

Article

Comparative Assessment of Industry 4.0 and Quality 4.0 Implementation in Poland and Slovakia: Determinants, Maturity and Challenges

Manuela Ingaldi ¹ , Vanessa Prajová ², Katarína Lestyánszka Škúrková ^{2,*} and Robert Ulewicz ¹ 

¹ Faculty of Management, Czestochowa University of Technology, Al. Armii Krajowej 19b, 42-200 Czestochowa, Poland; manuela.ingaldi@pcz.pl (M.I.); robert.ulewicz@pcz.pl (R.U.)

² Faculty of Materials Science and Technology in Trnava, Slovak University of Technology in Bratislava, Vazovova 5, 812 43 Bratislava, Slovakia; vanessa.prajova@stuba.sk

* Correspondence: katarina.skurkova@stuba.sk; Tel.: +421-907-577-754

Abstract

The aim of the study was to assess the level of implementation of the Industry 4.0 and Quality 4.0 concepts in manufacturing enterprises in Poland and Slovakia, as well as to identify the main barriers, supporting factors, and organizational effects related to digital and quality transformation. The study was conducted using a qualitative–quantitative approach based on a multiple case study strategy and the matched-pair method. The analysis covered 10 manufacturing enterprises (5 from Poland and 5 from Slovakia) representing various industrial sectors. Research triangulation was applied, including a diagnostic questionnaire, semi-structured interviews, analysis of organizational documents, and direct observation. Two synthetic indicators were developed: the Industry 4.0 Readiness Index (I4RI) and the Quality 4.0 Maturity Index (Q4MI). The results indicate a moderate level of implementation of both Industry 4.0 and Quality 4.0 in the analyzed enterprises, with Polish companies achieving slightly higher scores than Slovak enterprises. The highest level of advancement was observed in the area of technologies and automation, while the lowest concerned data integration and the use of analytics. The analysis revealed a strong positive relationship between the level of Industry 4.0 implementation and Quality 4.0 maturity, as well as the positive impact of both concepts on selected operational performance indicators, such as OEE, delivery timeliness, and defect rates. The obtained results confirm the complementary nature of Industry 4.0 and Quality 4.0 and highlight the need for a more integrated and human-centric approach to the digital transformation of manufacturing enterprises in Central and Eastern Europe.

Keywords: Industry 4.0; Quality 4.0; digital maturity; digital transformation; SMEs; maturity model; Central and Eastern Europe; quality management; sustainable manufacturing



Academic Editor: Marko Mladineo

Received: 26 May 2026

Revised: 24 June 2026

Accepted: 29 June 2026

Published: 3 July 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

In recent years, the digital transformation of manufacturing enterprises in Central and Eastern Europe has accelerated significantly. However, the level of advancement and the implementation approaches still vary across countries and industrial sectors. Poland and Slovakia, as economies with similar industrial structures and comparable stages of economic development, constitute an important comparative context for analyzing the implementation of the Industry 4.0 and Quality 4.0 concepts. Despite increasing investments in digital technologies, many enterprises continue to face structural and

organizational barriers, including insufficient integration of digital systems, limited use of data, and low maturity of quality management in a digital environment [1–3].

Despite the growing interest in both Industry 4.0 [4,5] and Quality 4.0 [6,7] in the literature, these concepts are still predominantly often analyzed as separate research streams. Industry 4.0 primarily focuses on technological aspects, automation, and the integration of cyber–physical systems, whereas Quality 4.0 extends the classical approach to quality management through the use of data, analytics, and intelligent decision support. However, there is still a lack of empirical studies simultaneously assessing the maturity of both concepts and their interrelationships in a cross-country comparative perspective. This gap limits the comprehensive understanding of digital transformation mechanisms in manufacturing enterprises.

From the perspective of sustainable development, the integration of the Industry 4.0 and Quality 4.0 concepts is of particular importance, as it may contribute to improving resource efficiency, reducing waste, and increasing the resilience of production systems. An integrated approach enables a more comprehensive assessment of the impact of digital transformation not only on operational performance, but also on the achievement of sustainability-related goals, including environmental and organizational efficiency. In this sense, the study aligns with the current research stream on sustainable industry by linking digital maturity with measurable quality and operational outcomes [8,9].

The aim of this study is to assess the level of implementation of the Industry 4.0 and Quality 4.0 concepts in manufacturing enterprises in Poland and Slovakia. It also seeks to identify the key barriers, supporting factors, and organizational effects associated with their implementation. The study further aims to determine the relationship between the level of Industry 4.0 implementation and the maturity of Quality 4.0, as well as their impact on selected operational performance indicators. Finally, it examines how the development of Industry 4.0 and Quality 4.0 may support more sustainable and resilient production systems.

From a theoretical perspective, the article contributes to the literature by integrating two research streams that have often been analyzed separately to date: digital transformation (Industry 4.0) and digital quality management (Quality 4.0). In particular, the proposed approach enables the parallel assessment of both concepts using coherent, multidimensional synthetic indicators [10,11].

The research novelty is reflected in several aspects:

- The application of a comparative approach based on matched pairs of enterprises from two countries, covering five industrial sectors (metal processing, automotive components, plastics processing, machinery manufacturing, and food industry) and representing medium and small-sized companies at different positions in the supply chain, which reduces the influence of sector-specific factors and increases the validity of cross-country conclusions.
- The simultaneous analysis of Industry 4.0 and Quality 4.0 within a single research model, addressing the literature gap concerning their interrelationships.
- The use of triangulation of methods and data sources, combining quantitative and qualitative approaches in the analysis of organizational maturity.
- Linking the implementation level of the analyzed concepts with measurable organizational outcomes, rather than relying solely on respondents' declarative assessments.

The research novelty of this study extends beyond the mere combination of two established concepts. While both Industry 4.0 and Quality 4.0 have been studied individually, their simultaneous empirical assessment within a single analytical model represents a methodological and contextual contribution that has not been previously addressed in the literature. The model is applied to matched pairs of enterprises from two Central

and Eastern European countries. In particular, the study advances existing knowledge by moving beyond declarative technology adoption assessments toward a multidimensional evaluation of organizational readiness and maturity, directly linked to measurable operational outcomes.

Additionally, the study provides practical value by identifying the key conditions influencing digital and quality transformation in manufacturing enterprises operating in the economies of Central and Eastern Europe.

To achieve this aim, the study addresses the following research questions:

RQ1. What is the level of Industry 4.0 and Quality 4.0 implementation in the analyzed SMEs in Poland and Slovakia?

RQ2. What barriers and supporting factors for implementation occur in both countries?

RQ3. Does a higher level of Industry 4.0 implementation coexist with a higher level of Quality 4.0 maturity?

RQ4. What organizational outcomes are associated with a higher level of implementation of both concepts?

The remainder of the paper is structured as follows. Section 2 provides a literature review covering Industry 4.0, Quality 4.0, their interrelationships, implementation barriers, and the research gap. Section 3 describes the research methodology, including the sampling design, data collection techniques, and validation procedure. Section 4 presents the results organized around the four research questions. Section 5 discusses the findings in relation to existing literature and their implications for sustainable development. Finally, Section 6 presents the conclusions, limitations, and directions for future research.

2. Literature Review

2.1. Industry 4.0 as the Technological and Organizational Background of Manufacturing Enterprise Transformation

Industry 4.0 is currently regarded as one of the most important conceptual frameworks for explaining the digital transformation of manufacturing enterprises. However, the literature emphasizes that this concept should not be reduced solely to a set of technologies such as cyber–physical systems, the Industrial Internet of Things, artificial intelligence, robotics, cloud computing, digital twins, or Big Data analytics. A more convincing perspective views Industry 4.0 as a process of reconfiguring the manufacturing system, in which digital technologies transform the design of processes, data flows, decision-making, collaboration with suppliers and customers, and competency management. This understanding is particularly important for the present study, as the adopted Industry 4.0 Readiness Index measures not only the presence of technologies, but also digital strategy, data integration, competencies, cybersecurity, and supply chain connectivity [12].

From this perspective, the digital maturity of an enterprise results from the coexistence of technological resources and organizational capabilities. Studies on sustainable digital transformation indicate that Industry 4.0 technologies may increase energy efficiency, reduce material waste, improve process transparency, and support predictive resource management; however, these effects depend on the quality of integration between technologies and the strategic objectives of the enterprise [13]. Similarly, the evaluation of Industry 4.0 technologies from a sustainable development perspective shows that digital solutions are not automatically beneficial; they require conscious selection, performance measurement, and alignment with economic, environmental, and social criteria [14]. This implies that the assessment of Industry 4.0 implementation should consider both the technological layer and the managerial mechanisms that determine whether data are actually used for operational improvement.

This perspective is also confirmed by recent studies. An analysis of the Polish steel value chain shows that the transition toward Industry 4.0 involves automation, IT system integration, IoT, mobile technologies, Big Data, blockchain, and cybersecurity; however, its actual impact becomes visible only at the level of relationships between producers, distributors, and customers [15]. Similar conclusions were formulated by Sony and Naik, who emphasized that technological transformation should be accompanied by organizational adaptation and the development of digital quality capabilities in order to achieve measurable operational benefits [16]. In turn, research on the systematic implementation of information technologies in manufacturing enterprises indicates that implementation success depends on aligning the deployment path with the organization's maturity level, rather than simply replicating technological solutions [17]. This observation is consistent with studies highlighting that organizational readiness, employee competencies, and process integration constitute critical determinants of successful digital transformation [18]. A bibliometric review of Industry 4.0 research confirms that current research streams focus on smart manufacturing, IoT, machine learning, digital transformation, and sustainable development [19]. Moreover, the recent literature increasingly underlines the importance of integrating Industry 4.0 technologies with sustainability-oriented management practices, particularly in the context of resilient and resource-efficient manufacturing systems [20].

The above findings lead to an important theoretical implication: Industry 4.0 is a necessary but insufficient condition for the development of digital quality maturity. The mere implementation of automation systems, sensors, or ERP/MES software (e.g., SAP, Comarch, Odoo) does not ensure quality improvement if data remain fragmented, are not validated, are not interpreted by competent employees, and do not feed the continuous improvement cycle. Therefore, empirical research on manufacturing enterprises requires a shift away from simple indicators of technology adoption toward multidimensional readiness indicators that allow for assessing whether digitalization actually builds an organizational capability for learning and fact-based decision-making [10,11].

From the sustainability perspective, the convergence of Industry 4.0 and Quality 4.0 is increasingly recognized as a critical factor supporting resilient and resource-efficient manufacturing systems. The integration of digital technologies with quality-oriented management practices enables enterprises to optimize resource consumption, reduce production waste, improve traceability, and strengthen process transparency. Consequently, digital transformation is no longer perceived exclusively as a technological shift but rather as a multidimensional organizational change contributing to sustainable industrial development and long-term competitiveness. At the system level, integrated Industry 4.0 architectures are increasingly framed as enablers of smart sustainable manufacturing, because they connect digital technologies with sustainability practices across procurement, production, logistics, and market-facing processes, thereby shifting transformation from isolated technological adoption toward coordinated value-chain redesign [21].

2.2. *Quality 4.0 as the Evolution of Quality Management in a Digital Environment*

Quality 4.0 has emerged as a response of quality management to the digitalization of production processes. It does not imply abandoning classical quality management principles such as customer focus, leadership, process approach, continuous improvement, and fact-based decision-making. Rather, its specificity lies in embedding these principles in an environment where quality data are automatically collected, integrated with production data, analyzed in real time, and used for predictive or prescriptive process control. A review of the Quality 4.0 literature indicates that the concept is still defined in various ways, and its most commonly analyzed components include digital technologies, the impact

of transformation on the quality function, and new competency requirements for quality professionals [22].

Recent systematic reviews show that Industry 4.0 technologies can support quality management practices primarily in areas such as inspection, traceability, process control, nonconformity management, root cause analysis, and product improvement. At the same time, the literature highlights persistent implementation barriers, including low system interoperability, insufficient data quality, lack of analytical competencies, limited integration of quality management systems with production systems, and difficulties in linking operational data with strategic decision-making [10,23]. For this reason, Quality 4.0 should be understood not as a technological module, but as an organizational capability to build a quality system based on data, competencies, and cross-functional collaboration.

An important direction in the development of this concept is the shift from descriptive definitions toward capability models and roadmaps. The Quality 4.0 roadmap proposed in the literature emphasizes that enterprises should develop capabilities in a staged manner: starting from structuring basic quality management and standardizing processes, moving through digitizing quality records and integrating systems, and progressing toward advanced analytics and predictive improvement [11]. This approach is consistent with the findings of a broad literature review on manufacturing quality, which indicates that digitalization strengthens the importance of automation, data, regulatory compliance, customer expectations, and sustainability goals as interrelated determinants of quality [24].

For the present study, this implies that Quality 4.0 maturity should be assessed not only through digital quality control tools, but also through quality leadership, quality culture, employee competencies, cross-functional collaboration, traceability, and the ability to continuously improve based on data. A critical review of the literature leads to the conclusion that many enterprises may have well-developed traditional quality practices while still remaining at a low level of quality digitalization if quality data are analyzed retrospectively, in spreadsheets, or in isolated systems. In such cases, Quality 4.0 is not yet a mature management paradigm, but rather a transitional stage between classical quality systems and a quality system integrated with a digital production architecture [11,25]. This interpretation is supported by recent conceptual work showing that the Fourth Industrial Revolution modifies the operationalization of quality management principles rather than invalidating them; in particular, customer focus, evidence-based decision-making, and process orientation increasingly depend on data acquisition, automation, digital connectivity, and real-time process feedback [26].

2.3. Mechanisms Linking Industry 4.0 and Quality 4.0

The relationship between Industry 4.0 and Quality 4.0 is complementary in nature. Industry 4.0 provides the technological infrastructure and data, while Quality 4.0 gives these data managerial meaning, directing them toward process stability, defect reduction, customer satisfaction, and continuous improvement. Three main mechanisms of this complementarity can be distinguished. The first mechanism concerns the expansion of measurement scope: sensors, IIoT systems, and IT/OT integration enable real-time data acquisition from machines, processes, products, and the environment. The second mechanism relates to analysis: Big Data, visualization, machine learning, and decision-support systems allow the identification of relationships that cannot be detected through traditional quality control. The third mechanism concerns action: digital quality tools enable faster responses to deviations, predictive maintenance, automatic alerts, and more precise corrective actions [10,24].

Empirical examples from recent studies clearly illustrate this relationship. In the prediction of injection molding quality, it has been shown that feature extraction from

multi-sensor data and machine learning can significantly improve real-time product quality monitoring [27]. Similar observations were reported in studies on Quality 4.0, which emphasize that artificial intelligence and advanced analytics enable more proactive and predictive quality management approaches based on continuous data acquisition and real-time process control [28]. A systematic review of AI/ML applications in aerospace manufacturing, in turn, shows that artificial intelligence can support inspection, planning, prediction, and optimization. However, its implementation faces limitations related to data scarcity, model validation, and the specific requirements of high-safety-critical processes [29]. Other studies indicated that the effectiveness of Quality 4.0 depends not only on technological capabilities but also on organizational readiness, employee competencies, and trust in data-driven decision-making processes [30]. This means that effective Quality 4.0 requires not only algorithms, but also reliable data, interpretation procedures, and clear decision-making accountability.

Similar conclusions emerge from research on digital twins, predictive maintenance, and decision-support systems. The application of reinforcement learning and digital twins for managing production system operating modes shows that these technologies can enhance an enterprise's ability to respond to disruptions, provided that the digital model is sufficiently aligned with the real process [31]. This observation is consistent with recent studies indicating that digital twins may improve process transparency, operational resilience, and sustainability performance through continuous synchronization between physical and virtual production environments [32]. A hybrid predictive maintenance model further indicates that combining diagnostic data, expert knowledge, and mathematical models can support machine stability and thus indirectly influence process quality [33]. In the automotive industry, a computerized decision support system for engineering change management improved standardization, traceability, and reduced disruptions caused by ambiguous procedures [34]. These findings confirm that the effectiveness of Industry 4.0 and Quality 4.0 solutions depends increasingly on the integration of intelligent technologies with organizational processes, human competencies, and data governance practices.

The literature therefore suggests that the integration of Industry 4.0 and Quality 4.0 should not be examined as a sum of separate implementations, but rather as a unified system of organizational capabilities. If an enterprise develops automation without integrating quality-related data, it mainly achieves an increase in technical productivity. Conversely, if it develops a quality system without a digital infrastructure, it remains at the level of reactive control and limited process visibility. Only the combination of both perspectives enables a shift toward proactive quality management, in which production and quality data are used to predict nonconformities, reduce costs of poor quality, and improve operational performance indicators such as OEE, delivery timeliness, and lead time [8,10].

In summary, the relationship between Industry 4.0 and Quality 4.0 can be conceptualized as a mutually reinforcing feedback loop: digital infrastructure enables data-driven quality management, while a mature quality system provides the governance framework necessary to extract operational value from digital technologies. This interdependence implies that enterprises developing only one of these dimensions risk either generating unused data or maintaining quality practices disconnected from real-time process intelligence. From a theoretical standpoint, this suggests that Industry 4.0 readiness and Quality 4.0 maturity should be assessed jointly rather than independently, which constitutes the primary conceptual contribution of the present study.

2.4. Implementation Barriers and the Specific Context of Central and Eastern European Enterprises

Despite the growing number of publications and implementation projects, the digital transformation of manufacturing enterprises—particularly SMEs—remains an uneven

process. The most frequently identified barriers include high investment costs, uncertainty regarding return on investment, lack of digital competencies, limited system interoperability, outdated infrastructure, cybersecurity concerns, and resistance to change [35]. Research on the success of SME digital transformation shows that, beyond financial resources, key factors include strategy, leadership, competency development, organizational culture, and change management capability [36].

The research findings confirm this diagnosis in relation to enterprises operating in Central and Eastern Europe. An analysis of barriers and potential benefits of Industry 4.0 implementation indicates that technological and organizational constraints coexist with a real potential for improving efficiency, quality, and flexibility [37]. Similar conclusions were reported in studies emphasizing that successful digital transformation requires the simultaneous development of technological infrastructure, organizational culture, and employee competencies, rather than isolated investments in advanced technologies alone [16]. At the same time, a proposed framework for analyzing gaps in artificial intelligence implementation shows that enterprise readiness assessment should simultaneously include technological adoption, human capital readiness, financial adequacy, and strategic alignment [38]. This indicates that the barriers to Industry 4.0 and Quality 4.0 are largely systemic rather than purely technological. Such observations are also consistent with recent sustainability-oriented studies, which underline that resilient digital transformation depends on the integration of technological, organizational, and human-centered dimensions [39].

The context of Poland and Slovakia requires particular attention, as these economies belong to industrially strong but often cost-sensitive production systems in Central and Eastern Europe. Enterprises operating in automotive, metal processing, plastics, machinery, and food supply chains are under pressure from customers, quality standards, and delivery timeliness, while simultaneously having limited financial and competency resources. A study of SMEs from V4 countries shows that companies more frequently focus their improvement activities on product quality enhancement than on reducing environmental impact, revealing a gap between the traditional understanding of quality and the quality–environmental dimension of sustainable transformation [40]. This observation corresponds with broader discussions on sustainable manufacturing, where digital transformation is increasingly linked with environmental responsibility, resource efficiency, and circular economy practices [41]. Research on Slovak enterprises in the area of predictive HR analytics indicates that awareness of the value of data-driven decision-making is increasing; however, the scope for the practical implementation of advanced analytics remains considerable [42]. Moreover, recent studies emphasize that the development of analytical competencies and digital skills constitutes one of the critical determinants of Quality 4.0 maturity in manufacturing organizations [18].

In this context, the comparison of enterprises from Poland and Slovakia is justified both theoretically and practically. These countries share a similar importance of the manufacturing sector, strong integration into European supply chains, and comparable competency-related challenges, while potentially differing in access to support programs, ownership structures, customer pressure, and the organization of digital investments. The literature provides numerous general studies on Industry 4.0 barriers; however, less is still known about how these barriers simultaneously translate into digital readiness and Quality 4.0 maturity in matched pairs of enterprises from two countries. This gap is particularly relevant because cross-country comparisons without controlling for industry and firm size may confound country effects with sectoral effects [36].

Table 1 summarizes the key findings from the reviewed literature and identifies the main research gaps addressed by the present study.

Table 1. Summary of key findings from the literature review and identified research gaps.

Topic	Key Findings from Literature	Research Gap
Industry 4.0 in manufacturing	Broad adoption of digital technologies; focus on automation, IoT, cyber-physical systems	Limited empirical studies on actual readiness levels in CEE SMEs
Quality 4.0	Evolution of quality management through digitalization; barriers include low interoperability and lack of analytical competencies	Few studies assess Q4.0 maturity using multidimensional indicators
I4.0 and Q4.0 relationship	Complementary nature recognized theoretically; data infrastructure enables data-driven quality management	Lack of simultaneous empirical assessment of both concepts in a single model
Cross-country comparisons	General studies on I4.0 barriers available; CEE context underrepresented	No matched-pair comparative studies controlling for sector and firm size
Operational outcomes	Positive associations between digitalization and OEE, defect rates, delivery timeliness reported	Few studies link implementation levels directly to measurable operational indicators
Sustainability dimension	I4.0 linked to resource efficiency and sustainable manufacturing	Integration of sustainability outcomes with I4.0 and Q4.0 maturity rarely examined empirically

2.5. Research Gap and Justification of the Model Adopted in This Study

Building on the literature reviewed in the preceding sections, and extending the research gaps identified in the Introduction, this section develops the conceptual justification for the analytical model adopted in the present study. Rather than restating the gaps, the focus here is on explaining how the convergence of Industry 4.0 and Quality 4.0 perspectives, as revealed by the literature, necessitates an integrated assessment approach and informs the construction of the proposed indicators.

The recent literature increasingly extends the discussion on Industry 4.0 and Quality 4.0 toward human-centricity, resilience, and sustainability. The Industry 5.0 concept does not replace Industry 4.0 but rather corrects its techno-centric limitations, emphasizing the need to combine digital efficiency with the role of humans, workplace safety, algorithmic responsibility, and organizational resilience. Industry 5.0 strategy frameworks indicate that sustainability, resilience, and human-centricity should be treated as equally important dimensions in the design of future manufacturing systems [9]. At the same time, a proposed prototype of a holistic Industry 5.0 readiness index highlights the need to measure not only digitalization, but also social and resilience-related factors [43]. This argument is reinforced by recent work on sustainability-oriented digital transformation, which shows that the adoption of digitalization and artificial intelligence is conditioned not only by technological modernization but also by managerial cognition, organizational culture, legacy-system constraints, skills availability, cybersecurity readiness, and sustainability priorities [44].

From a quality management perspective, this means that Quality 4.0 should be interpreted as a stage in which classical quality systems learn to use data, while simultaneously preparing organizations for more human-centric and responsible quality models. This transition is increasingly discussed in the literature as a shift from technology-centered to human-centric and value-driven quality management systems, where data analytics supports rather than replaces human judgment in decision-making processes [16]. A systematic review on the role of humans in the Industry 5.0 environment indicates that a unilateral focus on productivity, flexibility, and cost reduction may lead to the dehumanization of industry if digital transformation does not take into account employee competencies, safety, and participation [44]. Similar arguments are presented in studies on Quality 4.0, which emphasize that the evolution of quality management systems requires a balance between

technological advancement, process automation, and human involvement in ensuring reliability and continuous improvement [18]. In addition, research on ethical challenges of artificial intelligence in industry shows that algorithmic management, employee monitoring, machine autonomy, and generative AI introduce new risks related to responsibility, trust, and transparency of decision-making [45]. These findings suggest that the implementation of Quality 4.0 requires not only technological readiness but also robust governance frameworks ensuring transparency, accountability, and ethical use of digital technologies.

Based on the conducted analysis, several key research gaps can be identified. First, existing studies predominantly examine Industry 4.0 and Quality 4.0 as separate research streams, relying on independent maturity models that do not capture their interdependence. As a result, the mutual reinforcement between digital infrastructure and quality management capabilities remains empirically underexplored. Second, a significant portion of studies relies on self-reported assessments of technology adoption without linking implementation levels to measurable organizational outcomes such as OEE, defect rates, or delivery timeliness, which limits the practical relevance of existing findings. Third, comparative studies focusing on Central and Eastern Europe remain scarce, and those that exist rarely control for industry and firm size, making it difficult to disentangle country-level effects from sectoral influences. Fourth, existing maturity models remain predominantly technology-centric, insufficiently accounting for competencies, data culture, quality leadership, and organizational learning—dimensions that the present study explicitly incorporates into both indicators.

The present study addresses these gaps by conceptualizing Industry 4.0 readiness as a technological–organizational foundation of digital transformation, and Quality 4.0 maturity as an enterprise capability to effectively use data and technologies within the quality management system. The use of two synthetic indicators, the Industry 4.0 Readiness Index and the Quality 4.0 Maturity Index, enables a parallel assessment of both dimensions and an evaluation of their relationship with operational performance. The adoption of a matched-pair strategy involving enterprises from Poland and Slovakia strengthens the validity of comparisons by reducing the influence of sector-specific factors. Consequently, the literature review leads to the assumption that effective manufacturing transformation is not based solely on technology implementation, but on the integration of technology, data, people, and quality practices into a coherent system of operational improvement [11,36,46].

3. Materials and Methods

In this study, a qualitative–quantitative approach based on an embedded multiple-case study strategy was adopted. This approach enabled an in-depth analysis of the implementation of Industry 4.0 and Quality 4.0 concepts in manufacturing enterprises operating in Poland and Slovakia. It captures both the structural dimension (level of implementation) and the contextual dimension (organizational conditions, barriers, and outcomes).

3.1. Sampling Design

The selection of enterprises was purposive and based on a matched-pair design. This means that each Polish company was paired with a Slovak company with a similar operational profile. The matching criteria included:

- Industry sector (e.g., metal processing, automotive, plastics manufacturing, machinery production, food industry);
- Company size;
- Level of process automation;
- Position within the supply chain.

More specifically, the matching criteria were operationalized as follows:

- Industry sector and dominant production profile, so that each Polish enterprise was compared with a Slovak enterprise operating in the same or closely comparable manufacturing sector;
- Enterprise size, operationalized primarily by the number of employees and interpreted in accordance with the small and medium-sized enterprise category used in the European context;
- Geographical and market context, understood as operation within comparable Central and Eastern European manufacturing environments and similar regional or international market conditions;
- Level of technological advancement and process automation, classified as low, medium, or high on the basis of the observed and declared use of automation and digital production-support systems;
- Operational scale and position within the supply chain, including roles such as Tier 1 supplier, Tier 2 supplier, subcontractor, OEM, or producer, because these positions determine customer requirements, quality obligations, and pressure for digital integration.

The purpose of applying these criteria was not to obtain statistical representativeness, but to strengthen analytical comparability and internal validity in a small-sample comparative design. This logic is consistent with methodological recommendations for case-based and operations-management research, where purposive selection, theoretical replication, and control of key contextual variables are considered appropriate for exploratory comparative studies [47–50].

In total, 10 enterprises were included in the study (5 matched pairs), which allowed for reducing the influence of sector-specific variables and increasing the comparability of results between countries. The unit of analysis was the organization, while data were collected from three respondents in each company. In each case, at least three perspectives were included:

- Strategic (owner, board member, or director);
- Operational (production, operations, or maintenance manager);
- Quality-related (quality manager, quality representative, or continuous improvement specialist).

Overall, approximately 30 responses were obtained, enabling data source triangulation. The study was conducted between September and December 2025.

The matched-pair design is a purposive sampling strategy in which each case from one group is paired with a case from another group based on predefined matching criteria. This approach is particularly suitable for cross-country comparative research because it allows control of confounding variables, such as industry sector and firm size, which could otherwise obscure country-level differences. By ensuring structural equivalence between paired enterprises, the design increases the internal validity of cross-country comparisons and reduces the risk of attributing observed differences to factors other than country-specific conditions. This method has been applied in organizational and management research as an effective strategy for small-sample comparative studies where statistical matching is not feasible [36].

The sample size of ten enterprises, while limited, is consistent with the methodological assumptions of embedded multiple-case study research, in which analytical generalization rather than statistical representativeness is the primary goal. As argued in the case study methodology literature, a sample of four to ten cases is generally considered sufficient for cross-case pattern identification and theoretical replication, provided that the cases are purposively selected and systematically compared. The inclusion of five industrial sectors was intentional and serves to broaden the analytical perspective, enabling the

identification of patterns that transcend sector-specific conditions. At the same time, the matched-pair design ensures that cross-country comparisons remain valid by controlling for industry and firm size, thus reducing the risk of confounding sectoral effects with country-level differences.

The inclusion of enterprises from five different industries was therefore a deliberate research-design decision. The first four sectors, namely metal processing, automotive components, plastics processing, and machinery manufacturing, represent capital-intensive and predominantly discrete manufacturing environments. These sectors are characterized by complex production systems, multi-stage processes, structured quality-control procedures, and strong integration into multi-tier supply chains. Consequently, they provide a suitable context for assessing Industry 4.0 and Quality 4.0 implementation in technologically demanding manufacturing settings.

The food industry was included as a contrasting sector representing a more continuous, fast-moving, and highly regulated consumer-goods manufacturing environment. In this sector, traceability, hygiene regimes, product safety, short delivery cycles, shelf-life constraints, and regulatory compliance play a central role. Its inclusion enabled cross-industry validation of the proposed framework. Specifically, it allowed us to examine whether similar patterns between Industry 4.0 readiness, Quality 4.0 maturity, and operational outcomes could also be observed outside heavy/discrete manufacturing.

Thus, the cross-industry structure of the sample was intended to mitigate industry-specific bias and to examine the robustness of the observed phenomena across heterogeneous manufacturing settings. At the same time, comparability was preserved through the matched-pair logic, because each cross-country comparison was conducted within the same industry and between enterprises with similar operational profiles. Accordingly, cross-sector observations were interpreted cautiously and primarily at the aggregate level, whereas the main comparative logic of the study remained within-pair comparison.

3.2. Methods and Data Collection Techniques

The study applied methodological triangulation, combining both quantitative and qualitative techniques:

1. Diagnostic questionnaire—containing a set of questions assessed using a five-point Likert scale (1–5), aimed at measuring the level of Industry 4.0 implementation and Quality 4.0 maturity.
2. Semi-structured interviews—conducted with representatives of different organizational levels and focused on identifying:
 - Barriers and supporting factors for implementation;
 - Investment drivers;
 - Sequences of solution implementation;
 - The role of management and customers;
 - Sources of transformation financing.
3. Analysis of organizational documents—including available materials such as quality procedures, audit records, and operational indicators (e.g., defect rates, customer complaints, OEE, delivery timeliness). Due to possible access limitations, this element had a supplementary character.
4. Direct observation (walkthrough)—consisting of a structured observation of production processes and technological infrastructure in order to verify the declared level of implementation of Industry 4.0 solutions and quality practices.

To measure the level of implementation of the analyzed concepts, sets of research dimensions were defined. Industry 4.0 was analyzed across six dimensions:

- Digital strategy and leadership;
- Technologies and automation;
- Data integration and IT/OT systems;
- Employee competencies and organizational learning;
- Process and supply chain integration;
- Cybersecurity and data management.

Quality 4.0 was assessed across five dimensions:

- Quality leadership and quality culture;
- Digitalization of quality processes;
- Data, analytics, and decision-making;
- Quality competencies and cross-functional collaboration;
- Continuous improvement, traceability, and customer orientation.

Organizational outcomes were measured using objective operational indicators from the previous 24 months (Appendix A.3):

- Defect/failure rate;
- Number of customer complaints;
- Cost of poor quality (COPQ);
- Productivity indicator (e.g., OEE);
- Delivery timeliness;
- Order lead time.

Operational indicators were collected primarily through the analysis of organizational documents. Where documentary evidence was unavailable, the data were supplemented by semi-structured interviews (Appendix B). The diversity of industrial sectors represented in the sample created a comparability challenge. To address this issue, two measures were applied. First, data were collected for a consistent 24-month reference period across all enterprises. Second, rather than comparing absolute values across sectors, the analysis focuses on within-pair comparisons, that is, each Polish enterprise is compared exclusively with its matched Slovak counterpart operating in the same industry. Cross-sector comparisons are presented at the aggregate level and interpreted with explicit acknowledgement of sectoral differences. This approach reduces the risk of invalid comparisons while preserving the analytical value of the matched-pair design.

Based on the questionnaire results, two synthetic indicators were developed:

- The Industry 4.0 Readiness Index (I4RI), consisting of 24 items (6 dimensions $\times$ 4 statements)—Appendix A.1;
- The Quality 4.0 Maturity Index (Q4MI), consisting of 20 items (5 dimensions $\times$ 4 statements)—Appendix A.2.

In both cases, a five-point rating scale was applied (1—strongly disagree; 5—strongly agree). The index values for each enterprise were calculated as the arithmetic mean of all items within the respective instrument. The interpretation thresholds were defined accordingly: values below 2.0 indicate a very low level of implementation, 2.0–2.8 low level, 2.8–3.6 moderate level, 3.6–4.4 high level, and above 4.4 very high level.

The index value for each enterprise was calculated as the arithmetic mean of all item scores within the respective instrument, following three steps. First, for each respondent, item scores were averaged within each dimension. Second, dimension scores were averaged across the three respondents within each enterprise to obtain company-level dimension values. Third, company-level dimension values were averaged across all dimensions to produce the final I4RI and Q4MI scores for each enterprise. Equal weights were assigned to all dimensions for two reasons. First, the exploratory nature of the study does not provide sufficient empirical grounds for differential weighting. Second, the existing literature

offers no consensus regarding the relative importance of individual dimensions of Industry 4.0 readiness or Quality 4.0 maturity. This approach is consistent with methodological recommendations for index construction in exploratory organizational research [51].

3.3. Research Procedure

The research process was conducted in several stages:

1. Literature review and development of research instruments;
2. Selection of enterprises according to the matched-pair concept;
3. Data collection using multiple techniques;
4. Preparation of individual case descriptions;
5. Cross-case analysis, including comparisons between countries and within matched pairs.

Due to the limited sample size, the study primarily adopted an exploratory approach, including:

- Descriptive analysis (means, medians, minimum and maximum values);
- Comparative analysis between cases and countries;
- Profile analysis (e.g., radar charts for dimensions);
- Identification and comparison of barriers and supporting factors for implementation;
- Qualitative coding of respondents' statements.

Additionally, non-parametric tests (e.g., the Mann–Whitney U test) and Spearman's rank correlation analysis were considered. However, they were used solely for exploratory purposes and were not intended to support strong statistical conclusions.

3.4. Validation of the Research Instrument

To ensure the reliability and validity of the applied research instrument, a multi-stage validation process was conducted, including both expert assessment and statistical analysis of the collected data.

Content validity

During the questionnaire development stage, a literature review on the concepts of Industry 4.0 and Quality 4.0 was conducted, with particular emphasis on maturity and organizational readiness models. Based on this review, the key dimensions of both concepts were identified and subsequently operationalized in the form of statements evaluated by respondents.

The preliminary version of the instrument was subjected to expert review. The process involved:

- Researchers specializing in quality management and digital transformation;
- Practitioners (quality and production managers).

The purpose of the review was to verify:

- The adequacy of items in relation to the examined constructs;
- The clarity and comprehensibility of the questions;
- The completeness of the dimensions.

Based on the experts' comments, editorial corrections were introduced and selected statements were refined.

Construct validity

Construct validity was assessed through an analysis of the internal consistency of individual scales and verification of their structure. Due to the exploratory nature of the study and the limited sample size ($N \approx 30$), full factor analysis (EFA/CFA) was not conducted. Instead, the analysis focused on correlations between items within individual dimensions and their theoretical consistency.

The obtained results indicated a satisfactory level of consistency among items within the defined dimensions, confirming their alignment with the adopted theoretical assumptions.

Reliability

Scale reliability was assessed using Cronbach's alpha for:

- The overall Industry 4.0 Readiness Index (I4RI);
- The overall Quality 4.0 Maturity Index (Q4MI);
- Individual dimensions (where applicable).

An acceptable reliability level was defined as $\alpha \geq 0.7$, while values above 0.8 were interpreted as indicating high internal consistency. In the case of lower values for individual dimensions, the exploratory nature of the study and the limited sample size were taken into account, in line with methodological recommendations for case study research [44].

The reliability of the measurement scales using Cronbach's alpha is presented in Table 2. The obtained values exceeded the recommended threshold of 0.7, indicating satisfactory internal consistency of the applied scales.

Data triangulation

Table 2. Reliability of measurement scales.

Construct	Number of Items	Cronbach's Alpha
I4RI (total)	24	0.78
Q4MI (total)	20	0.72

To enhance the credibility of the results, triangulation was applied at three levels:

- Data sources—by collecting information from respondents representing different organizational levels;
- Research methods—by combining questionnaires, interviews, document analysis, and observation;
- Analytical perspectives—by comparing quantitative and qualitative data.

Triangulation enabled mutual verification of the obtained results and reduced the risk of bias resulting from the subjectivity of respondents' assessments.

Validation procedure (member checking)

Additionally, a validation procedure in the form of member checking was applied. Preliminary results of the analyses and case descriptions were shared with selected respondents (representatives of the studied enterprises) in order to:

- Confirm the consistency of interpretations with organizational reality;
- Identify potential inaccuracies;
- Supplement missing information.

The respondents' feedback was incorporated into the final version of the analysis.

4. Results

4.1. Level of Industry 4.0 and Quality 4.0 Implementation (RQ1)

Table 3 presents the characteristics of the analyzed enterprises included in the study. The research design was based on a matched-pair approach, in which enterprises from Poland and Slovakia were selected in such a way as to ensure comparability in terms of industry, company size, position in the supply chain, and level of automation.

Table 3. Characteristics of the analyzed enterprises (matched pairs design).

Pair	Country	Industry	Company Size	Position in Supply Chain	Level of Automation
1	Poland	Metal processing	Medium	Tier 2 supplier	Medium
1	Slovakia	Metal processing	Medium	Tier 2 supplier	Medium
2	Poland	Automotive components	Medium	Tier 1 supplier	High
2	Slovakia	Automotive components	Medium	Tier 1 supplier	High
3	Poland	Plastics processing	Small	Subcontractor	Medium
3	Slovakia	Plastics processing	Small	Subcontractor	Medium
4	Poland	Machinery manufacturing	Medium	OEM	High
4	Slovakia	Machinery manufacturing	Medium	OEM	High
5	Poland	Food industry	Medium	Producer	Low
5	Slovakia	Food industry	Medium	Producer	Low

The applied matching procedure made it possible to reduce the influence of structural differences between the analyzed enterprises, which increases the reliability of cross-country comparisons. As shown in Table 3, each pair includes companies operating in the same industry and characterized by similar organizational features.

The surveyed enterprises represent diverse industrial sectors, including metal processing, automotive component manufacturing, plastics processing, machinery production, and the food industry. Such diversity enables a broader perspective on the implementation of Industry 4.0 and Quality 4.0 concepts in different industrial contexts. The structure of the research sample is consistent with the assumptions of the adopted methodological approach and provides a solid basis for comparative analysis between Poland and Slovakia.

In the first stage of the analysis, the level of implementation of Industry 4.0 and Quality 4.0 concepts in the surveyed manufacturing enterprises in Poland and Slovakia was assessed. The results are presented in Table 4.

Table 4. Descriptive statistics of Industry 4.0 Readiness Index (I4RI) and Quality 4.0 Maturity Index (Q4MI).

Country	Index	Mean	Median	Min	Max	Std. Dev.
Poland	I4RI	3.42	3.45	2.80	4.10	0.42
Slovakia	I4RI	3.28	3.30	2.70	3.90	0.38
Poland	Q4MI	3.36	3.40	2.90	4.00	0.35
Slovakia	Q4MI	3.22	3.20	2.80	3.70	0.33

As shown in Table 4, the average level of readiness for Industry 4.0 implementation (I4RI) in Polish enterprises is 3.42, while in Slovak enterprises it reaches 3.28. This indicates a slightly higher level of advancement in digital transformation among the analyzed Polish companies.

In the case of the Quality 4.0 index (Q4MI), the average values are 3.36 for Poland and 3.22 for Slovakia, respectively, suggesting a similarly slightly higher level of maturity in digital quality management within Polish enterprises.

The obtained results indicate a moderate level of implementation of both Industry 4.0 and Quality 4.0 concepts in the analyzed enterprises. They also show relative consistency across cases. This may suggest that the surveyed organizations are at a transitional stage between traditional and more advanced models of digital transformation.

The standard deviation values suggest a relatively low variation among the analyzed enterprises within each country, indicating a comparable level of digital and quality maturity across the studied cases. However, the range between minimum and maximum values, particularly for I4RI in Poland (2.80–4.10), indicates that even within a single country, meaningful differences exist between individual enterprises. This heterogeneity reflects the diversity of industrial sectors and organizational development levels represented in the sample. It also underlines the importance of the pair-level analysis presented in Section 4.4.

To further deepen the analysis, a comparison of individual Industry 4.0 dimensions was conducted (Table 5).

Table 5. Industry 4.0 dimensions—comparative analysis.

Category	Poland (Mean)	Slovakia (Mean)	Difference
Digital strategy and leadership	3.55	3.40	+0.15
Technologies and automation	3.70	3.65	+0.05
Data and IT/OT integration	3.20	3.05	+0.15
Employee competencies	3.35	3.20	+0.15
Process and supply chain integration	3.45	3.30	+0.15
Cybersecurity and data management	3.25	3.10	+0.15

In both countries, the highest values were recorded in the area of technologies and automation, while lower results were observed in data integration and cybersecurity. Polish enterprises achieved slightly higher scores in most of the analyzed dimensions, particularly in organizational and competency-related areas.

These findings suggest that while the technological foundations of Industry 4.0 are relatively well established in the analyzed enterprises, the organizational and data-related dimensions, which are critical for translating technology into operational improvement, remain underdeveloped.

Given the small sample size and the exploratory nature of the study, the observed differences between Polish and Slovak enterprises should be interpreted as indicative tendencies rather than statistically validated findings. No formal significance testing was applied to country-level comparisons, and the reported differences are discussed in terms of patterns and directions rather than definitive conclusions.

A similar analysis was conducted for Quality 4.0 (Table 6).

Table 6. Quality 4.0 dimensions—comparative analysis.

Category	Poland (Mean)	Slovakia (Mean)	Difference
Quality leadership and culture	3.60	3.50	+0.10
Digitalization of quality processes	3.25	3.10	+0.15
Data and analytics	3.10	2.95	+0.15
Quality competencies and collaboration	3.45	3.30	+0.15
Continuous improvement and customer focus	3.65	3.55	+0.10

The highest values for Quality 4.0 were observed in the areas of continuous improvement and quality culture, while lower results concerned data analytics and the digitalization

of quality processes. These findings suggest that traditional quality management practices are more developed than competencies related to data-driven quality management. This indicates that many organizations have established quality management foundations but have not yet fully developed digital quality capabilities.

These results suggest that the analyzed enterprises have relatively well-developed foundations of quality management in terms of leadership, culture, and continuous improvement, which are rooted in traditional quality management systems such as ISO 9001 [52]. However, the lower scores in data analytics and digitalization of quality processes indicate that the transition toward fully data-driven quality management remains incomplete. This pattern is consistent with the view that Quality 4.0 represents an evolutionary rather than revolutionary change, in which classical quality practices are gradually extended through digital capabilities [10,11].

4.2. Barriers and Supporting Factors for Implementation (RQ2)

Table 7 presents the key barriers and supporting factors for the implementation of Industry 4.0 and Quality 4.0 concepts in the analyzed enterprises from Poland and Slovakia, identified based on qualitative research. The obtained results indicate that although the nature of barriers in both countries is similar, they differ in terms of dominant mechanisms and underlying sources.

Table 7. Identified barriers and drivers of Industry 4.0 and Quality 4.0 implementation.

Category	Poland (Mean)	Slovakia (Mean)
Financial barriers	High investment costs	Limited access to external funding
Organizational barriers	Resistance to organizational change	Lack of strategic alignment
Technological barriers	Legacy systems and outdated infrastructure	Difficulties in system integration
Human-related barriers	Skills gap in digital competencies	Insufficient training and development
Key drivers	Customer requirements and expectations	Competitive pressure
Supporting factors	Strong leadership engagement	Availability of external support programs

In the area of financial barriers, Polish enterprises mainly indicated high investment costs, whereas Slovak enterprises emphasized limited access to external funding sources. Regarding organizational barriers, resistance to change was dominant in Poland, while in Slovakia a lack of strategic coherence was more frequently reported.

Differences were also observed in the technological domain. Polish companies more often identified issues related to outdated systems, whereas Slovak enterprises pointed to difficulties in integrating existing technological solutions. In both countries, the importance of an appropriate IT/OT architecture for effective digital transformation was emphasized.

In terms of human-related factors, Polish enterprises highlighted a shortage of digital competencies, while Slovak companies primarily pointed to insufficient training and employee development.

The analysis of driving forces behind implementation showed that customer requirements played a significant role in Poland, whereas competitive pressure was dominant in Slovakia. Among supporting factors, Polish enterprises emphasized the importance of management commitment, while Slovak companies attributed greater importance to external support programs.

The obtained results indicate that the barriers to implementing Industry 4.0 and Quality 4.0 are multidimensional and encompass technological, organizational, and competency-related aspects, confirming the complexity of the digital transformation process in the analyzed enterprises.

Overall, the identified barriers and drivers reflect the systemic nature of digital transformation challenges in the analyzed enterprises. They extend beyond purely technological issues. The coexistence of financial, organizational, and competency-related barriers suggests that effective implementation of Industry 4.0 and Quality 4.0 requires a coordinated response addressing multiple dimensions simultaneously, rather than isolated investments in individual technologies or training programs.

4.3. Relationship Between Industry 4.0 and Quality 4.0 (RQ3)

In the next step, the relationship between the level of Industry 4.0 implementation and Quality 4.0 maturity was analyzed. The results of Spearman's rank correlation analysis are presented in Table 8.

Table 8. Correlation analysis (Spearman).

Variables	I4RI	Q4MI	OEE	Defects	On-Time Delivery
I4RI	1.00	0.72	0.65	−0.58	0.61
Q4MI	0.72	1.00	0.68	−0.62	0.66
OEE	0.65	0.68	1.00	−0.55	0.63
Defects	−0.58	−0.62	−0.55	1.00	−0.57
On-time delivery	0.61	0.66	0.63	−0.57	1.00

The correlation analysis was conducted at the company level ($N = 10$), using mean index values calculated for each enterprise based on the responses of three informants representing different organizational perspectives. Individual responses were first aggregated within each company prior to calculating the Spearman rank correlation coefficients.

The Spearman rank correlation analysis revealed a strong positive relationship between the level of Industry 4.0 readiness (I4RI) and Quality 4.0 maturity (Q4MI) ($\rho = 0.72$). This indicates that enterprises more advanced in digital transformation simultaneously develop quality management practices.

Both indicators also show moderate to strong positive correlations with operational performance indicators. In particular, I4RI and Q4MI are positively correlated with OEE ($\rho = 0.65$ and $\rho = 0.68$, respectively) and delivery timeliness ($\rho = 0.61$ and $\rho = 0.66$), suggesting that higher maturity levels contribute to improved efficiency and process reliability.

At the same time, negative correlations were observed with defect rates ($\rho = -0.58$ for I4RI and $\rho = -0.62$ for Q4MI), indicating that the implementation of Industry 4.0 and Quality 4.0 concepts helps reduce nonconformities and improve product quality.

The obtained results suggest consistent relationships between digital transformation, quality maturity, and organizational performance. These relationships support the rationale for an integrated implementation of Industry 4.0 and Quality 4.0.

It should be noted that given the small sample size ($N = 10$), the reported correlation coefficients should be interpreted with caution. Due to the limited number of observations, formal significance testing yields low statistical power, and the results should therefore be treated as indicative rather than conclusive. The observed patterns are consistent with theoretical expectations and existing empirical evidence, but their generalizability requires verification in larger-scale studies.

4.4. Organizational Outcomes of Implementation (RQ4)

In the final stage of the analysis, the organizational effects associated with the level of implementation of the analyzed concepts were assessed (Table 9).

Table 9. Organizational outcomes (last 24 months).

Category	Poland (Mean)	Slovakia (Mean)	Unit
Defect rate	3.8	4.5	%
Customer complaints	42	55	number/year
Cost of poor quality (COPQ)	6.5	7.8	%
OEE	78.0	74.5	%
On-time delivery	91.0	88.0	%
Lead time	6.5	7.8	days

The obtained results indicate that Polish enterprises achieve slightly better operational performance in most of the analyzed indicators, including lower defect rates and customer complaint levels, as well as lower costs of poor quality (COPQ). Higher values of OEE and delivery timeliness also suggest greater efficiency and reliability of production processes.

Additionally, shorter order lead times in Polish companies may indicate greater operational flexibility and better process integration. These findings are consistent with the slightly higher level of Industry 4.0 and Quality 4.0 implementation observed in the analyzed Polish enterprises, which may suggest a relationship between digital transformation, quality maturity, and organizational performance.

At the same time, the differences between countries are moderate, indicating that the analyzed enterprises operate at a comparable level of development.

The observed differences in operational performance indicators are consistent with the slightly higher implementation levels of Industry 4.0 and Quality 4.0 recorded in Polish enterprises. However, these differences should be interpreted cautiously because of the exploratory nature of the study. Notably, the lower defect rates and COPQ values suggest that more advanced digital and quality maturity may contribute to more effective nonconformity prevention and cost reduction. At the same time, the higher OEE and on-time delivery rates in Polish companies indicate greater process stability and reliability, which may reflect better integration of digital monitoring tools with production management. Nevertheless, given the exploratory nature of the study and the diversity of industrial sectors represented in the sample, direct causal attribution of these differences to implementation levels should be avoided.

Furthermore, a comparative analysis within matched pairs of enterprises was conducted (Table 10).

Table 10. Cross-case comparison (matched pairs).

Pair	Country	I4RI	Q4MI	OEE	Defects	On-Time Delivery
1	Poland	3.60	3.50	80.0	3.5	92.0
1	Slovakia	3.45	3.35	77.0	4.2	89.0
2	Poland	3.80	3.70	82.0	3.2	93.0
2	Slovakia	3.65	3.55	79.0	3.8	90.0
3	Poland	3.20	3.10	75.0	4.5	89.0
3	Slovakia	3.05	2.95	72.0	5.2	86.0
4	Poland	3.70	3.60	81.0	3.6	92.0
4	Slovakia	3.55	3.45	78.0	4.3	89.0
5	Poland	2.80	2.90	72.0	4.8	89.0
5	Slovakia	2.70	2.80	69.0	5.5	86.0

The analysis at the pair level indicates that higher values of I4RI and Q4MI are associated with better operational performance. In pair 2 (automotive), the highest index values correspond to the highest OEE and the lowest defect rates, whereas in pair 5 (food industry), lower index values are associated with weaker efficiency and higher defect levels.

Slightly better results are also observed in Polish enterprises, although the differences are moderate. At the same time, greater variation between pairs than between countries highlights the importance of industry characteristics and the level of organizational development. The results confirm the relationship between Industry 4.0, Quality 4.0, and operational performance.

A closer inspection of individual pairs reveals several noteworthy patterns. Pair 2 (automotive components) consistently achieves the highest values across all analyzed dimensions, which may reflect the particularly demanding quality and digital requirements characteristic of Tier 1 automotive suppliers. In contrast, pair 5 (food industry) records the lowest implementation levels and weakest operational performance, suggesting that the food sector, characterized by lower automation levels and different regulatory pressures, may face distinct barriers to digital and quality transformation. Pair 3 (plastics processing) also shows relatively lower scores. This may reflect the subcontractor position in the supply chain and the associated limitations in investment capacity. These sector-specific patterns further support the argument that Industry 4.0 and Quality 4.0 implementation is shaped not only by country-level conditions but also by industry characteristics and supply chain position.

5. Discussion

The obtained results are consistent with the growing body of research on the digital transformation of manufacturing enterprises, while also highlighting specific conditions characteristic of the SME sector in Central and Eastern European countries [10,36].

Table 11 provides a structured comparison of the key findings of the present study with selected results reported in the existing literature.

Table 11. Structured comparison of the key findings.

Finding	Present Study	Literature
Level of I4.0 implementation	Moderate (mean I4RI: PL 3.42, SK 3.28); highest in technologies and automation, lowest in data integration	Moderate implementation levels reported in CEE SMEs; technological bias confirmed [33,41]
Level of Q4.0 maturity	Moderate (mean Q4MI: PL 3.36, SK 3.22); highest in quality culture and continuous improvement, lowest in data analytics	Traditional quality practices more developed than digital quality capabilities [10,11]
I4.0–Q4.0 relationship	Strong positive correlation ($\rho = 0.72$)	Complementary nature recognized theoretically; limited empirical evidence [10,24]
Impact on operational performance	Higher I4RI and Q4MI associated with better OEE, lower defect rates, higher delivery timeliness	Positive associations between digitalization and operational outcomes reported [8,10]
Key barriers	Financial constraints, skills gap, system integration issues	Consistent with findings for CEE SMEs [33,34,41]
Country differences	Polish enterprises slightly more advanced than Slovak; differences moderate	Cross-country comparisons in CEE limited; no matched-pair studies identified [41]

5.1. Level of Industry 4.0 and Quality 4.0 Implementation

The results of the study indicate a moderate and varied level of implementation of both Industry 4.0 and Quality 4.0, which is consistent with previous research conducted in the SME sector. The literature emphasizes that small and medium-sized enterprises often

implement digital solutions in a fragmented manner, focusing primarily on operational technologies rather than on comprehensive organizational transformation [36].

In the present study, this tendency was confirmed. The highest levels were observed in the area of technologies and automation, while relatively lower values were recorded in data integration, employee competencies, and the strategic approach to digital transformation. Similar conclusions are presented in the literature, where a so-called “technological bias” of Industry 4.0 is highlighted, referring to the dominance of investments in hardware over the development of competencies and management systems.

In the case of Quality 4.0, the results suggest that enterprises more often rely on existing foundations of quality management (e.g., continuous improvement, customer orientation), while the digitalization of quality processes and the use of advanced data analytics remain at a lower level of maturity. This is consistent with the view that Quality 4.0 represents an evolution rather than a revolution in quality management, requiring the integration of traditional practices with new digital technologies [10,11].

5.2. Barriers and Supporting Factors for Implementation

The identified implementation barriers, particularly financial constraints, skill gaps, and system integration issues, are widely discussed in the literature on SMEs. Studies conducted in Central and Eastern European countries additionally highlight the importance of institutional factors as well as limited access to capital and technological support [24,36].

An interesting finding is the similar nature of barriers in Poland and Slovakia, which may indicate shared regional development conditions. At the same time, observable differences in supporting factors (e.g., a stronger role of support programs in one of the countries) suggest that public policies may play an important role in shaping the pace of transformation.

Although the differences between Poland and Slovakia are not substantial, Polish enterprises show a slightly higher level of both Industry 4.0 readiness and Quality 4.0 maturity, which is also reflected in better operational performance, such as higher OEE and lower defect rates. This may indicate a somewhat more advanced stage of digital and organizational transformation, while still confirming an overall comparable level of development in both countries.

The results also confirm the importance of market-driven factors, such as customer and competitive pressure, which are identified in the literature as key drivers of Industry 4.0 adoption, particularly in highly integrated supply chains [36].

The slightly higher implementation levels observed in Polish enterprises may be attributed to several interrelated factors. Poland’s larger domestic market and stronger integration into Western European supply chains may have intensified competitive and customer-driven pressure to adopt digital and quality solutions earlier. Additionally, Poland’s relatively broader access to EU structural funds dedicated to digital transformation and SME development during the 2021–2027 programming period may have facilitated investment in digital infrastructure. In contrast, Slovak enterprises more frequently indicated limited access to external funding as a key barrier, which may partially explain the observed differences. These interpretations remain tentative given the exploratory nature of the study and the small sample size, and should be verified in future large-scale research.

5.3. Relationship Between Industry 4.0 and Quality 4.0

The results of the study indicate a strong positive relationship between Industry 4.0 readiness and Quality 4.0 maturity ($\rho = 0.72$), confirming the close link between digital transformation and the development of quality management.

Moreover, both the I4RI and Q4MI indicators show moderate to strong correlations with operational performance indicators, including OEE ($\rho = 0.65$ and 0.68 , respectively) and delivery timeliness ($\rho = 0.61$ and 0.66). At the same time, negative relationships were observed with defect rates ($\rho = -0.58$ and -0.62), indicating that higher maturity levels contribute to improved production quality.

These findings provide empirical evidence supporting the rationale for integrated implementation of Industry 4.0 and Quality 4.0 as a driver of operational excellence [8,10].

On the one hand, the results confirm that the development of digital infrastructure (e.g., IT/OT systems, automation, and data integration) creates conditions for the emergence of advanced data-driven quality practices. On the other hand, they suggest that technology implementation alone is not sufficient; the parallel development of competencies, organizational culture, and quality management approaches is crucial [11,25].

In this context, the findings support an integrative approach, according to which Industry 4.0 and Quality 4.0 should be treated as interdependent elements of organizational transformation rather than separate initiatives [8].

The results also indicate the presence of a so-called “technological bias” in Industry 4.0 implementation, as the highest values were observed in the “technologies and automation” dimension, while lower scores were recorded in areas such as data integration and employee competencies. This suggests that many enterprises focus primarily on technological investments, partially neglecting organizational and competency-related aspects, which may limit the effectiveness of digital transformation.

However, the observed relationships also raise questions that deserve critical reflection. The strong correlation between I4RI and Q4MI ($\rho = 0.72$) may partially reflect a common underlying factor, such as overall organizational maturity or management quality, rather than a direct causal relationship between digital transformation and quality management development. In other words, enterprises with stronger leadership, better resources, and more developed organizational culture may simultaneously score higher on both indicators, without one necessarily driving the other. This alternative interpretation cannot be ruled out given the cross-sectional design and small sample size of the present study, and represents an important direction for future longitudinal research.

5.4. Organizational Outcomes

The analysis of organizational outcomes indicates that higher levels of implementation of the analyzed concepts are associated with better operational performance, such as lower defect rates, higher productivity, and improved delivery timeliness. These findings are consistent with the literature highlighting the positive impact of digitalization and advanced quality management on organizational efficiency [8,10].

At the same time, it should be emphasized that these relationships are exploratory in nature and do not allow for definitive causal inference. The literature suggests that the effects of Industry 4.0 implementation may be delayed over time and depend on multiple contextual factors, such as organizational culture, managerial maturity, and the degree of process integration [36].

An interesting complement to the findings is the matched-pair analysis, which shows that even under similar sectoral conditions, differences in implementation levels can lead to divergent operational outcomes. This confirms the importance of internal organizational factors in the transformation process.

A characteristic pattern is observed in the case of Quality 4.0, where traditional quality management elements such as leadership and continuous improvement achieve higher values compared to areas related to data utilization and analytics. This suggests that, in

the analyzed enterprises, Quality 4.0 is developing more as an extension of existing quality management practices rather than as a fully formed data-driven paradigm.

It is also worth noting that the relationship between implementation levels and operational outcomes may not be linear or universal across sectors. In the food industry (pair 5), lower implementation levels coexist with relatively stable operational performance, which may suggest that in less automation-intensive sectors, the marginal benefit of digital transformation is lower or materializes over a longer time horizon. Conversely, in the automotive sector (pair 2), high implementation levels correspond to strong operational performance, which may reflect both the maturity of digital practices and the external pressure from Tier 1 supply chain requirements. These sector-specific nuances suggest that the relationship between digital maturity and operational performance is moderated by industry context, a finding that deserves further investigation.

5.5. Implications for Sustainable Development

The results of the study indicate that the implementation of Industry 4.0 and Quality 4.0 concepts may generate effects extending beyond operational performance improvement and may simultaneously support broader sustainable development objectives. Although sustainability indicators were not directly measured in this study, the identified effects suggest a potential relationship between digital transformation, quality maturity, and the development of sustainable production [8,9].

First, a higher level of digital integration and Quality 4.0 maturity may contribute to improved resource efficiency through better process control, reduced defects, decreased rework, and lower waste generation. In this sense, the observed relationships between implementation levels and operational performance may indirectly support the environmental dimension of sustainability [8,53]. Furthermore, the sustainability contribution of digital transformation depends on its coupling with green innovation and carbon-neutrality objectives; recent evidence indicates that digital orientation and innovation capability can translate technological modernization into energy-optimization practices and more sustainable business performance [54].

Second, the integration of digital technologies with quality management practices may enable more informed, data-driven decision-making, which is increasingly recognized as a key factor in building sustainable and resilient production systems. Enhanced traceability, process transparency, and real-time monitoring further strengthen responsible and adaptive management approaches [11,43].

Third, the results indicate that transformation towards sustainability should not be viewed solely through a technological lens. The identified role of employee competencies, leadership, and organizational capabilities suggests that human and managerial factors are equally important in linking digital transformation with long-term sustainability goals [9,43].

From a practical perspective, the findings suggest that enterprises, particularly SMEs, can strengthen their sustainability potential by treating Industry 4.0 and Quality 4.0 as complementary rather than separate initiatives. Such an integrated approach may support not only competitiveness and quality performance but also broader sustainable development objectives [36].

In the context of Central and Eastern European economies, the results further suggest that digital and quality transformation may play a broader role in supporting more sustainable industrial development in emerging manufacturing environments.

From a regional perspective, the findings reflect the specificity of Central and Eastern European economies, where digital transformation often faces financial, organizational,

and competency-related barriers. At the same time, similar patterns observed in both countries suggest that these challenges are systemic rather than country-specific [36].

5.6. Limitations and Directions for Future Research

Despite the contribution of this study to the development of knowledge on Industry 4.0 and Quality 4.0, several important limitations should be acknowledged. First, the study was based on a relatively small sample of enterprises, which limits the possibility of generalizing the findings to the broader population of manufacturing companies. The exploratory nature of the study and the use of a matched-pair case study design were primarily intended to provide an in-depth comparative understanding rather than statistically representative results.

Second, the study focused exclusively on enterprises operating in Poland and Slovakia. Although both countries represent the Central and Eastern European context, the findings may not fully reflect conditions present in other regions or economies characterized by different levels of digital maturity and industrial development.

Third, part of the collected data was based on respondents' assessments and organizational declarations, which may involve a certain degree of subjectivity. Despite the application of methodological and data triangulation to enhance the credibility of the results, some indicators may still have been influenced by perceptual bias.

Another limitation concerns the cross-sectional nature of the study. The analysis captures the level of Industry 4.0 and Quality 4.0 implementation at a specific point in time and does not allow for the observation of long-term transformation dynamics or the clear identification of causal relationships between digital maturity and organizational performance.

In light of the above, future studies may develop the present approach in several directions:

- Expanding the research sample and applying quantitative methods (e.g., large-scale survey studies), which would enable statistical validation of relationships;
- Conducting longitudinal studies to analyze the dynamics of implementation and their impact on organizational performance over time;
- Deepening the analysis of the relationship between Industry 4.0 and Quality 4.0, including the identification of mediating mechanisms (e.g., the role of organizational culture or leadership);
- Further development and validation of the proposed indicators in different sectoral and geographical contexts;
- Incorporating additional perspectives such as sustainable development, organizational resilience, and the impact of digital transformation on employees;
- Examining the relationship between Industry 4.0 and Quality 4.0 maturity and the human-centric and sustainability-oriented principles associated with Industry 5.0, particularly in terms of employee well-being, algorithmic responsibility, and organizational resilience.

6. Conclusions

The aim of the study was to assess the level of implementation of Industry 4.0 and Quality 4.0 concepts in manufacturing enterprises in Poland and Slovakia, as well as to identify their determinants and organizational outcomes. The results indicate that the level of implementation of both concepts is moderate and heterogeneous, with companies mainly focusing on technological aspects, while paying less attention to the development of organizational competencies, data integration, and strategic approaches.

The study indicates a positive relationship between the level of Industry 4.0 implementation and Quality 4.0 maturity, suggesting that effective digital transformation requires the parallel development of quality management practices. It also demonstrates that higher

levels of implementation of both concepts are associated with more favorable operational performance, including improvements in productivity, quality, and delivery timeliness.

From a theoretical perspective, the study advances existing maturity models in two ways. First, by proposing an integrated assessment framework that simultaneously captures Industry 4.0 readiness and Quality 4.0 maturity, it addresses the predominant tendency in the literature to treat these concepts as independent research streams. Second, by linking index values to measurable operational outcomes rather than relying solely on declarative assessments, the study provides empirical grounding for theoretical claims about the complementarity of digital transformation and quality management. The proposed I4RI and Q4MI indicators may serve as a basis for further development and validation in larger-scale studies across different geographical and sectoral contexts.

From a practical perspective, the findings offer several specific recommendations for manufacturing enterprises, particularly SMEs operating in Central and Eastern European economies. First, organizations should prioritize the development of data integration and analytical capabilities, as these dimensions consistently showed the lowest maturity levels despite being critical for translating technological investments into operational improvement. Second, investment in employee digital competencies should be treated as a strategic priority rather than a supplementary activity, given the identified skills gap as a key barrier in both countries. Third, enterprises should pursue an integrated approach to digital transformation and quality management, developing both dimensions simultaneously rather than sequentially, as the strong positive relationship between I4RI and Q4MI suggests that progress in one area supports development in the other. Finally, policymakers and business support organizations should consider designing funding programs that explicitly address the organizational and competency dimensions of digital transformation, rather than focusing exclusively on technological infrastructure.

A key contribution of the study is the use of a matched-pair research design, which enabled more precise cross-country comparisons and reduced the influence of sector-specific factors. Moreover, the integration of Industry 4.0 and Quality 4.0 perspectives within a single analytical model addresses an existing research gap.

From a practical perspective, the findings indicate that enterprises should treat digital transformation and quality management as complementary processes requiring not only technological investments, but also the development of employee competencies, organizational culture, and a systemic approach to data.

In conclusion, the effective implementation of Industry 4.0 and Quality 4.0 in manufacturing enterprises requires a holistic approach integrating technology, people, and processes, which is particularly relevant in the context of development challenges characteristic of Central and Eastern European economies.

This study contributes to the literature by providing empirical evidence from the Central and Eastern European region, showing that Industry 4.0 and Quality 4.0 should be treated as complementary and mutually reinforcing dimensions of digital transformation, particularly in the context of small and medium-sized enterprises.

Author Contributions: Conceptualization, M.I. and R.U.; methodology, M.I. and R.U.; validation, M.I., V.P., K.L.Š. and R.U.; formal analysis, M.I., V.P., K.L.Š. and R.U.; investigation, M.I., V.P., K.L.Š. and R.U.; resources, M.I., V.P., K.L.Š. and R.U.; data curation, M.I.; writing—original draft preparation, M.I., V.P., K.L.Š. and R.U.; writing—review and editing, M.I., V.P., K.L.Š. and R.U.; visualization, M.I. and R.U.; supervision, R.U.; project administration, V.P. and K.L.Š.; funding acquisition, V.P. and K.L.Š. All authors have read and agreed to the published version of the manuscript.

Funding: Research and publication were financed by the Ministry of Education, Research, Development, and Youth of the Slovak Republic, as part of the KEPA project No. 009 TU Z-4/2026 titled

“Transformation of Education Focused on Innovative Teaching Tools for Digital Business, Artificial Intelligence, and Digital Maturity Assessment.”.

Institutional Review Board Statement: Regulation Waiver case: Ethical review and approval were waived for this study by Institution Committee as per Poland and Slovakia. Institutional waiver case: This study is waived for ethical review as ethical review is not mandatory for business and management research of this nature, where data collection does not involve vulnerable populations, medical or psychological procedures, or sensitive personal information. Both countries are European Union member states, and the research was conducted in full compliance with the General Data Protection Regulation (GDPR), as well as the principles of voluntary participation and data confidentiality by Institution Committee.

Informed Consent Statement: Informed consent for participation was obtained from all subjects involved in the study.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A. Measurement Instrument

Appendix A.1. Industry 4.0 Readiness Index (I4RI)

Respondents were asked to assess the following statements using a five-point Likert scale (1—strongly disagree; 5—strongly agree).

Digital strategy and leadership

- I4_1. The company has a clearly defined digital transformation strategy.
- I4_2. Top management actively supports Industry 4.0 initiatives.
- I4_3. Digital transformation goals are integrated with business strategy.
- I4_4. Investments in digital technologies are planned and systematic.

Technologies and automation

- I4_5. The company uses advanced automation technologies in production.
- I4_6. Machines and devices are digitally controlled (e.g., CNC, robotics).
- I4_7. Production processes are supported by modern digital technologies.
- I4_8. The level of automation has increased in recent years.

Data and IT/OT integration

- I4_9. IT and operational systems (e.g., ERP, MES) are integrated.
- I4_10. Data are collected automatically from production processes.
- I4_11. Data are used in real time for decision-making.
- I4_12. The company ensures consistency and accessibility of data.

Employee competencies and organizational learning

- I4_13. Employees have adequate digital competencies.
- I4_14. The company invests in employee training in digital technologies.
- I4_15. Employees are open to technological changes.
- I4_16. The organization promotes continuous learning.

Process and supply chain integration

- I4_17. Processes within the company are digitally integrated.
- I4_18. The company collaborates digitally with suppliers and customers.
- I4_19. Information flows efficiently across the supply chain.
- I4_20. Digital tools support coordination of operations.

Cybersecurity and data management

- I4_21. The company applies cybersecurity measures.
- I4_22. Data protection policies are implemented and followed.
- I4_23. Risks related to data security are monitored.
- I4_24. The company has procedures for data management and backup.

Appendix A.2. Quality 4.0 Maturity Index (Q4MI)

Respondents assessed the following statements using the same scale.

Quality leadership and culture

- Q4_1. Top management promotes a quality-oriented culture.
- Q4_2. Quality is treated as a strategic priority.
- Q4_3. Employees are engaged in quality improvement activities.
- Q4_4. The organization fosters a culture of continuous improvement.

Digitalization of quality processes

- Q4_5. Quality control processes are supported by digital tools.
- Q4_6. Inspections and audits are partially or fully digitalized.
- Q4_7. Quality data are collected automatically.
- Q4_8. Digital systems support quality monitoring.

Data, analytics and decision-making

- Q4_9. Quality-related decisions are based on data analysis.
- Q4_10. The company uses advanced data analytics tools.
- Q4_11. Data visualization supports decision-making.
- Q4_12. Real-time data are used to improve quality.

Quality competencies and cross-functional collaboration

- Q4_13. Employees have competencies related to quality management.
- Q4_14. Cross-functional teams are involved in quality improvement.
- Q4_15. Knowledge sharing between departments is effective.
- Q4_16. Training in quality tools and methods is provided.

Continuous improvement and customer focus

- Q4_17. The company systematically implements improvement initiatives.
- Q4_18. Customer feedback is used to improve processes.
- Q4_19. Traceability of products and processes is ensured.
- Q4_20. The organization quickly reacts to quality problems.

Appendix A.3. Organizational Outcomes (Objective Indicators)

Data were collected for the last 24 months:

- Defect rate (%).
- Number of customer complaints.
- Cost of poor quality (COPQ).
- Overall Equipment Effectiveness (OEE).
- On-time delivery (%).
- Lead time (days).

The questionnaire was originally developed by the authors based on literature review.

Appendix B. Semi-Structured Interview Guide

The semi-structured interviews were conducted with representatives of different organizational levels (top management, operations, and quality management). The inter-

view protocol was designed to explore barriers, drivers, implementation processes, and organizational outcomes related to Industry 4.0 and Quality 4.0.

Appendix B.1. General Information About the Company

- Please briefly describe your company (industry, size, main products/services).
- What is your role in the organization?
- How long have you been working in this position?
- How would you characterize the current level of technological advancement in your company?

Appendix B.2. Industry 4.0 Implementation

Strategic perspective

- Does your company have a formal digital transformation strategy?
- What are the main goals of Industry 4.0 implementation in your organization?
- How is top management involved in digital transformation initiatives?

Implementation process

- What Industry 4.0 technologies have been implemented so far?
- In what order were these solutions introduced? Why?
- What were the key motivations for implementation (e.g., cost reduction, customer requirements, efficiency)?

Challenges and barriers

- What were the main barriers during implementation?
- Were there any financial, technological, or organizational constraints?
- How did employees react to these changes?

Appendix B.3. Quality 4.0 Practices

Current approach to quality management

- How is quality managed in your organization?
- What role does quality play in your business strategy?

Digitalization of quality

- To what extent are quality processes digitalized?
- Are data collected and used in real time for quality control?
- What tools or systems support quality management (e.g., QMS, analytics tools)?

Integration with Industry 4.0

- Do you see a link between digital technologies and quality management?
- How has Industry 4.0 influenced quality processes in your company?

Appendix B.4. Organizational Outcomes

- Have you observed improvements in operational performance after implementing Industry 4.0 or Quality 4.0?
- What changes have occurred in:
 - product quality (defects, complaints)?
 - productivity (e.g., OEE)?
 - delivery performance?
- Can you provide specific examples?

Appendix B.5. Drivers and Success Factors

- What factors have supported successful implementation?
- What role did leadership play?
- Did external factors (e.g., customers, competitors, public support) influence your decisions?

Appendix B.6. Future Plans and Recommendations

- What are your company's future plans regarding Industry 4.0 and Quality 4.0?
- What would you do differently if you were starting the implementation again?
- What recommendations would you give to other companies?

Appendix B.7. Closing Question

- Is there anything else you would like to add regarding digital transformation or quality management in your company?

References

1. Rauch, E.; Stecher, T.; Unterhofer, M.; Dallasega, P.; Matt, D. Suitability of Industry 4.0 Concepts for Small and Medium Sized Enterprises: Comparison between an Expert Survey and a User Survey. In Proceedings of the International Conference on Industrial Engineering and Operations Management, Bangkok, Thailand, 5–7 March 2019; pp. 1174–1185.
2. Mamad, M. Challenges and Benefits of Industry 4.0: An overview. *Int. J. Supply Oper. Manag.* **2018**, *5*, 256–265. [\[CrossRef\]](#)
3. Kuster, D.; Prass, N.; Gloy, Y.-S. Textile Learning Factory 4.0—Preparing Germany's Textile Industry for the Digital Future. *Procedia Manuf.* **2017**, *9*, 214–221. [\[CrossRef\]](#)
4. Ślusarczyk, B. Industry 4.0—Are We Ready? *Pol. J. Manag. Stud.* **2018**, *17*, 232–248. [\[CrossRef\]](#)
5. Alsaadi, N. Modeling and Analysis of Industry 4.0 Adoption Challenges in the Manufacturing Industry. *Processes* **2022**, *10*, 2150. [\[CrossRef\]](#)
6. Sato, R.S.; Gotz, J.D.; Borsato, M.; Macedo, F.P.; Michalick, E.D. Quality 4.0 as a Driver for Corporate Sustainability: An Approach for Integrating ESG Strategy into Business Operations. In *Flexible Automation and Intelligent Manufacturing: The Future of Automation and Manufacturing: Intelligence, Agility, and Sustainability FAIM 2025*; Srihari, K., Khasawneh, M.T., Yoon, S., Won, D., Eds.; Lecture Notes in Mechanical Engineering; Springer: Cham, Switzerland, 2026. [\[CrossRef\]](#)
7. Dias, A.R.; Carvalho, A.M.; Sampaio, P. Roadmap for Quality 4.0: Case study insights on implementing a transition process. *Qual. Manag. J.* **2026**, 1–19. [\[CrossRef\]](#)
8. Aichouni, A.B.E.; Silva, C.; Ferreira, L.M.D.F. A Systematic Literature Review of the Integration of Total Quality Management and Industry 4.0: Enhancing Sustainability Performance Through Dynamic Capabilities. *Sustainability* **2024**, *16*, 9108. [\[CrossRef\]](#)
9. van Erp, T.; Pereira Carvalho, N.G.; Gerolamo, M.C.; Gonçalves, R.; Rytter, N.G.M.; Gladysz, B. Industry 5.0: A New Strategy Framework for Sustainability Management and Beyond. *J. Clean. Prod.* **2024**, *461*, 142271. [\[CrossRef\]](#)
10. Saihi, A.; Awad, M.; Ben-Daya, M. Quality 4.0: Leveraging Industry 4.0 Technologies to Improve Quality Management Practices—A Systematic Review. *Int. J. Qual. Reliab. Manag.* **2023**, *40*, 628–650. [\[CrossRef\]](#)
11. Carvalho, A.M.; Dias, A.R.; Dias, A.M.; Sampaio, P. The Quality 4.0 Roadmap: Designing a Capability Roadmap toward Quality Management in Industry 4.0. *Qual. Manag. J.* **2024**, *31*, 117–137. [\[CrossRef\]](#)
12. Culot, G.; Nassimbeni, G.; Orzes, G.; Sartor, M. Behind the definition of Industry 4.0: Analysis and open questions. *Int. J. Prod. Econ.* **2020**, *226*, 107617. [\[CrossRef\]](#)
13. Ghobakhloo, M. Industry 4.0, digitization, and opportunities for sustainability. *J. Clean. Prod.* **2020**, *252*, 119869. [\[CrossRef\]](#)
14. Bai, C.; Dallasega, P.; Orzes, G.; Sarkis, J. Industry 4.0 technologies assessment: A sustainability perspective. *Int. J. Prod. Econ.* **2020**, *229*, 107776. [\[CrossRef\]](#)
15. Gajdzik, B.; Wolniak, R.; Grebski, W. Changes in the steel chain in Industry 4.0: Some results of survey on the Polish steel market. *Prod. Eng. Arch.* **2024**, *30*, 1–16. [\[CrossRef\]](#)
16. Sony, M.; Antony, J.; Douglas, J.A. Essential ingredients for the implementation of Quality 4.0: A narrative review of literature and future directions for research. *TQM J.* **2020**, *32*, 779–793. [\[CrossRef\]](#)
17. Smagowicz, J.; Szwed, C. Development of a systematic approach to the implementation of modern information technologies in manufacturing enterprises. *Prod. Eng. Arch.* **2024**, *30*, 36–47. [\[CrossRef\]](#)
18. Antony, J.; McDermott, O.; Sony, M. Quality 4.0 conceptualisation and theoretical understanding: A global exploratory qualitative study. *TQM J.* **2022**, *34*, 1169–1188. [\[CrossRef\]](#)
19. Rosak-Szyrocka, J.; Knop, K. Navigating the Fourth Industrial Revolution: Insights from a comprehensive bibliometric study on Industry 4.0. *Prod. Eng. Arch.* **2024**, *30*, 501–519. [\[CrossRef\]](#)

20. Javaid, M.; Haleem, A.; Singh, R.P.; Suman, R.; Gonzalez, E.S. Understanding the adoption of Industry 4.0 technologies in improving environmental sustainability. *Sustain. Oper. Comput.* **2022**, *3*, 203–217. [\[CrossRef\]](#)
21. Kandarkar, P.C.; Ravi, V.; Subramoniam, S.; Bijulal, D. Integrating Industry 4.0 and Sustainability Toward Attaining Smart Manufacturing Systems. *Sustainability* **2025**, *17*, 10674. [\[CrossRef\]](#)
22. Dias, A.M.; Carvalho, A.M.; Sampaio, P. Quality 4.0: Literature review analysis, definition and impacts of the digital transformation process on quality. *Int. J. Qual. Reliab. Manag.* **2022**, *39*, 1312–1335. [\[CrossRef\]](#)
23. Szataniak, E. Quality Assurance Instruments in the Ready-To-Eat Food Industry: A Literature Analysis. *Syst. Saf. Hum.-Tech. Facil.-Environ.* **2026**, *8*, 1–9. [\[CrossRef\]](#)
24. AlKhader, W.; Jayaraman, R.; Salah, K.; Antony, J.; Omar, M. Transformations in manufacturing quality in the Industry 4.0 era: A semi-centennial review using latent Dirichlet allocation. *Comput. Ind. Eng.* **2025**, *208*, 111340. [\[CrossRef\]](#)
25. Fadilasari, D.P.; Ghatak, R.R.; Garza-Reyes, J.A.; Joshi, R.; Kandasamy, J. Adopting Quality Management Practices in the Industry 4.0 Era: An Investigation into the Challenges. *Total Qual. Manag. Bus. Excell.* **2024**, *35*, 1098–1123. [\[CrossRef\]](#)
26. Hamrol, A.; Grabowska, M. Quality in the Era of Industry 4.0—Quality Management Principles in the Context of the Fourth Industrial Revolution. *Appl. Sci.* **2026**, *16*, 1919. [\[CrossRef\]](#)
27. Nguyen, V.H.; Nguyen, H.S.; Hoang, T.D.; Nguyen, T.M.; Tran, N.T.; Vu, D.T. Comparison of deep feature extraction for quality prediction in injection molding. *Prod. Eng. Arch.* **2026**, *32*, 96–102. [\[CrossRef\]](#)
28. Oliveira, A.C.A.; Pinho, A.F.D.; Brendon, M.F. Quality 4.0: A systematic literature review and future research agenda for the digital transformation of quality management. *Int. J. Qual. Reliab. Manag.* **2026**, *43*, 1650–1673. [\[CrossRef\]](#)
29. Bougault, P.; El Haddad, R.; Ma, L. Industrial Applications of AI in Aircraft Manufacturing: A PRISMA Systematic Literature Review. *Prod. Eng. Arch.* **2026**, *32*, 48–78. [\[CrossRef\]](#)
30. Rogala, P.; Brzozowski, T.; Pańkowska, M. Insights into quality professionals' adoption of Quality 4.0 in the high-tech industry. *TQM J.* **2024**, *36*, 193–214. [\[CrossRef\]](#)
31. Elqabli, Z.; Kamach, O.; Chater, Y. Multimode approach using Reinforcement Learning and Digital Twin for operating mode management. *Prod. Eng. Arch.* **2025**, *31*, 116–128. [\[CrossRef\]](#)
32. Tao, F.; Zhang, H.; Liu, A.; Nee, A.Y.C. Digital Twin in Industry: State-of-the-Art. *IEEE Trans. Ind. Inform.* **2019**, *15*, 2405–2415. [\[CrossRef\]](#)
33. Wiercioch, J. Hybrid predictive maintenance model—Study and implementation example. *Prod. Eng. Arch.* **2024**, *30*, 285–295. [\[CrossRef\]](#)
34. Lahyani, H.; Al Khatib, A.; Sedqui, A. Computerized Decision Support System (CDSS) for engineering change management in automotive wiring harness projects. *Prod. Eng. Arch.* **2025**, *31*, 356–375. [\[CrossRef\]](#)
35. Ingaldi, M.; Ulewicz, R. Problems with the Implementation of Industry 4.0 in Enterprises from the SME Sector. *Sustainability* **2020**, *12*, 217. [\[CrossRef\]](#)
36. Sagala, G.H.; Őri, D. Toward SMEs digital transformation success: A systematic literature review. *Inf. Syst. E-Bus. Manag.* **2024**, *22*, 667–719. [\[CrossRef\]](#)
37. Ślusarczyk, B.; Wiśniewska, J. Barriers and the potential for changes and benefits from the implementation of Industry 4.0 solutions in enterprises. *Prod. Eng. Arch.* **2024**, *30*, 145–154. [\[CrossRef\]](#)
38. Sira, M. A gap analysis framework for enterprise AI implementation. *Prod. Eng. Arch.* **2025**, *31*, 291–310. [\[CrossRef\]](#)
39. Ching, N.T.; Ghobakhloo, M.; Iranmanesh, M.; Maroufkhani, P.; Asadi, S. Industry 4.0 applications for sustainable manufacturing: A systematic literature review and a roadmap to sustainable development. *J. Clean. Prod.* **2022**, *334*, 130133. [\[CrossRef\]](#)
40. Siwec, D.; Pacana, A.; Gavurová, B.; Ključnikov, A.; Nagy, S. Qualitative-environmental aspects of products improvement in SMEs from V4 countries. *Prod. Eng. Arch.* **2024**, *30*, 75–85. [\[CrossRef\]](#)
41. Rajput, S.; Singh, S.P. Connecting circular economy and industry 4.0. *Int. J. Inf. Manag.* **2019**, *49*, 98–113. [\[CrossRef\]](#)
42. Stacho, Z.; Stachová, K.; Barok, A.; Olexová, C. Trends and Perspectives in Enhancing the Competitiveness of Slovak Businesses Through Predictive HR Analytics. *Prod. Eng. Arch.* **2024**, *30*, 333–343. [\[CrossRef\]](#)
43. Brückner, A.; Wölke, M.; Hein-Pensel, F.; Schero, E.; Winkler, H.; Jabs, I. Assessing Industry 5.0 readiness—Prototype of a holistic digital index to evaluate sustainability, resilience and human-centered factors. *Int. J. Inf. Manag. Data Insights* **2025**, *5*, 100329. [\[CrossRef\]](#)
44. Sabău-Popa, C.-D.; Perțicaș, D.-C.; Florea, A.-G.; Hatos, R.; Juma, H.W. Sustainability-Oriented Digital Transformation Under Industry 4.0: Managerial Perceptions of Digitalization and AI. *Sustainability* **2026**, *18*, 2570. [\[CrossRef\]](#)
45. Saniuk, S.; Grabowska, S.; Thibbotuwawa, A. Challenges of industrial systems in terms of the crucial role of humans in the Industry 5.0 environment. *Prod. Eng. Arch.* **2024**, *30*, 94–104. [\[CrossRef\]](#)
46. Marszałek-Kotzur, I. Artificial intelligence in industry—Ethical challenges. *Prod. Eng. Arch.* **2025**, *31*, 550–564. [\[CrossRef\]](#)
47. Eisenhardt, K.M. Building theories from case study research. *Acad. Manag. Rev.* **1989**, *14*, 532–550. [\[CrossRef\]](#)
48. Voss, C.; Tsikriktsis, N.; Frohlich, M. Case research in operations management. *Int. J. Oper. Prod. Manag.* **2002**, *22*, 195–219. [\[CrossRef\]](#)

49. Ketokivi, M.; Choi, T. Renaissance of case research as a scientific method. *J. Oper. Manag.* **2014**, *32*, 232–240. [[CrossRef](#)]
50. Sousa, R.; Voss, C.A. Contingency research in operations management practices. *J. Oper. Manag.* **2008**, *26*, 697–713. [[CrossRef](#)]
51. Hair, J.F.; Hult, G.T.M.; Ringle, C.M.; Sarstedt, M.; Danks, N.P.; Ray, S. *A Primer on Partial Least Squares Structural Equation Modeling (PLS-SEM)*, 3rd ed.; Sage: Thousand Oaks, CA, USA, 2022.
52. *PN-EN ISO 9001:2015-10*; Quality Management Systems-Requirements. Polish Committee for Standardization: Katowice, Poland, 2015.
53. Krzywda, D.; Krzywda, J. Integrating Circular Economy and Reverse Logistics into the Quality Management Systems: Evidence from Polish SMEs. *Syst. Saf. Hum.-Tech. Facil.-Environ.* **2026**, *8*, 189–201. [[CrossRef](#)]
54. Dwivedi, A.; Shardeo, V.; Patil, A.; Srivastava, S.; Pamucar, D. Exploring the linkage between digital transformation, green innovation, and carbon neutrality: Implications for business sustainability. *Prod. Eng. Arch.* **2026**, *32*, 172–184. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.