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REVIEW ARTICLE

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From total quality management to Quality 4.0: A systematic literature review and future research agenda

Abstract Quality 4.0 is an emerging concept that has been increasingly appreciated because of the intensification of competition, continually changing customer requirements and technological evolution. It deals with aligning quality management practices with the emergent capabilities of Industry 4.0 to improve cost, time, and efficiency and increase product quality. This article aims to comprehensively review extant studies related to Quality 4.0 to uncover current research trends, distil key research topics, and identify areas for future research. Thus, 46 journal articles extracted from the Scopus database from 2017 to 2022 were collected and reviewed. A descriptive analysis was first performed according to the year-wise publication, sources of publication, and research methods. Then, the selected articles were analyzed and classified according to four research themes: Quality 4.0 concept, Quality 4.0 implementation, quality management in Quality 4.0, and Quality 4.0 model and application. By extracting the literature review findings, we identify the Quality 4.0 definitions and features, develop the quality curve theory, and highlight future research opportunities. This study supports practitioners, managers, and academicians in effectively recognizing and applying Quality 4.0 to enhance customer satisfaction, achieve innovation enterprise efficiency, and increase organizational competitiveness in the era of Industry 4.0.

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1 Introduction

Quality 4.0 is an emerging quality management concept that has recently attracted much attention because of the increasingly complex customer requirements coupled with fiercer competition and technological evolution. It refers to the future of quality in the environment of Industry 4.0. Quality 4.0 deals with aligning the practices of quality management with the technologies of Industry 4.0, like artificial intelligence (AI) and digitalization, to achieve innovation enterprise efficiency and performance (Broday, 2022; Thekkoote, 2022). Quality 4.0 empowers quality managers to undertake daily tasks in completely new manners. Via implementing Quality 4.0, quality costs can be reduced significantly by improving product design and operational efficiencies, reducing nonconformances and defect rates, and ensuring on-time deliveries (Antony et al., 2023). Furthermore, it can increase responsiveness and customer satisfaction because of early defect detection and root cause elimination and speed up the time to market products. The main advantages of Quality 4.0 are related to the application of real-time and continuous monitoring systems, defect prediction systems, in-line intelligent quality control, and total inspection solutions (Christou et al., 2022; Antony et al., 2023). Therefore, the previously unavailable information can now be obtained in real time, handling advanced tasks can be faster, and control can be achieved via advanced systems for automatic quality monitoring and improvement (Maganga and Taifa, 2023).

Some literature reviews have been performed to investigate the Quality 4.0 topic from different perspectives. For example, Thekkoote (2022) conducted a literature review to analyze the factors contributing to the successful implementation of Quality 4.0 in the digital transformation era. Sony et al. (2020) performed a narrative literature

review to identify key ingredients for the effective application of Quality 4.0. Broday (2022) conducted a literature review on Quality 4.0 to explore how traditional quality concepts are being adapted within organizations. Saihi et al. (2023) provided a systematic review on the state of the research leveraging Industry 4.0 technologies to improve quality management practices. Ranjith Kumar et al. (2022) conducted an integrative literature review of the literature on Quality 4.0 and developed a conceptual framework for quality management in the digital era. In Dias et al. (2022), bibliometric analysis and a descriptive literature review were carried out to analyze the literature related to Quality 4.0 and the influence of the digital transformation process on quality. Chiarini (2020) employed a systematic literature review to determine the relationships among Industry 4.0, quality management, and total quality management (TQM). Furthermore, Souza et al. (2022) provided a bibliometric analysis to review the papers related to TQM 4.0, and Baran and Korkusuz Polat (2022) presented a classification of Industry 4.0 studies in terms of TQM.

The literature reviews above provided valuable insights and interesting research suggestions in the Quality 4.0 field. Nevertheless, they mainly focus on a specific aspect of Quality 4.0 and have general limitations concerning the number of research articles, article screen, article classification, time determination, and subjective clarification. Unlike previous literature reviews, the present study aims to undertake a comprehensive literature review on the topic of Quality 4.0 to identify the current research trends, distil key research topics, and find out areas for future research. Thus, 46 journal papers published from 2017 to 2022 were selected from the Scopus database. These publications were analyzed and classified into four research themes, including Quality 4.0 definition, Quality 4.0 implementation, quality management in Quality 4.0, and Quality 4.0 model and application. A descriptive analysis was further conducted according to the year-wise publication, sources of publication, and research methods. Moreover, the Quality 4.0 definitions and features are discussed, and quality curve theory is introduced based on this literature review. This study can facilitate practitioners and academics to obtain a holistic understanding of Quality 4.0 research and grasp the research hotspots and emerging trends of the domain.

The rest part of this article is arranged as follows. Section 2 presents the conceptual background of Industry 4.0 and Quality 4.0. Section 3 describes the research methodology for conducting the literature review. Section 4 provides the literature review results through descriptive and content analyses. Section 5 analyzes the Quality 4.0 definitions and features and develops quality curve theory. Section 6 presents current research gaps and outlines future research directions based on the in-depth literature analysis. Finally, Section 7 concludes this study with a summary of the research findings.

2 Conceptual background

This section provides the background for the literature review and introduces the historical development of Industry 4.0 and Quality 4.0.

2.1 Industry 4.0

Industry 4.0 was initially proposed by the German Government in 2017 at the Hannover Fair Event to increase the competitiveness of the manufacturing industry in Germany (Sader et al., 2019). It aims to transform the industry into a smart manufacturing system by using novel technologies, including big data, AI, the Internet of Things (IoT), cyber-physical systems (CPS), digital twins, additive manufacturing, and cloud computing. In this new environment, all production facilities are interconnected with each other over the IoT and in the form of CPS. Thus, machines, logistic vehicles, warehouses, and the whole value chain can exchange information and control production flow. Industry 4.0 employs intellectual processes and products supported by autonomous data collection and analysis, leading to smart, intelligent, and efficient processes. Via the production processes integration and product connectivity, higher industrial performance can be obtained for firms by improving product quality, smoothing production processes, and increasing production efficiency (Asif, 2020).

The first industrial revolution, emerged in the 1760s, relied on steam power and mechanical production, thus called “mechanization”. The second revolution, began in the 1870s, advanced the industry to mass production and assembly lines powered by electricity, thus called “electrification”. The third revolution, started in the 1970s, facilitated the automation of industrial production based on electronics, telecommunications, and computers, hence called “automatization”. Recently, the new fourth industrial revolution, called Industry 4.0, was launched by utilizing intelligent devices, identification technologies, localization and navigation machinery, and robotics technologies (Glogovac et al., 2022). These technologies resulted in new types of production systems, such as smart factories, machines, manufacturing, and products (Sader et al., 2022).

Industry 4.0 provides the ability to analyze big data collected in the entire value chain, translate it into useful information, replace the traditional monitoring and decision-making strategies, and provide a key enabler for industrial effectiveness and efficiency (Sader et al., 2019). It is built on self-configuring, knowledge-based, sensor-equipped, and spatially distributed networks of industrial resources (manufacturing machinery, robots, conveyor and storage systems, and production facilities). Industry 4.0 aims to develop autonomous and dynamic production that uses information and communication technologies to

make mass production of highly personalized items easier. As a result, factories are becoming more intelligent, which can self-plan and self-adapt to provide more customized products and fulfill customer expectations autonomously.

2.2 Quality 4.0

Industry 4.0 provides great opportunities for quality management to become a leading power in improving organizational performance. With the advance of new technologies and diversity of customer needs, achieving high-quality levels with conventional quality management methods is difficult (Balouei Jamkhaneh et al., 2022). The tools of Industry 4.0 could help improve the quality of production processes, such as the quality of information for optimization, planning and operation, forecasting, simulations and prototyping, and improved employee participation and engagement (Glogovac et al., 2022). Through the implementation of Industry 4.0, traditional quality management has changed because of the digitalization of all functions of a company (Sony et al., 2020).

By aligning quality management with Industry 4.0, Quality 4.0 can increase company operational efficiency, performance, innovation, and business models (Sony et al., 2020). Furthermore, new production schemes have emerged focusing on customized and complex products generated through dynamic and complicated manufacturing processes (Sader et al., 2022). Industry 4.0 technologies reduced the cost of quality, including sampling and inspection costs, and improved performance by monitoring processes and products simultaneously. Industry 4.0 also enhanced quality-related decision-making activities supported by the instant data flow. As a result, quality management methods and practices have changed in the era of Industry 4.0. For example, quality control procedures are automated; sensors inspect the entire production process and eliminate defective products.

According to the American Society for Quality, Quality 4.0 is the future of quality and organizational excellence within the environment of Industry 4.0 (Jacob, 2017). It stands for the fourth evolution stage for quality management. As illustrated in Fig. 1, the first three quality management stages include quality through inspection and control (Quality 1.0), quality through standards and quality assurance (Quality 2.0), and quality through TQM (Quality 3.0) (Chiarini and Kumar, 2022). Quality control is a product-oriented approach to ensure that all products meet the specifications for satisfying customers' requirements. It excludes defective goods from production using inspection and statistical methods, such as statistical quality control and statistical process control. Quality assurance is a process-oriented method to ensure that the production processes are standardized and maintained to keep the same quality level of products. Its main purpose is to verify that all processes related to production are maintained to deliver non-defective products. TQM is a company-oriented approach to ensure that all activities within a firm are implemented to satisfy customers' requirements and expectations. Quality 4.0 provides an extended scope to quality management with intensive monitoring of all activities contributing to the product value chain. It transforms quality management activities from reactive or proactive to predictive with the help of automation inspection, advanced data analysis, and analysis result integration.

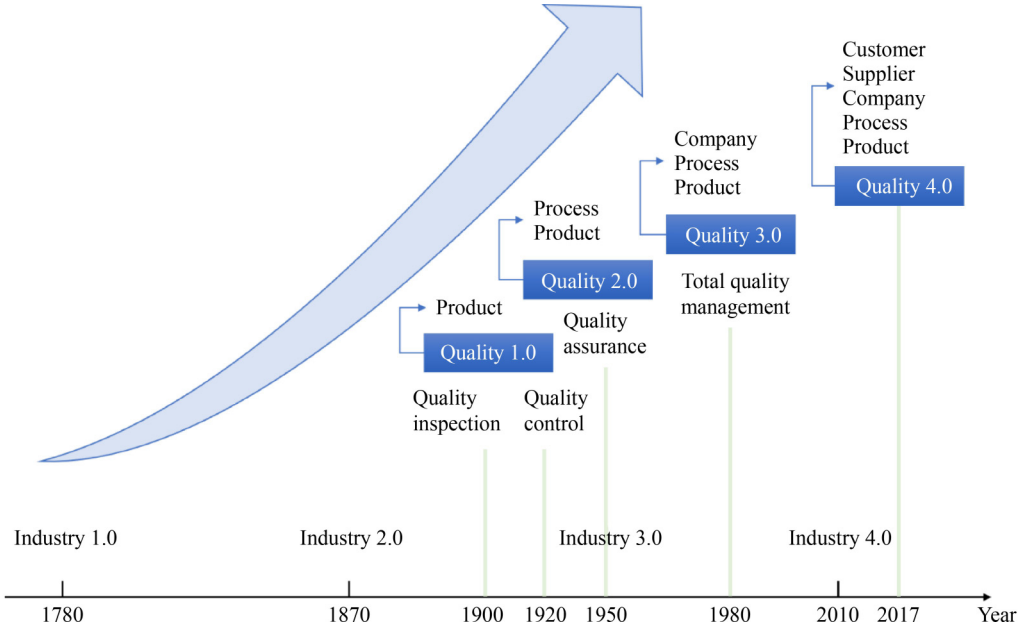

Fig. 1 Illustration of Quality 4.0.

3 Research methodology

This study employed a systematic literature review procedure to review the academic publications regarding Quality 4.0. The method is more transparent than other conventional or unsystematic review methods and has been widely applied in similar studies (Tan et al., 2021; Zheng et al., 2021; Gebhardt et al., 2022). It consists of retrieval keyword definition, data gathering and identification, literature analysis, and descriptive analysis. First, a list of search strings was created via an exploratory review of the existing Quality 4.0 studies. To ensure that the Quality 4.0 articles are fully captured, the keywords "Quality 4.0" and ("Industry 4.0" AND "Quality Management") are used for the literature search in article titles, abstracts, and keywords. Second, the Scopus database was adopted to acquire the relevant articles for the literature review because it has more than 50 million documents and is a reliable source for obtaining worldwide academic information effectively (Di Vaio et al., 2022). Only English papers in peer-reviewed journals published from 2017 to 2022 were included in this stage. The initial retrieval result was comprised of 206 items. Via removing duplicate items, 175 papers were identified. Then, we reviewed the remaining articles' titles, abstracts, and whole texts to eliminate unrelated ones. The following rules were compiled to obtain target literature: 1) The article that focused on theoretical or empirical research on Quality 4.0 was retained; and 2) The article that discussed quality management in the context of Industry 4.0 was included. In the end, 46 documents were considered within the review scope and selected for further analysis. The initial literature related to the topic was published in 2017. Thus, the time range of this review study is from 2017 to 2022. Lastly, the classifications were determined according to the highlights and contributions of the selected papers. Figure 2 shows the detailed review process of this literature review study.

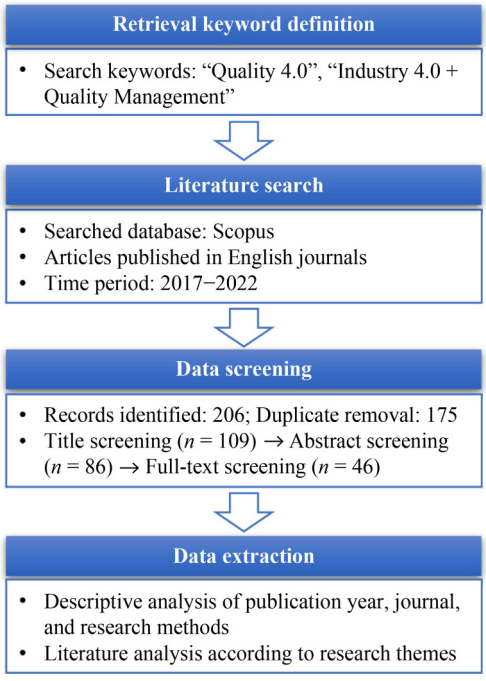

Fig. 2 Schema of systematic literature review.

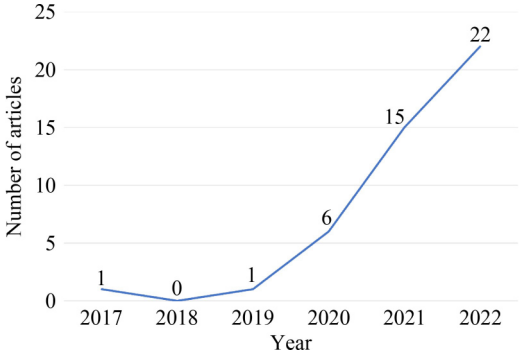

Fig. 3 Annual production of research articles.

4 Results of the literature review

4.1 Descriptive analysis

In this section, we provide a descriptive analysis of year-wise publications and sources of publication. A primary mapping was conducted based on the annual production of articles to achieve a general view of the reviewed documents. Figure 3 shows an upward trend in the quantity of publications per year about Quality 4.0, indicating that this research area has gained increasing attention from researchers over the last years. From 2020, the publications began to rise rapidly, especially in 2022, resulting in about twofold the publications of 2021.

Figure 4 displays the relevant journals with two or more papers on Quality 4.0. As can be seen, the *International Journal of Quality and Reliability Management* and *TQM Journal* are the top two journals in which Quality 4.0 articles are published. The majority of the articles have been published in quality-focused journals. Besides, the reviewed research was published in various journal types, involving manufacturing, operations, and sustainability, which shows the multifaceted impact of Quality 4.0. Regarding the research methods used, the reviewed articles utilized a wide variety of methods, as depicted in Fig. 5, with literature review (n = 21), analytical model (n = 10), and questionnaire survey (n = 9) being the most popular ones.

4.2 Content analysis

The selected studies have examined diverse aspects of Quality 4.0. This section presents all the reviewed papers

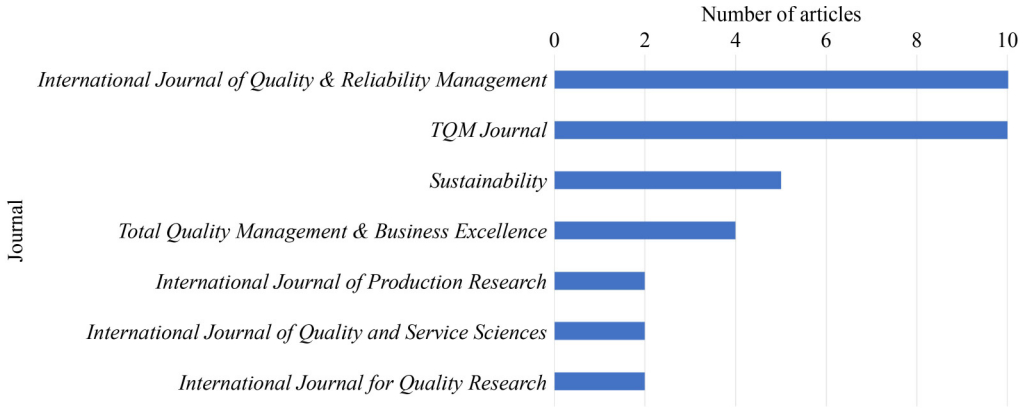

Fig. 4 Number of publications per journal.

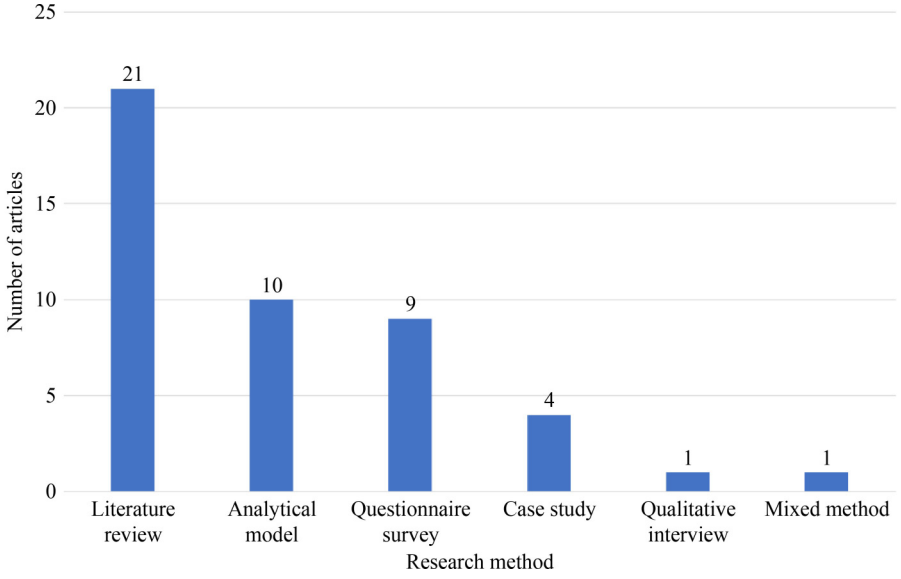

Fig. 5 Research methods used in the reviewed documents.

and evaluates them in-depth according to their research themes.

4.2.1 Quality 4.0 concepts

First, the reviewed literature showed that ten studies explored the related concepts of Quality 4.0 for adapting quality management in Industry 4.0. Table 1 summarizes the related publications based on their main contributions and conclusions. In this line, Souza et al. (2022) addressed the relationships between TQM and Industry 4.0 and developed an ecosystem for TQM 4.0 by integrating technology, quality, and people in the industrial scenario. The TQM 4.0 ecosystem consists of three spheres (Industry 4.0, TQM, and quality culture), each of which denotes a sub-sphere: Technology, quality, and people. Chiarini and Kumar (2022) explored the relationship between Industry 4.0 and quality management and developed a Quality 4.0 theoretical model based on an exploratory sequential mixed study of Italian manufacturing firms. The developed model includes eleven themes of Quality 4.0 across the categories of people, process, and technology. Through an extensive integrative literature review, Ranjith Kumar et al. (2022) identified the dimensions and capabilities of Quality 4.0 and presented a holistic framework representation of Quality 4.0 by linking people, process, and technology dimensions with Quality 4.0 attributes.

Sader et al. (2022) proposed a balanced definition for Quality 4.0 based on the implication of Industry 4.0 and the independent development of quality management practices. The authors indicated that Quality 4.0 is an extended approach to quality management. New technologies are combined with traditional quality activities (quality control, quality assurance, and TQM) to expand the quality management scope. In Dias et al. (2022), a descriptive review of Quality 4.0 was conducted to provide a summary of main topics in the digital transformation process, and a definition for Quality 4.0 was suggested for a better understanding of the concept. The findings revealed that technology and its implications for quality, business management and strategy models,

Table 1 The studies on the Quality 4.0 concept

Paper	Research purpose	Contribution
Souza et al. (2022)	To explore the new concept of TQM 4.0 as a way of adapting quality management in Industry 4.0	An ecosystem for TQM 4.0 was built by integrating technology, quality, and people in the industrial scenario
Chiarini and Kumar (2022)	To explore the main theoretical themes underpinning the Quality 4.0 model	Eleven themes across three categories of people, process, and technology were revealed, and a theoretical model for Quality 4.0 was proposed
Ranjith Kumar et al. (2022)	To provide a conceptual framework for quality in the digital transformation context	A holistic conceptual framework of Quality 4.0, including people, process, and technology, was developed
Sader et al. (2022)	To define Quality 4.0 and its related features, technologies, applications, and challenges	Quality 4.0 is the new generation and evolution of quality management
Dias et al. (2022)	To understand the definition and impacts of the digital transformation process on quality	An overview of the main topics and directions for quality management in digital transformation was offered
Antony et al. (2022a)	To understand Quality 4.0 from a practitioner's viewpoint	Various aspects of Quality 4.0 in terms of motivations, benefits, challenges, and readiness were determined
Hyun Park et al. (2017)	To build a new culture for quality management in the era of Industry 4.0	New concepts of quality and quality management in Industry 4.0 were proposed
Broday (2022)	To investigate how quality concepts are being evolved from inspection to Quality 4.0	The main characteristics of the studies on the subject of Quality 4.0 were verified
Sureshchandar (2022)	To identify and understand the critical dimensions of Quality 4.0	Twelve axes of Quality 4.0 were identified and prioritized using the analytic hierarchy process method
Maganga and Taifa (2023)	To explore the current understanding of Quality 4.0 in manufacturing industries	Quality 4.0 concepts were reviewed bibliometrically and scientometrically

systems, and human or soft factors are the most common topics in Quality 4.0.

Antony et al. (2022a) investigated the concept of Quality 4.0 from a practitioner's perspective to understand and conceptualize Quality 4.0. Using a qualitative interview approach, different aspects of Quality 4.0, such as the benefits and motivating implementation factors, critical success factors, challenges and organizational readiness factors and the skills required by quality professionals, were determined. In Hyun Park et al. (2017), a new culture for quality and a multiway flow system were proposed for quality management in the era of Industry 4.0. Besides, the composite dimension, team creativity, total inspection, and new valuation methods based on big data, AI and IoT were introduced for realizing the multiway flow in practical situations.

Broday (2022) examined the evolution of quality from inspection to Quality 4.0 to verify how traditional quality concepts are being adopted within organizations. The results showed that traditional quality methods would not be replaced but improved; the digitalization of traditional quality methods is mandatory for the success of Quality 4.0. Based on a literature review on quality management, Sureshchandar (2022) identified 12 critical dimensions of Quality 4.0 and further determined their relative importance in implementing Quality 4.0 using the analytic hierarchy process technique. By reviewing Quality 4.0 concepts bibliometrically and scientometrically, Maganga and Taifa (2023) explored the definitions, available models, readiness factors, motivations, and leveraged technology of Quality 4.0 for manufacturing industries.

4.2.2 Quality 4.0 implementation

Eleven reviewed studies investigated the motivations, barriers, and related factors of implementing Quality 4.0 in an organization. These papers are summarized in Table 2 for the convenience of reading and understanding. Via a narrative literature review, Sony et al. (2020) recognized eight critical factors for the effective implementation of Quality 4.0: Handling big data, enhancing prescriptive analytics, effective vertical, horizontal and end-to-end integration, strategic advantage, leadership, training, company culture, and top management support. Based on a survey study on quality professionals in manufacturing and service companies, Sony et al. (2021) found the top five motivations (reliable information, big data-driven quality management, higher customer satisfaction, improved productivity, and cost and time savings), the top five barriers (high cost, lack of resources, lack of knowledge, company culture, and completive advantage not clear), and the readiness factors (top management support, quality culture, leadership, Quality 4.0 strategy, quality knowledge and awareness, customer centeredness, supplier-centric, training, and rewards) for Quality 4.0 implementation. Using a quantitative research methodology, Antony et al. (2023) explored the organizational readiness factors for implementing Quality 4.0 at an intercontinental level. The results showed top management commitment, leadership, and organizational culture are the top three readiness factors for implementing Quality 4.0. Based on a comprehensive review, Thekkoote (2022) examined the factors for the successful implementation of Quality 4.0 in the digital transformation era. As a result, data, analytics, connectivity, collaboration, development of APP, scalability, compliance, organization culture, leadership, and training were identified as the vital factors contributing to Quality 4.0 implementation. Ali and Johl (2022) examined the connection of TQM with Industry 4.0 from the objective and subjective perspectives

Table 2 The studies on Quality 4.0 implementation

Paper	Research purpose	Contribution
Sony et al. (2020)	To investigate the key ingredients for the effective implementation of Quality 4.0	Eight key ingredients for the effective implementation of Quality 4.0 were revealed
Sony et al. (2021)	To investigate the motivations, barriers and readiness factors for Quality 4.0 implementation	The top five motivations and barriers and readiness factors for Quality 4.0 implementation were found
Antony et al. (2023)	To examine the organizational readiness factors for the successful implementation of Quality 4.0	The pros, cons and readiness factors for implementing Quality 4.0 were identified
Thekkoote (2022)	To examine the vital elements for the Quality 4.0 implementation in the digital transformation era	Ten factors that contributed to the successful implementation of Quality 4.0 were identified
Ali and Johl (2022)	To examine the connection of TQM with Industry 4.0	Four soft dimensions and three hard dimensions were revealed to implement Quality 4.0 effectively
Sureshchandar (2023)	To design a measurement instrument to measure the degree of Quality 4.0 implementation	A measurement instrument model was formulated and checked using the confirmatory factor analysis
Yadav et al. (2021)	To identify critical success factors for Lean Six Sigma when implemented using Quality 4.0 technologies	Twenty factors were evaluated for Lean Six Sigma success
Escobar et al. (2021)	To investigate the big data challenges in manufacturing to implement Quality 4.0 successfully	A seven-step problem-solving strategy for the Quality 4.0 initiative was introduced
Balouei Jamkhaneh et al. (2022)	To identify the drivers of human resource empowerment in understanding Quality 4.0	Twenty-nine Quality 4.0 drivers of readiness and workforce ability were identified
Nenadál et al. (2022)	To present a framework to assess the maturity level for implementing Quality 4.0	A Quality 4.0 assessment model comprising four main dimensions and 22 partial items was developed
Maganga and Taifa (2022)	To develop a transition framework from traditional quality approaches to Quality 4.0	A Quality 4.0 transition framework based on the people-process-technology method was proposed

and found that the critical success factors for the effective implementation of Quality 4.0 include top management commitment, customer focus, employees training and learning, quality of big data and analysis, process management, continuous improvement, and product/service design.

Sureshchandar (2023) indicated that Quality 4.0 is a multidimensional concept containing 12 axes and found that traditional quality factors (e.g., leadership, culture, customer centricity, quality systems, metrics, and data analysis) and technical factors (e.g., data governance, innovation, and advanced analytics) are fundamental for the Quality 4.0 transformation. Yadav et al. (2021) evaluated the success factors for Lean Six Sigma in the Quality 4.0 environment and showed that seven Quality 4.0 factors and 11 traditional factors were found critical. The critical Quality 4.0 factors include timely and accurate data availability, data processing software, enterprise resource planning (ERP) system, application software with the capability to auto-adjust processes, radio frequency identification (RFID)-enabled inventory system, data analysis and prediction system, and automation.

Escobar et al. (2021) discussed four challenges of big data initiatives in manufacturing (paradigm, project selection, process redesign, and relearning problems) and introduced a seven-step problem resolution approach (identify, acsensorize, discover, learn, predict, redesign, and relearn) to increase the possibility of successfully deploying Quality 4.0 initiatives. Balouei Jamkhaneh et al. (2022) explored the drivers affecting the readiness and capability of human resources for managing Quality 4.0 and analyzed their cause-and-effect relationships with a grey decision-making trial and evaluation laboratory method. The study identified 29 drivers in the four categories of new valuation, composite dimension, team creativity, and comprehensive inspection and reported that "technical abilities and capability to solve problems" are the most important ones.

Nenadál et al. (2022) developed a conceptual model of maturity assessment for Quality 4.0 and applied it to assess the maturity level of Czech production companies for implementing Quality 4.0. Based on the people-process-technology method, Maganga and Taifa (2022) proposed a Quality 4.0 transition framework for manufacturing industries and found a high level of Quality 4.0 awareness among Tanzanian manufacturing companies.

4.2.3 Quality management in Quality 4.0

Fourteen articles in our reviewed literature examined the quality management methods or activities in the environment of Industry 4.0. The related studies are tabulated in Table 3 to facilitate reading and comparison. Glogovac et al. (2022) investigated the usability of ISO 9004:2018 quality management system elements to assess the maturity level of Quality 4.0. Via confirmatory factor analysis, the ISO 9004:2018, with its fundamentals and relationships, was proved to be practical for assessing the quality maturity level in Industry 4.0. Fonseca et al. (2021) identified the relationships and insinuations between the European Foundation for Quality Management (EFQM) 2020 model and the Industry 4.0 paradigm to support digital conversion by integrating quality and excellence with Industry 4.0. Elibal and Özceylan (2022) compared Industry 4.0 maturity models from the perspective of TQM principles using an integrated fuzzy decision-making method.

Asif (2020) evaluated the alignment of current quality

Table 3 The studies on quality management in Quality 4.0

Paper	Research purpose	Contribution
Glogovac et al. (2022)	To investigate the usability of the ISO 9004:2018 maturity model in the context of Quality 4.0	The ISO 9004:2018 model was used to assess an organization's Quality 4.0 maturity level
Fonseca et al. (2021)	To analyze EFQM 2020 model's novelties and its relationships and implications with Industry 4.0	Several linkages between EFQM 2020 model and Industry 4.0 have been identified at the criteria level and guidance points
Elibal and Özceylan (2022)	To conduct a comparison for Industry 4.0 maturity models based on TQM principles	Four Industry 4.0 maturity models have been evaluated using a decision-making method from the perspective of business practice
Asif (2020)	To evaluate the alignment of quality management models with Industry 4.0	Quality management models were not aligned with Industry 4.0; advances in Industry 4.0 have outpaced quality management models
Saihi et al. (2023)	To explore the impact of Industry 4.0 on improving quality management practices	The findings showed that Industry 4.0 technologies could be leveraged to improve quality management practices at different levels
Chiarini (2020)	To analyze the relationships between Industry 4.0, quality management, and TQM	Four categories of topics related to Quality 4.0 were identified
Bui et al. (2022)	To provide new insights and a collective perspective for supply chain quality management 4.0	A supply chain quality management 4.0 framework and evolutionary perspective were proposed
Kannan and Garad (2021)	To determine the skills and competence of quality professionals required to adapt to Industry 4.0	Technical, methodological, social, and personal competencies required were identified for quality professionals in the era of Industry 4.0
Santos et al. (2021)	To investigate the needed quality management skills for quality managers in Industry 4.0	Quality 4.0 professionals should have creative thinking, be leaders, know how to communicate, work as a team, and have knowledge of new technologies
Silva et al. (2022)	To investigate how smart technologies and human factors contribute to employees' involvement and improve quality control	Seven key elements for the integration of information technologies in quality control to improve quality performance were identified
Antony et al. (2022b)	To analyze the potential impact of Quality 4.0 on organizational performance	Quality 4.0 impacts financial performance, customer value proposition, internal business processes, learning and growth, environmental performance, and social performance
Tambare et al. (2022)	To understand the main techniques to measure performance and manage the quality in Industry 4.0	The industrial standards and key performance indicators used for assessing the performance and quality in Industry 4.0 were discussed
Prashar (2022)	To develop an organizing framework for quality management in Industry 4.0	A morphological analysis framework with six dimensions was presented
Clancy et al. (2022)	To provide a framework for improving quality management in Industry 4.0	A hybrid digitization approach to process improvement framework based on Lean Six Sigma was presented

management models with Industry 4.0. It indicated that they should be updated with the features like managing networked enterprises, enabling quality prediction from big data, and intellectual capital management. Saihi et al. (2023) investigated the impact of Industry 4.0 on improving quality management practices and how digital technologies can be leveraged for the field of quality management through a systematic literature review. Chiarini (2020) analyzed the relationships among Industry 4.0, quality management and TQM and found that the most relevant topics with Quality 4.0 are "creating value within the company via quality analytics and artificial intelligence", "developing Quality 4.0 skills and culture for quality people", "customer value co-creation", and "CPS and ERP for quality assurance". Bui et al. (2022) defined the supply chain quality management 4.0 and gave its evolutionary perspectives based on an integration of Industry 4.0, quality management, and supply chain management.

Based on the case strategy in an electronics manufacturing company, Kannan and Garad (2021) investigated the skills and capability of quality specialists required to adapt to Industry 4.0. The research recognized the technical, methodological, social, and personal competencies gap of quality experts within the context of Industry 4.0 by looking at factory, business, product, and customer changes. Santos et al. (2021) researched quality management employees in Portugal to analyze the newly needed quality management skills for Quality 4.0 professionals. Based on a case study of two information technology projects, Silva et al. (2022) highlighted the human-centered approach in the Quality 4.0 development. They indicated that the technological perspective should be integrated with the human factor in the digital transformation era.

Through an integrative literature review, Antony et al. (2022b) studied the potential influence of Quality 4.0 on various metrics of organizational performance. Quality 4.0 was found to positively affect financial performance, customer value proposition, internal company process, learning and growth, environmental performance, and social performance. Tambare et al. (2022) reviewed the current methods, industrial standards, and key performance indicators to understand the performance measurement system and quality management in data-driven Industry 4.0.

In addition, Prashar (2022) developed an organizing framework for quality management in the Industry 4.0 environment based on six dimensions: Production and operations function, scope of quality management activities,

enabling technologies, latent digitalization capabilities, performance metrics and quality management principles. Clancy et al. (2022) provided a hybrid digitization approach to process improvement framework, integrating Lean Six Sigma and digitalization for improved quality management in Industry 4.0.

4.2.4 Quality 4.0 model and application

The literature review has presented 10 studies that developed various Quality 4.0 models or focused on the application of Quality 4.0 technologies. Table 4 shows those studies, whose detailed literature analysis is given here. Zonnenshain and Kenett (2020) suggested a framework of applied and practical topics that can fill the context of Quality 4.0 based on the innovation elements of Industry 4.0. Sader et al. (2019) presented a theoretical framework for combining Industry 4.0 characteristics with the TQM principles and discussed the role of Industry 4.0 in implementing TQM practices. Baran and Korkusuz Polat (2022) conducted a literature review and classification study regarding Industry 4.0 and Industry 4.0 technologies for TQM. Sariyer et al. (2021) proposed a multi-stage model using big data analytics technologies for quality management in micro, small, and medium firms. The proposed model can detect defects automatically, predict the required numbers of re-works, and identify the problems' root causes. Ramezani and Jassbi (2020) developed a smart fault diagnosis model using neural networks and an expert system for dealing with control chart patterns.

Regarding the application of Quality 4.0 technologies, Alzahrani et al. (2021) explored the environment of higher education organizations against a Quality 4.0 framework and provided insights regarding their readiness for Quality 4.0 transformation. Singh et al. (2022) used the Quality 4.0 concept to digitalize the traditional quality management system and demonstrated its efficiency in an automotive manufacturing organization. Sozinova and Saveleva (2022) studied the problem of product quality management of Industry 4.0 in transborder markets. Emblemsvåg (2020) analyzed some crucial characteristics of project-based industries concerning Quality 4.0 and found that the credibility and transparency of Quality 4.0 technologies can support relational contracting. In Christou et al. (2022), the authors presented the architecture, design, practical implementation, and evaluation of an end-to-end platform for Quality 4.0 applications.

5 Discussion

5.1 Quality 4.0 definitions

The literature review above reveals that some articles have proposed the definitions of Quality 4.0, but no exact definition has been agreed upon. Dias et al. (2022) gave one simple description, indicating that Quality 4.0 is the delivery of superior quality utilizing advanced technologies to enhance the capabilities of both people and quality methods. According to Sader et al. (2022), Quality 4.0 is an extended approach to quality management, where new technologies are combined with traditional quality practices to expand the scope of quality management and enhance the performance and efficiency of quality activities. Chiarini and Kumar (2022) pointed out that Quality 4.0 is a customer-centric and digitally-enabled technique for integrating people with process and technology to take evidence-based decisions in cooperation with internal and external stakeholders in the value chain. Chiarini (2020) argued that Quality 4.0 refers to the digitalization

Table 4 The studies on the Quality 4.0 model and application

Paper	Research purpose	Contribution
Zonnenshain and Kenett (2020)	To present a framework for the quality discipline supporting Industry 4.0	Future directions for quality and reliability engineering that leverage opportunities from Industry 4.0 were discussed
Sader et al. (2019)	To discuss the role of Industry 4.0 in developing TQM practices	A theoretical framework for integrating Industry 4.0 features with the TQM principles was proposed
Baran and Korkusuz Polat (2022)	To conduct a classification study by considering Industry 4.0 in terms of TQM	The quality in Industry 4.0 and the relationship between quality and Industry 4.0 technologies were analyzed
Sariyer et al. (2021)	To propose a model implementing big data analytics technologies for quality management in Industry 4.0	A multi-stage model was proposed to detect defects, predict re-work quantities, and identify root causes
Ramezani and Jassbi (2020)	To propose a smart fault diagnosis model for dealing with control chart patterns	A hybrid fault diagnosis system was proposed using neural networks and an expert system
Alzahrani et al. (2021)	To assess the environments of higher education institutions against a Quality 4.0 framework	Insights about the readiness of higher education institutions for Quality 4.0 transformation were provided
Singh et al. (2022)	To use the Quality 4.0 concept to digitalize the autonomous quality management system (AQMS) in automotive manufacturing	The AQMS has improved the mean process capability and performance indices
Sozinova and Saveleva (2022)	To investigate the marketing quality management in Industry 4.0 in transborder markets	The marketing quality management features in transborder markets have been summarized
Emblemsvåg (2020)	To discuss some of the critical aspects of project-based industries concerning Quality 4.0	Contractors can utilize Quality 4.0 and make a change in the contracting regime
Christou et al. (2022)	To present an end-to-end industrial platform for Quality 4.0 applications	A digital platform for quality management and predictive maintenance was introduced

of TQM and its impact on quality technology, people, and processes. It focuses on connectivity, intelligence, and automation to improve performance and make timely data-driven decisions in an end-to-end scenario, involving all the stakeholders and providing visibility and transparency.

Antony et al. (2022a) provided a complete definition, describing Quality 4.0 as the use of recent technologies to design, operate, and maintain adaptive, predictive, self-corrective, and automated quality systems along with improved human interaction through quality planning, quality assurance, quality control, and quality improvement to achieve new optimums in performance, operational excellence, and innovation to meet the vision, mission and goals of an organization. Chiarini and Kumar (2022) highlighted that Quality 4.0 is aligning the quality management practices and methods with the emerging capabilities of Industry 4.0. It provides quality managers with an industry-aligned framework and language to derive step-change performance benefits that stretch across the entire value chain, including customers, field service, logistics, manufacturing, engineering, and suppliers.

According to the above-reviewed definitions, this study suggests that Quality 4.0, as the fourth quality management evolution phase, is a framework applying cutting-edge technologies in quality management activities of an organization to attain excellence in quality, enhance enterprise efficiency, and improve performance. It is the digitization of quality management (e.g., design quality, conformance quality, and performance quality) utilizing modern technologies. It considers connection, intelligence, and automation for improving performance in the entire value chain.

Quality 4.0 is a method for improving quality in which digital tools increase the organization's ability to offer customers with high-performing products constantly. In Quality 4.0, the term "quality" is defined in terms of product specifications, flexibility, agility, responsiveness, and product usage experience. The difference between Quality 4.0 and traditional quality is the transition from manual measurement to fully automated activity (Sader et al., 2022). Quality 4.0 integrates manufacturing processes with quality management data and is connected to real-time analysis systems that can monitor, analyze and control the entire value chain to make any needed actions that prevent production stops or product rejections.

The advantages of Quality 4.0 will be reduced quality costs through improved operational efficiencies, increased revenue, decreased non-conformances, enhanced product compliance, on-time deliveries, lower supplier failure rates, and more successful new product introductions (Antony et al., 2022a). Quality 4.0 can direct the manufacturing process to produce higher quality products at a lower cost, improving responsiveness and attaining greater competitiveness. The effectiveness of Quality 4.0 can be measured in line with customer satisfaction, headcount reduction, market share increase, and financial impacts on profit (Antony et al., 2022a).

5.2 Quality 4.0 features

The main evolution from TQM toward Quality 4.0 summarizes into four characteristics: 1) quality management digitization, 2) predictive quality management, 3) mass personalization, and 4) intelligent quality management. Thus, this study proposes a four-dimension Quality 4.0 framework, as described in Fig. 6. In the following subsections, details of the Quality 4.0 features are explained.

(1) Quality management digitization

Quality 4.0 is first featured by digitization quality management. Quality 4.0 is the digitization of traditional quality practices and emphasizes using digital tools to enhance an organization's capacity to meet customer expectations with high quality. Managing Quality 4.0 means digitalizing all three phases of quality management, that is, design quality, conformance quality, and performance quality, using advanced techniques (Balouei Jamkhaneh et al., 2022). The use of digital technologies changes quality in different ways and improves the ability of companies to produce high-quality products. In Quality 4.0, digitization is employed in process adjustment, signal feedback, adaptive learning, and self-induced correction systems (Antony et al., 2023).

Quality 4.0 requires the digitalization of quality technology, processes, and people. By automatically collecting and analyzing the product usage data in the hands of consumers using AI, the quality of performance can be efficiently monitored. Suppliers are instantly informed about inventory consumption and can fulfill demand just in time. Utilizing sensors and real-time inspection technologies allowed for the instant exclusion of defective products, not only from a sample of products but from the

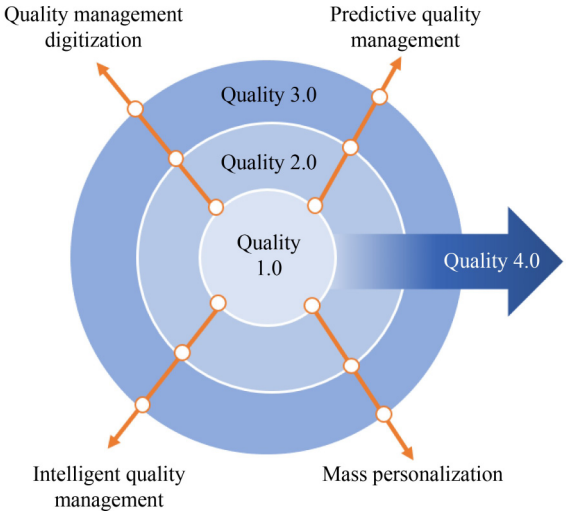

Fig. 6 The four-dimension Quality 4.0 framework.

overall manufacturing population. Additionally, given that intelligent quality control systems are in operation throughout the entire production process, the cost of quality is minimized as production defects are detected early and root causes are analyzed and resolved early. The implications of Quality 4.0 are expected to reach an outstanding position of business excellence, effectiveness, and efficiency and, ultimately, a higher satisfaction of customers.

(2) Predictive quality management

Predictive quality management is the second characteristic of Quality 4.0, in which quality data are collected automatically and analyzed in time, thus resulting in just-in-time quality management. Real-time quality monitoring has replaced traditional quality control as a result of Quality 4.0. The new sensor technologies, coupled with powerful analytical capabilities, allow for predicting product and process errors in advance and change the role of quality from preventive to predictive quality management (Chiarini and Kumar, 2022).

In Quality 4.0, the entire value chain can be monitored, analyzed, and controlled to recognize abnormal patterns in real-time and make necessary countermeasures to prevent product rejections. Industry 4.0 technologies can control the production value chain based on instant data monitoring and analysis, eliminating all waste and achieving zero-defect and high process quality (Sader et al., 2022). They enable the company to obtain real-time visibility of quality indicators, including production effectiveness, supplier performance, engineering manufacturing, and customer support. Furthermore, smart devices can send data about product use, performance, and issues, which contributes to the enhancement of future products. As a result, quality problems will be predicted earlier, and the customer's role will change from being a receiver to contributing to the product value chain.

(3) Mass personalization

Another feature of Quality 4.0 is mass personalization, as customers have been further involved in designing and producing individualized products. Nowadays, productions tend to be in small batches with low volume and wide variety. Quality 4.0 supports new business models based on personalized production, offering customized products adapted to individual customers' preferences.

Owing to Industry 4.0, customers will be involved in the manufacturing process by providing means of communication before, during, and after the manufacturing process. Based on big data analysis, a company can holistically understand customer requirements, early predict market demand, and thus provide the right products at the right time. Moreover, AI will make it possible to predict consumer needs accurately and manage the entire supply chain from inbound logistics to production, outbound logistics, marketing and sales, and service.

In Quality 4.0, customers have control over what they purchase, the number of products purchased, and the ability to change orders at any time during production without additional costs. Smart products offer customers product usage information and product utilization tailored to the customers' needs (Kannan and Garad, 2021). Customers have higher awareness and higher expectations for the quality and reliability of products with access to information and technical details of products. Trends in individual customer demands may result in more individualized manufactured products and increased market volatility because of changing customer expectations and needs.

(4) Intelligent quality management

The key characteristic of Quality 4.0 is the intelligent quality management supported by smart sensors, smart machines, and smart factories in an integrated production system (see Fig. 7). The manufacturing in the smart factory will be completely equipped with sensors, actors and autonomous systems. Smart sensors can identify, monitor, and collect all types of data associated with raw materials, work in process and finished products. Consequently, companies can apply analytics to forecasting quality problems and maintenance requirements. Smart machines are self-learned and connected. They form a

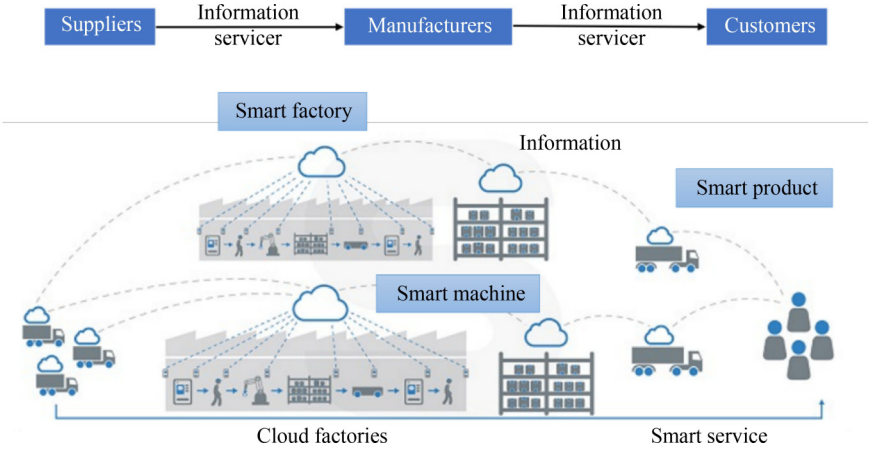

Fig. 7 Quality 4.0 integrated management system.

collaborative community, gather and analyze data, make self-optimized and autonomous decisions, and manage productivity in an objective, data-oriented manner. With new methodologies, machine health signals may be notified in advance, reducing downtime and enabling timely repair.

Rapid and efficient data collection and processing from multiple sources are key elements of Quality 4.0. The products will be smart by carrying information, communicating with humans and transmitting information back to the manufacturing systems for design and process optimization (Kannan and Garad, 2021). Furthermore, designers can predict customer usage and maintenance requirements by tracking and monitoring product performance. The role of workers in Quality 4.0 is changed from being "machine operators" to supervising the work done by machines. The work content is also changed to a more coordinated position, where workers must be skilled in decision-making and problem-solving.

5.3 Quality 4.0 curve theory

Given the use of intelligent manufacturing technologies, robots and digital twins in Quality 4.0, the manufacturing quality can be guaranteed, and the production process will have few or not have quality differences (Sader et al., 2019; Balouei Jamkhaneh et al., 2022). Therefore, the focus of Quality 4.0 is on design quality and service quality, because they will have a greater impact on customer satisfaction and are essential in a competitive environment. Design and service speed, production and delivery, connectivity quality, and software and data quality are the most important elements of the quality concept in Quality 4.0, as a necessity for meeting advanced customers' demands. Thus, in this study, we propose a quality curve theory to satisfy customers and realize business excellence through effectiveness and efficiency. It is a graphical depiction of how quality can be created across different stages of the entire value chain (see Fig. 8). According to this theory, the activities under the curve are categorized into three types: Design, manufacturing, and service. In Quality 4.0, the two ends of the value chain—design and service—generate greater quality-added to the products than does the middle part of the value chain—manufacturing. That is, the design and service activities cause a greater quality difference to the products and should be specially focused on in the Quality 4.0 era.

5.4 Research gaps

Although Quality 4.0 has made great progress, it still has some limitations and challenges. Based on the literature survey of Quality 4.0 articles, the following research gaps are identified for future research.

(1) In previous studies, the relationships between traditional quality management and Quality 4.0 have been investigated, and various concepts for Quality 4.0 have been proposed. But the research of Quality 4.0 is still in its infancy, and current relevant theories are fragmented and need to be further improved. Therefore, the foremost issue in Quality 4.0 is establishing an integrated theoretical system from the aspects of people, process, and technology, so that the Quality 4.0 can be easily understood and successfully implemented in a complex and dynamic manufacturing environment.

(2) Some attempts have been made into the improvement of traditional quality management methods for quality management in Quality 4.0. However, there are still a large number of quality management techniques that have not been fully discussed, which include failure mode and effect analysis (FMEA), fault tree analysis, and quality function deployment (QFD). Thus, another challenge to quality management in Quality 4.0 is integrating new advanced technologies with current quality management

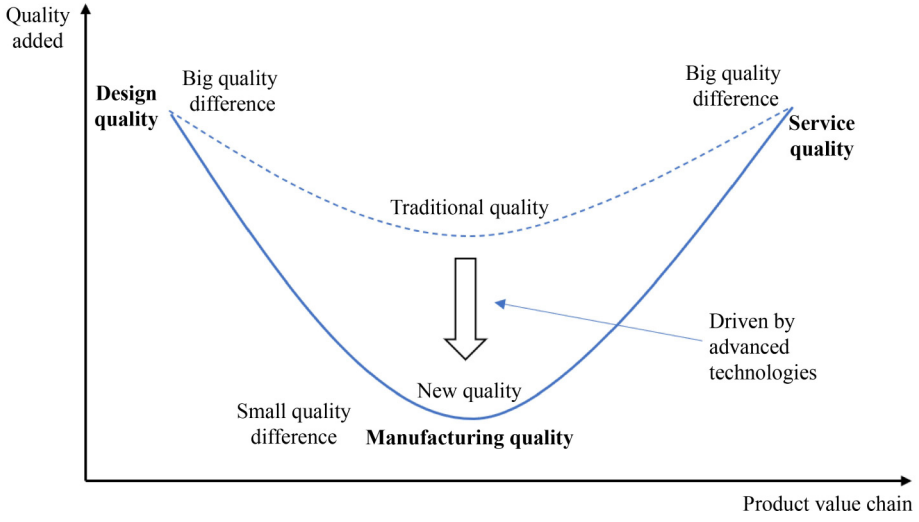

Fig. 8 Quality 4.0 curve.

methods and tools to improve the value chain performance and lead to efficiency quality control and management in the production process.

(3) Some research has focused on implementing Quality 4.0 or applied Quality 4.0 in different fields. However, Quality 4.0 theory needs to be deeply integrated with enterprise quality management practice, and the current applications of Quality 4.0 are largely understudied. The key is how theoretical results can be reconciled with practical applications, approaching this reconciliation not from the theoretical results but from real-world quality management problems. Thus, exploring how to set a quality management plan based on Quality 4.0 theory, how to pass the bottleneck period of Quality 4.0 transformation, and how to overcome the management pressure brought by initial higher cost is necessary.

6 Future research agenda

The reviewed literature has shown that Quality 4.0 will completely revolutionize existing quality management practices and bring many benefits to the manufacturing industry. Theoretical and practical aspects of quality management will change in the coming future. According to the results of the systematic literature review, some fruitful directions for further studies are recommended as follows.

(1) The incompatibilities between current quality management practices and Quality 4.0 and how to overcome them are suggested to be explored in the future. The reviewed studies have discussed the benefits of new emerging technologies. However, real case studies and scenarios are still lacking on how advanced technologies can be used for quality management.

(2) Future research areas should update quality management practices and methods to align with Quality 4.0. On the one hand, well-established quality management tools and principles can be enhanced in the future. On the other hand, new quality management methods based on cutting-edge technologies can be developed and verified with real-world data in future studies.

(3) In Quality 4.0, a business ecosystem should be created in which every factory is intricately networked and dependent upon others. The quality management of networked organizations is different from that required in traditional quality management theory. Thus, researchers must address this transition in the future.

(4) Research studies proposed different quality theoretical frameworks and models for quality management optimization and consequent quality improvement. However, most current researches on this topic remain conceptual, with the frameworks and models limited to proof-of-concept studies and exemplary cases. Thus, we recommend conducting further research in the future to focus more on empirical testing of novel quality management methods in Quality 4.0.

(5) Considering the growing popularity of Industry 4.0, we encourage future researchers to examine the impact of Industry 4.0 enabling technologies on current quality management methods, such as Six Sigma, QFD, and FMEA. Moreover, research should empirically investigate the influence of Industry 4.0 on the quality performance of firms.

(6) A strategic transition framework that corporations can employ to prepare, introduce, and implement Quality 4.0 successfully is needed. Empirical studies can be conducted in the future to analyze the increments and costs of Quality 4.0 implementation compared with traditional quality management methods.

(7) The reviewed papers provide interesting insights into product quality management based on emerging technologies, but other quality issues remain greatly underexamined. Thus, the quality of connectivity and software, service quality, data quality, analysis quality, and information quality in the Quality 4.0 system would be interesting to explore in future studies.

7 Conclusions

In this article, we systematically reviewed the available literature concerning Quality 4.0. 46 papers published in scientific journals were identified and analyzed through descriptive and content analyses. According to the focused research themes, the selected articles were classified into four categories: Quality 4.0 concept, Quality 4.0 implementation, quality management in Quality 4.0, and Quality 4.0 model and application. According to the trend of publications, the number of articles on Quality 4.0 has significantly increased after 2019, and the majority were published in the past two years. Furthermore, the top journal in which Quality 4.0 articles are published is the *International Journal of Quality and Reliability Management*; and the most frequently used research method is literature review.

Based on this review, we gave a general definition of Quality 4.0 and outlined four characteristics of Quality 4.0, which include quality management digitization, predictive quality management, mass personalization, and intelligent quality management. Moreover, we introduced the quality curve theory to describe how quality can be created across different stages of a product value chain. In addition, the existing research gaps were clarified, and the possible directions for future research were pointed out by analyzing the selected studies. This review study provides academics and practitioners with a guideline and insights into further refining the Quality 4.0 theory and applying the Quality 4.0 technologies to help companies gain higher competitive performance via improved

customer satisfaction, product quality, and operational efficiencies.

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