance to remote work, risk assessment in processes, and the need for knowledge transfer.

When referring to Industry 4.0, respondents indicated that: it has enabled the shaping of a global economy based on more efficient and sustainable production (75% of respondents), Industry 4.0 solutions will eliminate problems related to inadequate product and service quality and reduce resource waste, lower operating costs resulting from the implementation of IT techniques and digitization processes, which mean far-reaching automation (75%). According to 74% of respondents, it leads to the consolidation of scientific and research institutions aiming to integrate the resources of industry, business and science.

The analysis and evaluation of the results measured on a nominal scale were based on Pearson's chi-squared test of independence, the chi-square 2HR test (highest reliability), Phi correlation coefficient, contingency coefficient, and Cramer's V. For the variables in which a relationship was identified between opinions on Quality 4.0 and the size of the organization, a multiple correspondence analysis was conducted. The relationship between Quality 4.0 and Industry 4.0 solutions and the size of an organisation (micro, small, medium, large) is illustrated in Table 1.

Table 1. *The relationship between Quality 4.0 and the digital solutions of Industry 4.0.*

No.	Understanding Quality 4.0	Number of degrees of freedom *df*	*p* level	*Cramer's V*.	Relationship — *conclusion*
1.	Quality 4.0 should include machine learning	3	0.0102	0.3398	occurs
2.	Quality 4.0 should include predictive analytics	3	0.0108	0.3503	occurs
3.	Quality 4.0 should include the Internet of Things	3	0.0065	0.3540	occurs
4.	Quality 4.0 should include big data	3	0.0292	0.3032	occurs
5.	Quality 4.0 should include cloud computing combined with traditional systems (QMS).	Unmet assumptions for performing the chi-squared test			

Source: *Results of own research.*

The relationship between the understanding of Quality 4.0 and the digital solutions of Industry 4.0, as identified by the chi-squared test of independence, was further specified using multiple correspondence analysis, the results of which are

summarised in a correspondence map. The analyses presented, based on the data obtained, show a wide variation in the attitudes of the companies surveyed towards selected areas of Quality 4.0.

The adopted statistical measures made it possible to identify statistical relationships, however, treating respondents' positions as representative of specific groups, such as enterprise size, requires conducting research on a larger scale. The research confirms the familiarity of respondents with the terms Quality 4.0, Industry 4.0 Quality Management 4.0, TQM 4.0, however, the implementation of solutions in this area does not demonstrate a satisfactory level.

Therefore, initiatives aimed at raising awareness of the need to make decisions that adapt quality-related solutions to the requirements of Industry 4.0 are necessary. Further research in this area on an international scale is justified.

The data obtained from one hundred companies surveyed formed the basis for statistical analysis. The presented results illustrate the state and development directions of the concepts of Quality 4.0, TQM 4.0, and Quality Management 4.0, as well as their place and significance in organizations operating under the conditions of Industry 4.0.

They indicate areas that need to be adapted to the changing solutions of Industry 4.0. They identify areas requiring improvement in relation to employee skills, knowledge, and AT solutions. They demonstrate the necessity of making real-time decisions and their consequences.

4. Discussion

Numerous studies conducted in the area of Quality 4.0 prove that production, research and development benefit enormously from the implementation of Quality 4.0 solutions. Research on human resource management in the context of the development of Quality 4.0 has identified the following problems: technical problem-solving skills, rapid response to change, and precision in new product design.

The use of smart diagnostic tools should contribute to the creation and improvement of local quality compliance systems, while the development of decision-making levels in Quality Management 4.0 enables significant cost and time savings. Among the many studies, the following are particularly noteworthy:

- the study indicating challenges towards improving the quality of information collected to meet real-time decision-making needs in IoT applications (Kim, Abdelzaher, Sha, Bar-Noy, and Dron 2016),
- the study concerning data-driven design, which is necessary for intelligent fault management due to the increasing number of connected machines and

customer complaints (Tuertmann, Russmann, Schroeder, Linder, and Schmitt, 2016),

- the study concerning the impact of individual readiness for change on the implementation of TQM. It has been found that Quality 4.0 solutions influence the optimization of processes throughout the entire product life cycle (Haffar, Irani, Djebarni, and Gdadamosi, 2019),
- the study by World Economic Forum's predictions regarding the domination of the public domain by Industry 4.0 technologies, which showed that 2025 is identified as a critical moment in terms of the latest digital presence (84% of respondents), ubiquitous computerization (84%), and technology (IoT (89%) (Global Logistic, 2021),
- the study by the UN Inter-Agency Task Force on Financing for Development 2020, which identified development trends in AI, the benefits of Industry 4.0 technologies, a new approach to assessing online markets, technological maturity, and Quality 4.0. It has been pointed out that many companies are adopting new digital tools to improve operational efficiency and product quality, with products and equipment at the heart of smart manufacturing. (Wang, Wan, Li, and Zhang, 2016),
- the study indicating new directions for the development of equipment enabling the proper use of Quality 4.0 solutions pointed to the need to develop tools for simulating technological processes, for automatic configuration, development of new quality control technologies, integration of control and process equipment, development of tools minimizing the impact of the human factor (Becue, Praca, and Gama, 2021),
- the study in the field of Industry 4.0, taking into account its impact on various areas of business operations, is continuing and concerns intelligent product design, supply chains, lean manufacturing, production planning and control (Rosit, Tohme, and Frutos, 2019),
- the study on tools for assessing readiness or maturity for the implementation of solutions in relation to new challenges in Quality Management 4.0 (Gusc, Jarka, and Zwarte, 2020; Zonnenshain and Kenett, 2020; Nenedal, Vykydal, Halfarova, and Tyleckova, 2022).

There is considerable overlap between the results of the referenced studies and research presented herein. The author's research extends the understanding of Quality 4.0. They point to the relationships that exist between Quality 4.0, Quality Management 4.0, TQM 4.0 and Industry 4.0.

Quality 4.0 in Industry 4.0, in light of research results, can be presented as, a multifaceted approach to quality, a tool for improving business performance, a technology and a new way of managing quality, a dynamic concept, a solution for improving processes, a tool for intelligent quality management, a concept justifying standardization and normalization 4.0, a platform for producing better products and controlling processes in real time, an opportunity for success, digitization of a comprehensive approach to quality, a combination of intelligence and automation, a

new technology-supported management method, a tool for strengthening a new approach to quality, an opportunity for better and more comprehensive customer satisfaction while maintaining greater safety, higher efficiency, and meeting environmental and sustainability requirements.

In addition, as direct electronic communication with the customer, a platform for the analysis and use of data collected in quality management systems, remote working and remote management of teams of employees, highly automated work, automatic quality control, exchange of quality information directly between machines, advanced integration of supply chains and the opportunity for comprehensive quality cost analysis.

An analysis of the results of selected studies indicates that many companies are adopting new digital tools to improve product quality, which are at the heart of smart manufacturing. The key factors for the development of Quality 4.0 include strong integration, continuous data acquisition and rapid processing, advanced future-oriented competencies, the development of multidisciplinary teams, and the support and advancement of innovation.

5. Conclusion

The research results provide the basis for the formulation of the following conclusions: Quality 4.0 is an evolving concept, and effective Quality 4.0 management is closely linked to Industry 4.0. The advancement of Industry 4.0 tools enables the improvement of organizational management in the area of quality, including quality control.

Under conditions of digitalization, decentralization, networking, and the influence of social media, a broader perspective on quality and its applications is necessary in light of required changes. Quality 4.0 in the context of Industry 4.0 represents the digitalization of quality management aimed at integrating technological structures, processes, and people to enhance the quality of products and services, thereby contributing to increased organizational maturity.

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