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SKILLS AND COMPETENCIES FOR QUALITY MANAGEMENT IN INDUSTRY 4.0: A LITERATURE REVIEW

HABILIDADES E COMPETÊNCIAS PARA A GESTÃO DA QUALIDADE NA INDÚSTRIA 4.0: UMA ANÁLISE DA LITERATURA

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Abstract: This study examines how Industry 4.0 has been reshaping quality management and what this shift implies for the competencies expected from professionals working in digital production settings. A bibliometric review of studies published between 2011 and 2021 was carried out using VOSViewer and the Methodi Ordinatio procedure to organize and assess the selected works. The review shows that, despite being presented separately in many publications, the competencies mentioned across the studies tend to align around a set that combines technical, methodological, social, and personal elements. These dimensions are closely tied to daily tasks in data-intensive environments, particularly those involving digital tools, automated systems, and the interpretation of information flows. A contribution of the study is a picture of how competency requirements for quality professionals have been approached in the literature. The review also identifies aspects that remain insufficiently examined, such as how these competencies appear in real industrial settings or how organizations and educational programs support their development. These points open space for empirical investigations and for evaluating training approaches that reflect digitally mediated work routines.

Keywords: Industry 4.0. Quality Management. Skills. Competencies. Bibliometric Analysis.

Resumo: Este estudo examina como a Indústria 4.0 tem remodelado a gestão da qualidade e o que essa mudança implica para as competências esperadas de profissionais que atuam em ambientes de produção digital. Uma revisão bibliométrica de estudos publicados entre 2011 e 2021 foi realizada utilizando o VOSViewer e o método Methodi Ordinatio para organizar e avaliar os trabalhos selecionados. A revisão mostra que, apesar de serem apresentadas separadamente em muitas publicações, as competências mencionadas nos estudos tendem a se alinhar em torno de um conjunto que combina elementos técnicos, metodológicos, sociais e pessoais. Essas dimensões estão intimamente ligadas às tarefas diárias em ambientes com grande volume de dados, particularmente àquelas que envolvem ferramentas digitais, sistemas automatizados e a interpretação de fluxos de informação. Uma contribuição deste estudo é oferecer um panorama de como os requisitos de competência para profissionais da qualidade têm sido abordados na literatura. Também são apresentados aspectos que permanecem insuficientemente examinados, como a forma como essas competências se manifestam em contextos industriais reais e como organizações e programas educacionais apoiam seu desenvolvimento. Esses pontos abrem espaço para investigações empíricas e para a avaliação de abordagens de treinamento que reflitam rotinas de trabalho mediadas digitalmente.

Palavras-chave: Indústria 4.0. Gestão da Qualidade. Habilidades. Competências. Análise Bibliométrica

1 INTRODUCTION

The first paradigm of quality management emerged during the era of mass production, between 1900 and 1940. During this period, quality inspection activities focused mainly on delivering manufactured products without known defects (Weckenmann et al., 2015). Quality management evolved from inspection to Statistical Process Control, Quality Assurance, and finally to Business Excellence Models (Fonseca, 2015). After various evolution steps, we experience Quality 4.0, a term used by quality professionals in the era of the Fourth Industrial Revolution (Yurin et al., 2021). The path to Industry 4.0 may be different for each company, leading to significant changes in organizational strategies, particularly in culture and resource management (Schuh, Anderl, Wahlster, 2017). Quality 4.0 encompasses the application of Industry 4.0 technologies such as the Internet of Things (IoT), Machine Learning, Artificial Intelligence (AI), Big Data, and Robotics to ensure quality improvement (Yadav, Shankar, and Singh, 2021). However, Quality 4.0 extends beyond the digitalization of tools and introduces new forms of value creation based on data and analytics, highlighting the need to develop the skills and culture that support this paradigm (Chiarini, 2020).

In this transition, human-machine interaction becomes evident as professionals are required to interpret large volumes of data and to coordinate work in decentralized environments that demand technical, methodological, social, and personal competencies (Di Nardo, Forino and Murino, 2020). Quality control is not a sufficient skill anymore, while analytical thinking, critical thinking, innovation, and complex problem solving are expected to be high-demand skills for future professionals (WEF, 2018).

With the rapid evolution of digital technologies, organizations face increasing difficulties in adapting their work processes to environments shaped by automation, data flows, and interconnected systems. In this sense, Flores, Xu, and Lu (2020) indicate the need to clarify which competencies allow professionals to work effectively in technology-mediated contexts. Difficulties in identifying which competencies support data-driven decision-making, automation, and human-machine interaction indicate a gap in the literature. Clarifying these competencies contributes to a more precise understanding of the professional profile required by Quality 4.0. Evidence from different studies converges in showing that digital transformation raises expectations regarding data-oriented work, problem-solving, and interaction with intelligent systems. These indications reinforce the relevance of investigating the skills and competencies required from Quality professionals in the Industry 4.0 environment.

Thus, this paper aims to fill this gap by identifying relevant studies that address the profile of professionals meeting the requirements of Industry 4.0 in terms of skills and competencies related to quality management in the industrial sector. Through a literature review using bibliometric techniques, this study seeks to provide insights into the evolving landscape of quality management and the emerging skillsets necessary for professionals in the age of Industry 4.0.

2 LITERATURE REVIEW

Industry 4.0 brings a radical transformation in production and management processes, and it has changed profoundly how companies operate and manage quality. This section explores the transformative nature of Industry 4.0 in quality management, dividing the discussion into two main subtopics: the first addresses the transformative paradigm in quality management, while the second focuses on the professional development and analytical skills required to meet the emerging demands of this new industrial era.

2.1 Transformative Paradigm in Quality Management

Industry 4.0, a term introduced in Germany in 2011, referred initially to a high-tech strategic plan aimed at enhancing the competitiveness of the German manufacturing industry (Chiarini, 2020). This revolutionary production paradigm has since expanded globally (Mayard, 2015), impacting millions of workers worldwide (WEF, 2018). The transformative nature of Industry 4.0 extends beyond production methods, influencing the dynamics of factories, companies, and society at large (Faria et al., 2017). This paradigm shift is particularly disruptive across all dimensions (Mayard, 2015), including the concept of quality.

In the context of the Fourth Industrial Revolution, the notion of quality is poised to evolve significantly. According to Park et al. (2017), quality in Industry 4.0 will encompass personalized service quality as mass customization and personalized production become feasible. This shift will place greater emphasis on design, safety, and service quality rather than solely on product quality. Quality 4.0, as described by Fonseca et al. (2021), integrates quality management with digitization and technology, providing a robust framework for digital transformation. According to Kannan and Garad (2021), as organizations seek to create value for customers using innovation, the quality management professionals begin to be seen as a central and strategic player; that is, quality managers begin to act as agents of change and process excellence experts.

Despite the philosophical foundations of traditional quality management being data-driven, quality engineers have often relied on intuition and qualitative assessments (Sony et al., 2021). However, advancements in information and communication technologies (ICT) have rendered quality management increasingly data-centric, facilitated by the proliferation of sensors and big data analytics (Sony et al., 2021).

2.2 Professional Development and Analytical Skills in Quality 4.0

Making full use of workers' skills and talents, rather than moving towards workerless production, according to Kannan and Garad (2021), can be a key success factor in adapting to new technologies. Human-machine interface solutions, according to Kannan and Garad (2021), enable operators to interact with intangible assets and digital content using sensors to collect real-time process data. This allows operators to gain a broader understanding of the process and perform quality checks.

Big Data Analysis, a cornerstone of Industry 4.0 (Fonseca et al., 2021), involves the examination and investigation of vast and complex data sets. As a result, these data originate from various sources, including suppliers and customers, and exist in diverse forms such as text, numerical data, web logs, videos, and tweets. The diversity and scale of these datasets create substantial challenges for interpretation and decision-making, especially as organizations deal with increasingly heterogeneous and unstructured information. Consequently, advanced techniques are required to capture, store, distribute, manage, and analyze this information (Fonseca et al., 2021), necessitating specialized skills from professionals. Big data, AI, predictive software, and a new kind of problem-solving seem to be a new frontier for quality people (Chiarini, 2020).

According to Ejsmont (2021), professionals must understand how technologies function, possess open-mindedness, and adapt to changes to meet Industry 4.0's demands. The ability to retrieve and process data swiftly amplifies the importance of analytical skills. Ejsmont (2021) emphasizes the continuous development of these professionals, a sentiment echoed by Sony et al. (2021), who assert that quality employees must be trained to utilize advanced technologies effectively. Additionally, a reward system incentivizes the adoption of new quality management practices, with training and rewarding being key dimensions of Quality 4.0.

The skills required in the era of Quality 4.0, according to Babatunde (2020), range from active learning, analytical thinking and complex problem solving to coordination, creativity, emotional intelligence, leadership, resource management, manual dexterity, verbal skills, persuasion, reading, writing, mathematics, reasoning, resilience, service orientation, systems analysis, technology design and programming. Skills also include combining experience in quality management with data science, embracing statistical and analytical thinking for innovative quality management.

In this context, competencies for quality management acquire a broader configuration, combining technical, analytical, and socio-cognitive dimensions. Flores, Xu and Lu (2020) describe this profile as “a future-proofing set of competences” that integrates digital literacy, problem-solving, and adaptability. Kannan and Garad (2021) reinforce this view by grouping essential competencies into technical, methodological, social, and personal domains, highlighting the need for quality professionals to operate in data-intensive and interconnected environments. Di Nardo, Forino and Murino, (2020) emphasize that technological advances only generate real improvements when supported by strong human capabilities. It means that the process of digital transformation that companies are called to deal with, to be competitive and protagonists in the markets, is not just a technological issue, but a skill-related one

(Nardo, Forino and Murino, 2020). Without a focus on human skill, quality improvements could be useless (Nardo, Forino and Murino, 2020).

In conclusion, as highlighted by Sony et al. (2021), the complexity of existing jobs necessitates a comprehensive skill set. The role of quality professionals will increasingly involve solving complex problems, demonstrating emotional competence, and applying Quality 4.0 tools.

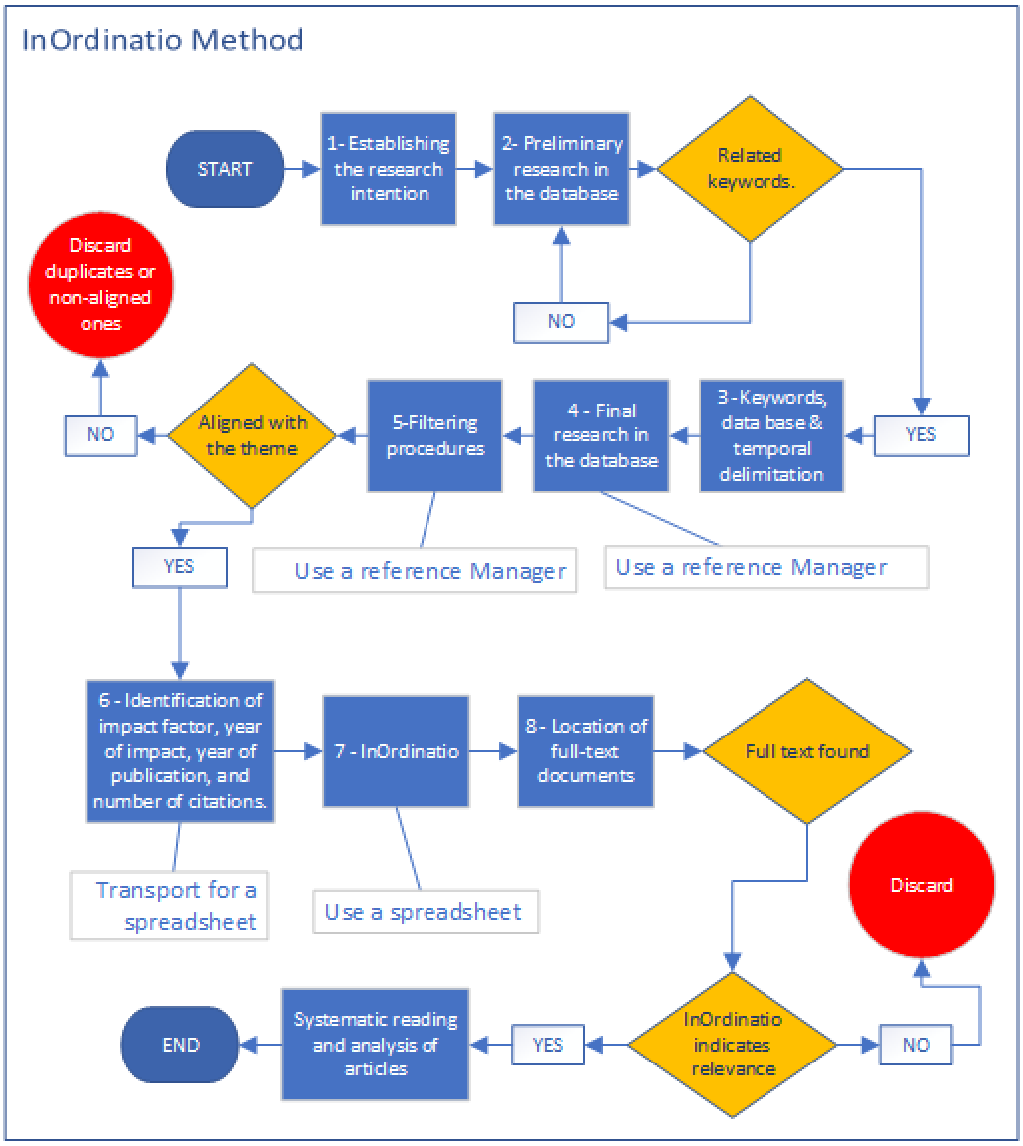
3 METHODOLOGY

A comprehensive literature review was conducted to identify and profile professionals who meet the Industry 4.0 requirements concerning skills and competencies in quality management within the industrial sector. The review employed bibliometric techniques using VOSViewer software, a free tool designed for creating, visualizing, and exploring bibliometric maps (Eck & Waltman, 2020), and the Methodi Ordinatio methodology.

Bibliometrics operates on the premise that scientific knowledge is cumulative and cooperative, built upon research addressing gaps for future investigation. This aligns with Cabral Netto & Laurindo's (2015) argument that scientific progress is achieved through the cumulative work of scientists building on their predecessors' contributions. According to Chueke & Amatucci (2015), bibliometric studies consider: (1) Journal attraction – Bradford's Law, identifying the most relevant journals that publish specific topics based on their reputation; (2) Keyword frequency – Zipf's Law, estimating the most recurring themes in a knowledge field from an ordered list; and (3) Author productivity – Lotka's Law, assessing the impact of an author's contributions in a knowledge area based on size/frequency criteria. Zupic & Čater (2015) highlight that scientific mapping with bibliometric methods is beneficial in two main ways: (a) it provides new researchers a rapid understanding of the field's structure, and (b) it introduces quantitative rigor into traditional literature reviews.

The Methodi Ordinatio methodology, as described by Pagani et al. (2015), integrates impact factor, citation count, and publication year through an equation, producing the Ordinatio index to compare the most relevant works. This classification occurs before systematic analysis, ensuring the paper's importance is recognized early in the process (Pagani et al., 2015), making it a crucial tool for bibliometric studies. The nine phases of Methodi Ordinatio are illustrated in Figure 1. VOSViewer was utilized to create visual maps of co-author relationships, co-citations, terms, and keywords related to skills and competencies relevant to quality and Industry 4.0.

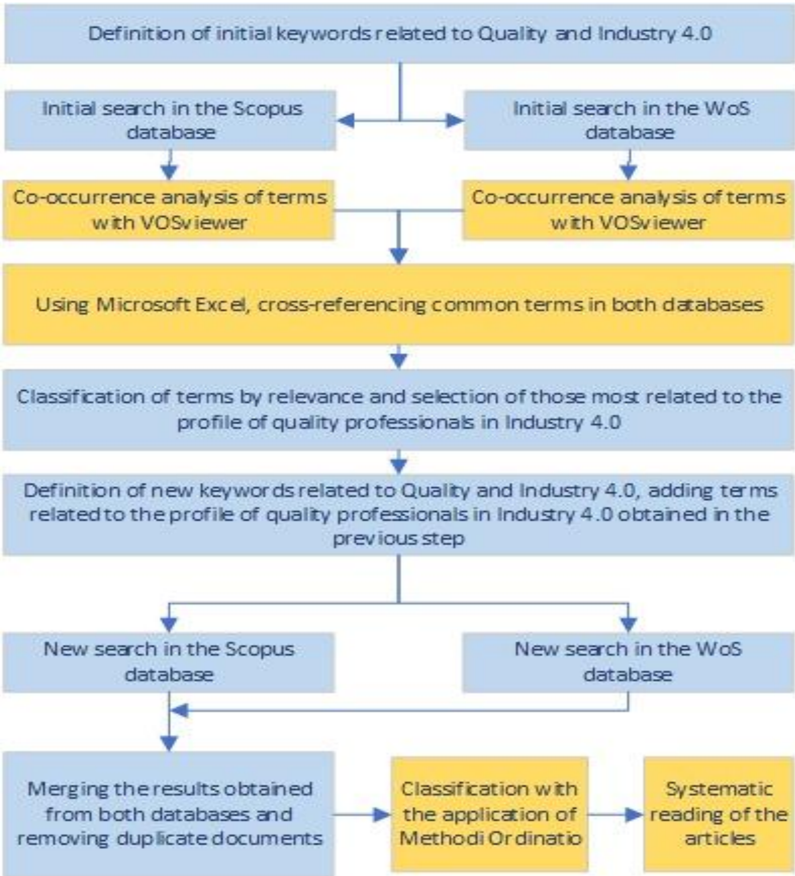
Figure 1 – Stages of the Methodi Ordinatio.



source: Adapted from Pagani et al. (2018).

The search for articles was conducted in the Web of Science (WoS) and Scopus databases. By cross-referencing and classifying terms from both databases, further searches refined the results, followed by applying the Methodi Ordinatio methodology. Only journal articles were considered at this stage, excluding conference papers, book chapters, editorial materials, etc. According to Steinhardt (2017), journal articles represent basic research outputs providing valuable knowledge to the scientific community. The selected period was from 2011 to 2021, coinciding with the initial presentation of "Industrie 4.0" at the Hannover Fair in 2011 (Xu et al., 2018). The search strings used are detailed in the results and discussion section. Figure 2 shows the steps followed to conduct the search and for selecting the papers, which are detailed next.

Figure 2 – Research stages



Source: Authors, (2021).

4 RESULTS AND DISCUSSION

The initial searches conducted on the Web of Science (WoS) and Scopus databases provided an overview of publications involving the keywords "Quality," "Quality 4.0," and "Industry 4.0." The search strings and total publications are listed in

Table 1. The results from both databases were cross-referenced, duplicates were removed, and term and keyword maps were generated using the text mining function ("create a map based on text data") of VOSViewer. The set of articles exclusive to WoS (194) was added to the Scopus template, resulting in 931 articles, which was used as input for VOSViewer.

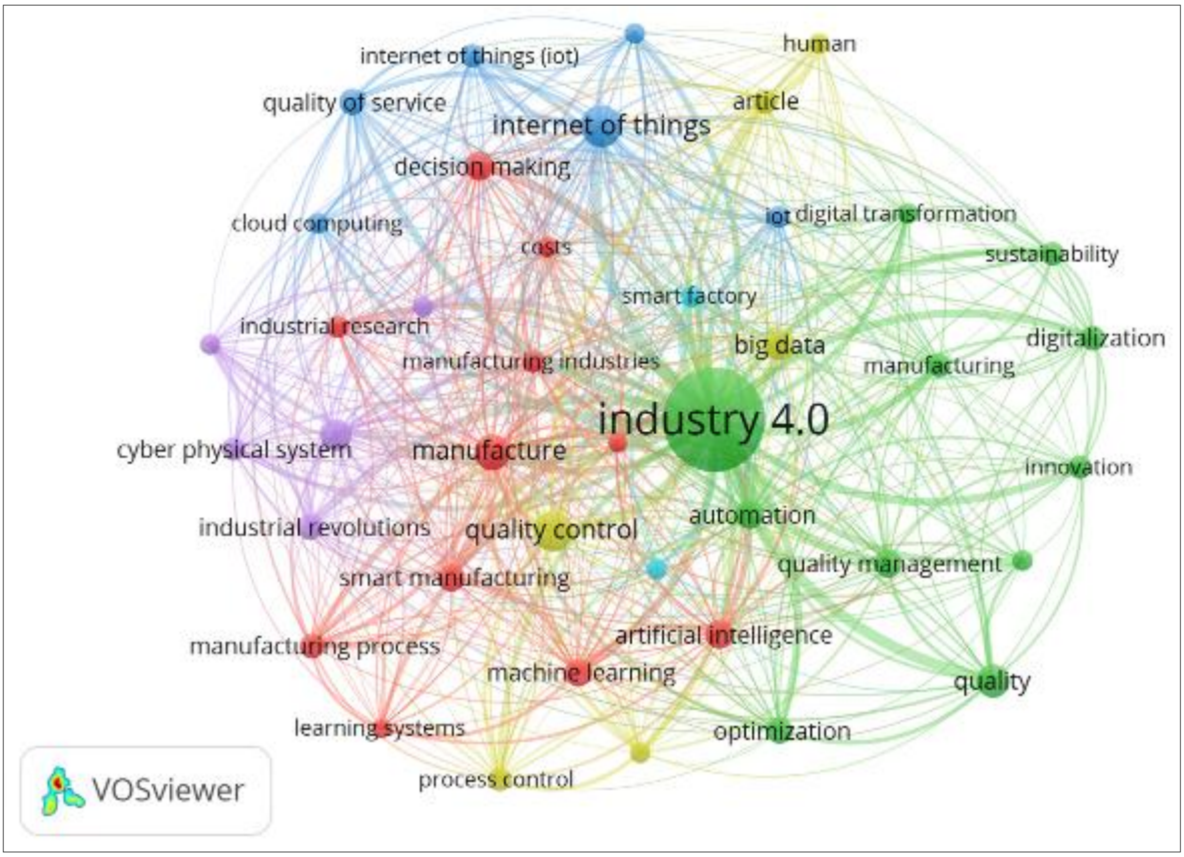
Table 1 – Searches in WoS and Scopus databases

#String	Databases	Strings	Number of publications
[1]	WoS	Topic: (quality AND "Industr* 4.0") OR Topic: ("quality 4.0") Refined by: DOCUMENT TYPES: (ARTICLE) Time frame: 2011-2021. Indexes: SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, ESCI.	639
[1]	Scopus	(TITLE-ABS-KEY (quality AND "industr* 4.0") OR TITLE-ABS-KEY ("quality 4.0")) AND PUBYEAR > 2010 AND (LIMIT-TO (DOCTYPE , "ar"))	737

Source: The Authors (2021).

The keyword co-occurrence analysis, illustrated in Figure 3, was configured as follows: Type of analysis - Co-occurrence; Unit of analysis - All keywords; Counting method - Full counting. Analyzing only Scopus with this configuration resulted in 5721 keywords. When both databases were analyzed, with duplicates removed, the result was 6588 keywords. In both analyses, a minimum occurrence threshold of 20 was set, resulting in 33 and 41 matches, respectively. Figure 4 shows the term map obtained through text mining ("create a map based on text data") in VOSViewer, focusing on terms from titles and abstracts while ignoring those related to copyright statements. The other configurations were: Counting method - Full counting; minimum number of term occurrences = 20. This configuration returned 198 out of 21391 terms, excluding terms such as author, China, region, research limit implication, research, review, and study. By default, VOSViewer displays 60% of the terms found in the results (Eck & Waltman, 2020).

Figure 3 – Keyword map obtained from Scopus and WoS databases using search string [1] – Jun/2021



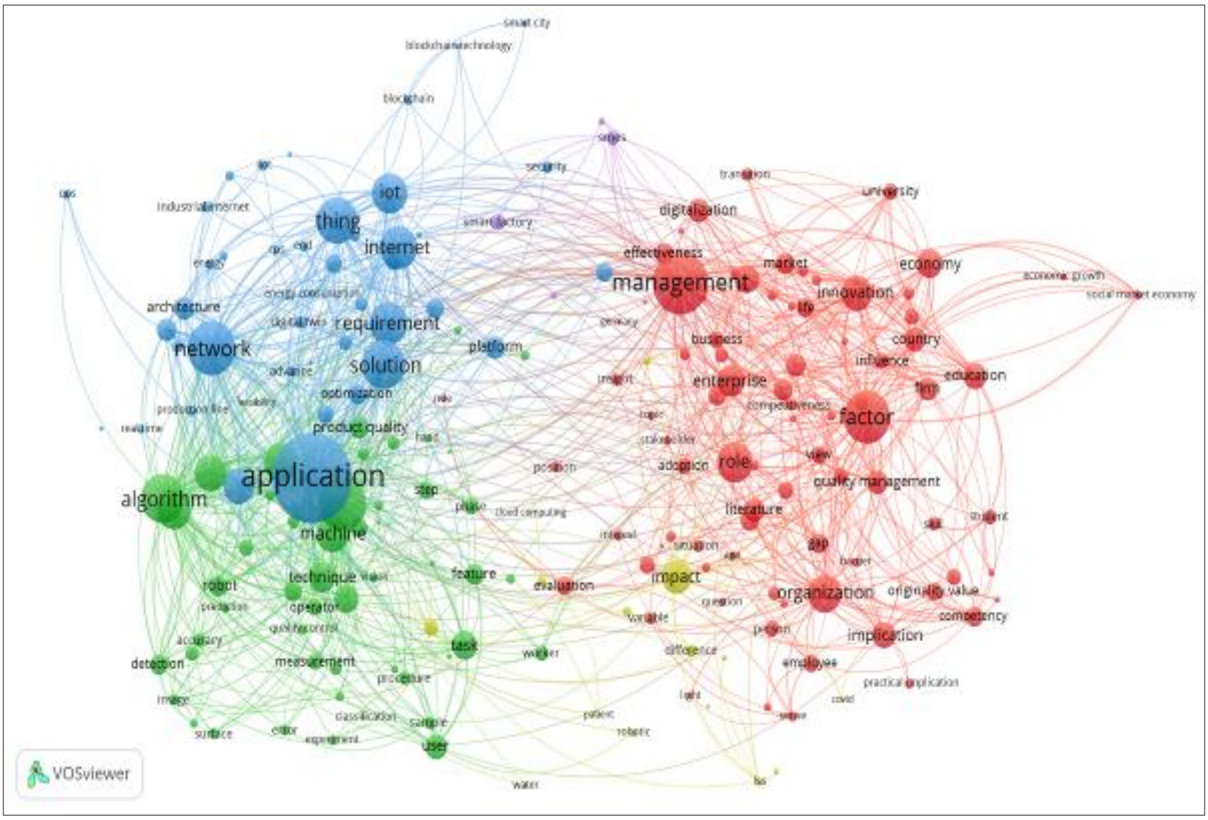
Source: VOSViewer 1.6.16 (Center for Science and Technology Studies, Leiden, Netherlands) Jun/2021.

The keyword analysis depicted in Figure 3 reveals a notable absence of terms related to work, skills, competencies, or their synonyms. The map identifies six clusters, with "Industry 4.0" (green cluster) being particularly prominent, connecting with all other clusters as expected, given its central role in the initial search string. Other significant terms include "quality management" within the same cluster and "smart manufacturing" (cluster 1 – red), which, according to Frank et al. (2019), signifies the inception and primary objective of Industry 4.0, rooted in advanced manufacturing systems and their integration with other processes.

However, it is important to note that there are no keywords directly associated with quality professionals in the context of Industry 4.0. Conversely, the term map includes words related, albeit indirectly, to professionals and work, which will inform the new search strings aimed at refining our searches. Table 2 lists these terms, ranked by relevance according to VOSViewer.

This refined approach will help ensure a more targeted and comprehensive understanding of the competencies and skills required by quality professionals in the evolving landscape of Industry 4.0.

Figure 4 – Term map obtained from Scopus and WoS databases using search string [1] – Jun/2021



Source: VOSViewer 1.6.16 (Center for Science and Technology Studies, Leiden, Netherlands) Jun/2021.

Table 2 – Terms related to skills and competencies obtained with string [1] – Scopus + WoS

Position	id	Term	Ocurrence	Relevance VOSViewer score
4	25	competency	48	29147
11	163	skill	58	23108
21	50	employee	62	18555

164	198	worker	66	3677

Source: The Authors (2021).

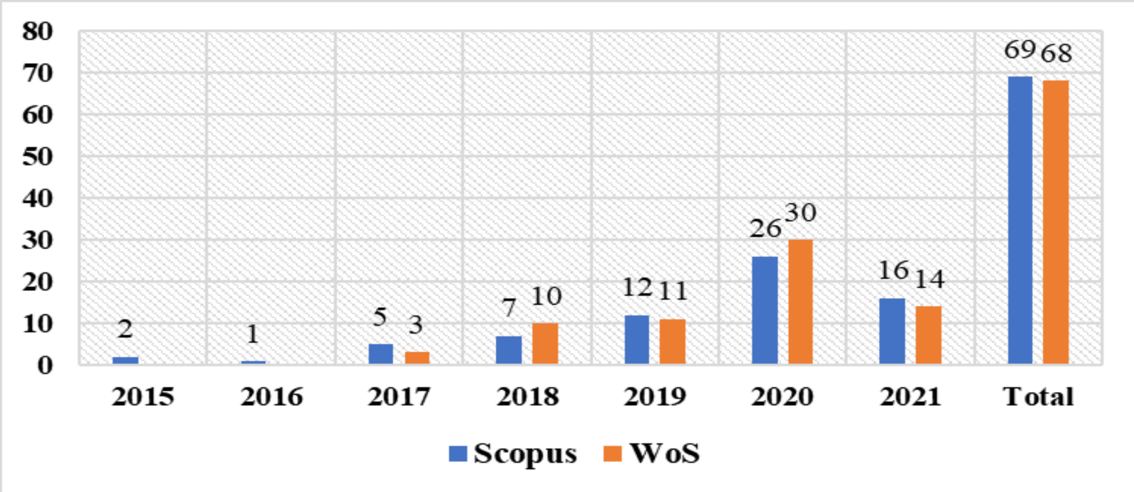
The "position" column ranks the terms according to their relevance or link strength as determined by VOSViewer. Consequently, terms such as "competency," "skill," "employee," and "worker" will be utilized to better direct and delineate the research. Table 3 presents new search strings that associate Industry 4.0 and Quality 4.0 with competencies, skills, and workers. Only articles published in journals from 2011 onwards were considered; however, the earliest relevant publications appeared in 2015, with approximately 80% of the publications emerging from 2019 onwards. This trend indicates a growing interest in these topics. The evolution of publications over the years is depicted in Figure 5.

Table 3 – Searches in WoS and Scopus databases relating to Quality, Industry 4.0, and Skills – string [2]

#String	**Database**	***Strings***	**Number of publications**
[2]	WoS	TOPIC: (quality AND "industr* 4.0") AND TOPIC: (competenc* OR skill OR employ* OR worker) Refined by: DOCUMENT TYPES: (ARTICLE) AND LANGUAGES: (ENGLISH) AND RESEARCH AREAS: (ENGINEERING OR BUSINESS ECONOMICS) Time frame: 2011-2021. Indexes: SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, ESCI.	68
[2]	*Scopus*	(TITLE-ABS-KEY (quality AND "Industr* 4.0") AND TITLE-ABS-KEY (competenc* OR skill OR employ* OR worker)) AND PUBYEAR > 2010 AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (PUBSTAGE , "final")) AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (SRCTYPE , "j")) AND (LIMIT-TO (SUBJAREA , "ENGI") OR LIMIT-TO (SUBJAREA , "BUSI"))	69

Source: The Authors (2021).

Figure 5 – Evolution of Publications – search string [2] – Jun/2021



Source: Adapted from *Scopus* e WoS (junho / 2021).

Using the results obtained from search string [2], data from the databases were merged using software, with duplicates removed. Entries without abstracts, titles, authors, or DOI/ISSN were eliminated. The set of articles exclusively from the WoS database (n=35) was added to the Scopus template, resulting in a total of n=104. After reviewing the titles and keywords, this number was reduced to n=51. Subsequently, reading the abstracts further reduced the set to n=31, which were then classified using the Methodi Ordinatio.

4.1 Methodi Ordinatio Classification

As previously mentioned, Methodi Ordinatio considers the impact factor, year of publication, and the number of citations to determine the relevance of a journal. The CiteScore from Scopus, which, according to Al-Hoorie & Vitta (2019), is calculated as the total number of citations in a given year divided by the total number of citable publications over the preceding three years, was accessed in June 2021 and adopted as the impact factor for this research. This choice was made because it covered the majority of journals, missing only three of the 26 journals responsible for publishing the 31 articles to be classified. The classification of the journals, as described by Pagani et al. (2015), is obtained using the InOrdinatio equation (1), where: Fi is the impact factor; α is a factor ranging from 1 to 10 assigned by the researcher, with 1 favoring older publications and 10 favoring more recent ones; and SCi is the sum of citations.

InOrdinatio = (Fi / 1000) + α . [10 – (YearResearch – YearPublication)] + SCi **eq.(1)**

The InOrdinatio classification was conducted with α = 3 to favor the most cited articles without excluding older ones, as none of the 31 articles in the collection were published before 2017. Table 4 presents the top twenty-ranked articles, including authors, titles, and journals. As mentioned in the methodology section, Methodi Ordinatio consists of nine phases. After completing phase 7, which involves ranking through the equation, the full texts of the top ten articles were downloaded (phase 8) for reading. According to Pagani et al. (2015), Methodi Ordinatio provides a quantitative classification based on multiple criteria; however, the decision on the number of articles to be read lies with the researcher.

Table 4 – InOrdinatio Classification – Phase 7

Cl	Authors, title, journal	Cite Score	α	Citations	Year	In Ordinatio
1	PERUZZINI, M; PELLICCIARI, M 2017.A framework to design a human-centred adaptive manufacturing system for aging workers. ADVANCED ENGINEERING INFORMATICS	8,6	3	41	2017	68,01
2	KRUGH M., MEARS L. 2018.A complementary Cyber-Human Systems framework for Industry 4.0 Cyber-Physical Systems. Manufacturing Letters	5,6	3	31	2018	61,01
3	LONGO F., NICOLETTI L., PADOVANO A. 2019.Ubiquitous knowledge empowers the Smart Factory: The impacts of a Service-oriented Digital Twin on enterprises' performance. Annual Reviews in Control	12,1	3	20	2019	53,01

4	DI NARDO M.D., FORINO D., MURINO T. 2020.The evolution of man–machine interaction: the role of human in Industry 4.0 paradigm. Production and Manufacturing Research	3,9	3	16	2020	52,00
5	TAYLOR M.P., BOXALL P., CHEN J.J.J., XU X., LIEW A., ADENIJI A. 2020.Operator 4.0 or Maker 1.0? Exploring the implications of Industrie 4.0 for innovation, safety and quality of work in small economies and enterprises. COMPUTERS & INDUSTRIAL ENGINEERING	7,9	3	14	2020	50,01
6	CHIARINI A. 2020.Industry 4.0, quality management and TQM world. A systematic literature review and a proposed agenda for further research.TQM Journal	4,3	3	12	2020	48,00
7	MATT, DT; ORZES, G; RAUCH, E; DALLASEGA, P 2020.Urban production - A socially sustainable factory concept to overcome shortcomings of qualified workers in smart SMEs . COMPUTERS & INDUSTRIAL ENGINEERING	7,9	3	11	2020	47,01
8	FLORES E., XU X., LU Y. 2020.Human Capital 4.0: a workforce competence typology for Industry 4.0 . Journal of Manufacturing Technology Management	8,4	3	9	2020	45,01
9	MUNOZ, A; MAHIQUES, X; SOLANES, JE; Marti, A; Gracia, L; Tornero, J 2019.Mixed reality-based user interface for quality control inspection of car body surfaces . JOURNAL OF MANUFACTURING SYSTEMS	12,7	3	11	2019	44,01
10	RUNJI J.M., LIN C.-Y. 2020.Markerless cooperative augmented reality-based smart manufacturing double-check system: Case of safe PCBA inspection following automatic optical inspection . Robotics and Computer-Integrated Manufacturing	12,5	3	7	2020	43,01

11	SZÁSZ L., DEMETER K., RÁCZ B.-G., LOSONCI D. 2021.Industry 4.0: a review and analysis of contingency and performance effects . Journal of Manufacturing Technology Management	8,4	3	2	2021	41,01
12	KANNAN K.S.P.N., GARAD A. 2021.Competencies of quality professionals in the era of industry 4.0: a case study of electronics manufacturer from Malaysia . International Journal of Quality and Reliability Management	4,2	3	2	2021	41,00
13	LOW,SP;GAO,S;Ng,EWL2021.Future-ready project and facility management graduates in Singapore for industry 4.0 Transforming mindsets and competencies. ENGINEERING CONSTRUCTION AND ARCHITECTURAL MANAGEMENT	4	3	2	2021	41,00
14	DUONG, MTH; NGUYEN, DV; NGUYEN, PT 2020.Using Fuzzy Approach to Model Skill Shortage in Vietnam's Labor Market in the Context of Industry 4.0 . ENGINEERING TECHNOLOGY & APPLIED SCIENCE RESEARCH	0	3	5	2020	41,00
15	HAO, RY; LU, BY; CHENG, Y; LI, X; HUANG, BQ 2021.A steel surface defect inspection approach towards smart industrial monitoring . JOURNAL OF INTELLIGENT MANUFACTURING	10,6	3	1	2021	40,01
16	DE ARAUJO, PRM; LINS, RG 2020.Computer vision system for workpiece referencing in three-axis machining centers . INTERNATIONAL JOURNAL OF ADVANCED MANUFACTURING TECHNOLOGY	5,6	3	4	2020	40,01
17	BABATUNDE O.K. 2020.Mapping the implications and competencies for Industry 4.0 to hard and soft total quality management. TQM Journal	4,3	3	4	2020	40,00

18	YADAV N., SHANKAR R., SINGH S.P. 2021.Critical success factors for lean six sigma in quality 4.0 . INTERNATIONAL JOURNAL OF QUALITY AND SERVICE SCIENCES	3,7	3	1	2021	40,00
19	BUCUR P.A., ARMBRUST P., HUNGERLÄNDER P. 2021.On the propagation of quality requirements for mechanical assemblies in industrial manufacturing. Expert Systems with Applications	12,7	3		2021	39,01
20	ZHOU H., YU K.-M., CHEN Y.-C., HSU H.-P. 2021.A Hybrid Feature Selection Method RFSTL for Manufacturing Quality Prediction Based on a High Dimensional Imbalanced Dataset . IEEE Access	4,8	3		2021	39,00

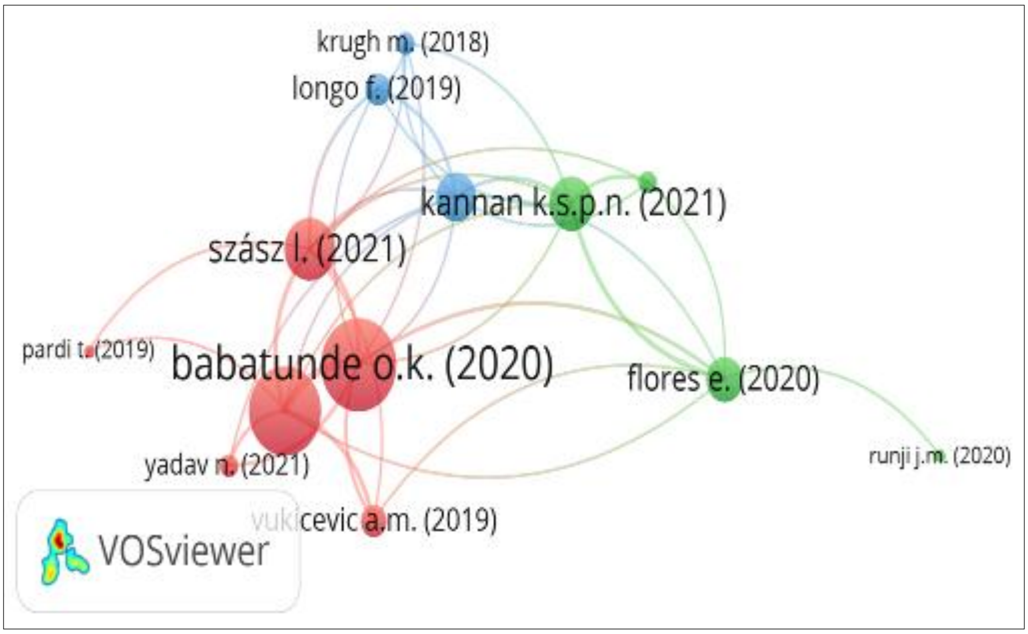
Source: The Authors (2021).

The same InOrdinatio-ranked list was used for bibliographic coupling analysis with VOSViewer, as shown in Figure 6. The generated map yielded interesting results by showing the relationships among the listed authors. For instance, cluster 1 (red) highlights a strong relationship among works addressing quality in Industry 4.0 concerning skills and labor. Notably, Babatunde's (2020) publication, "Mapping the implications and competencies for Industry 4.0 to hard and soft total quality management," stands out in this cluster alongside Chiarini's (2020) publication, "Industry 4.0, quality management and TQM world: A systematic literature review and a proposed agenda for further research."

Cluster 2 (green) prominently features Kannan & Garad (2021) with their work "Competencies of quality professionals in the era of Industry 4.0: A case study of an electronics manufacturer from Malaysia." This work is strongly linked to Flores, Xu, & Lu's (2020) "Human Capital 4.0: A workforce competence typology for Industry 4.0".

Finally, cluster 3 (blue) includes Di Nardo, Forino, & Murino's (2020) "The evolution of man-machine interaction: The role of humans in the Industry 4.0 paradigm." These highlighted publications in the clusters, ranked by link strength, appear in the InOrdinatio ranking as follows: Babatunde at 17, Chiarini at 6, Kannan & Garad at 12, Flores, Xu & Lu at 8, and Di Nardo, Forino & Murino at 4.

Figure 6 – Term map obtained from Scopus and WoS databases using search string [2] n=30 – Jun/2021



Source: VOSViewer 1.6.16 (Center for Science and Technology Studies, Leiden, Netherlands) Jun/2021.

The approach provided by the Methodi Ordinatio methodology enabled a quantitative and qualitative evaluation of the most relevant articles at the intersection of quality management and Industry 4.0. Table 5 presents detailed comments on the main articles identified by InOrdinatio and the VOSViewer instruction analysis. These comments provide insights into the central themes planned in each publication, such as human-machine interaction, mandatory competencies for quality professionals in the Industry 4.0 era, and the application of cyber-physical systems and artificial intelligence in quality management. The analysis highlights the diversity of approaches and perspectives in the area, highlighting the importance of technical, methodological, social, and personal skills for adaptation and success in the context of Industry 4.0.

Table 5 – Comments on articles related to InOrdinatio and citation analysis from VOSViewer

CI	Author , Title, Journal	Comments
4	DI NARDO M.D., FORINO D., MURINO T. 2020.The evolution of man–machine interaction: the role of human in Industry 4.0 paradigm . Production and Manufacturing Research	This article focuses on the nature of human-machine interaction, made possible by the Internet of Things (IoT) and Cyber-Physical Systems (CPS). These key Industry 4.0 technologies are examined in relation to the standard Deming cycle to underscore the importance of human-machine interaction. A new perspective that places the human at the center is proposed. The article introduces a new framework to explain the dependence of quality measures on the quality skills of the workforce and how this enhances the efficiency and effectiveness of an industrial process.
6	CHIARINI A. 2020.Industry 4.0, quality management and TQM world. A systematic literature review and a proposed agenda for further research . TQM Journal	Four categories of topics emerged: creating value within the company through quality (big) data, analytics, and artificial intelligence; developing Quality 4.0 skills and culture for quality personnel; co-creating value for the customer; and cyber-physical systems and ERP for quality assurance and control. This study also aimed to understand if there is a definition of Quality 4.0 based on specific methods.
8	FLORES E., XU X., LU Y. 2020.Human Capital 4.0: a workforce competence typology for Industry 4.0 . Journal of Manufacturing Technology Management	This study aimed to identify and address a significant shift for human capital in the future of Industry 4.0, proposing a human-centered perspective for companies under the new Industrial Revolution. Design/Methodology/Approach: The research study follows a state-of-the-art literature review process, presenting three relevant aspects for Industry 4.0 and its human workforce: a workforce architecture with new interactions, a term encompassing the future human capital, and a typology referencing the competencies required for Industry 4.0. Research Limitations/Implications: The article highlights an important aspect for the emerging Industrial Revolution: the human workforce.

12	KANNAN K.S.P.N., GARAD A. 2021.Competencies of quality professionals in the era of industry 4.0: a case study of electronics manufacturer from Malaysia . International Journal of Quality and Reliability Management	According to the author, quality professionals will be required to have technical competencies to interpret large amounts of process data for strategic decision-making, use new augmented reality tools, and be aware of data security risks. Methodological competencies will be necessary to use data to identify the root causes of problems, access reliable learning sources, and utilize new tools to efficiently solve complex problems. Social competencies will be demanded for interdisciplinary communications, interactions with suppliers and customers on new collaborative virtual platforms, and the ability to retain tacit and explicit knowledge in a decentralized environment that requires leadership skills for decision-making. Personal competencies will include the ability to work in flexible workplaces and schedules, and adapt to more frequent job-related changes. The quality professionals involved in this study were executives, quality engineers, and managers, regardless of gender, age, length of service, and experience in the quality field.
17	BABATUNDE O.K. 2020.Mapping the implications and competencies for Industry 4.0 to hard and soft total quality management . TQM Journal	The results validated the importance of the theory based on socio-technical systems for Industry 4.0 and the continued relevance of both hard and soft TQM for Industry 4.0. According to the authors, this study filled a gap by adapting an existing TQM matrix to map the essential implications and competencies for Industry 4.0. Therefore, the implications for research, practice, and society are significant. Academic institutions, human resources managers, TQM professionals, and researchers will find this approach beneficial.

Source: The Authors (2021).

4.2 Evolution and Future Directions of Quality Management in Industry 4.0

This study provides an examination of the progression and future direction of quality management within the framework of Industry 4.0, emphasizing the critical shift towards Quality 4.0. The historical evolution of quality management is documented, tracing its roots from the era of mass production, when the primary focus was on quality inspection, to the modern-day, when complex technologies drive quality assurance processes. This historical perspective sets the stage for understanding the transformative potential of Quality 4.0, which integrates advanced technologies such as IoT, AI, Big Data, and Robotics to enhance product and service quality. The transition from traditional quality management techniques to these advanced, data-driven methods signifies a paradigm shift that is central to the ongoing industrial revolution.

The results detail the skills and competencies required of professionals operating within the context of Industry 4.0. The findings underscore the increasing demand for skills such as analytical thinking, critical thinking, innovation, and complex problem-solving. These skills are crucial as they enable professionals to navigate and to leverage the sophisticated technologies that characterize Industry 4.0. The ability to work with advanced ICT technologies and perform comprehensive data analysis is highlighted as particularly vital for quality professionals. This shift towards a more analytical and technologically adept workforce reflects the broader changes in the industrial landscape, where data and technology play pivotal roles in ensuring quality and efficiency.

The use of bibliometric techniques and tools such as VOSViewer and Methodi Ordinatio in this study provides a structured and quantitative understanding of the research landscape related to Quality 4.0 and Industry 4.0. By employing these tools, the study maps out key journals, authors, and recurrent themes, thereby offering a detailed overview of the field's development. The keyword and term co-occurrence maps generated through VOSViewer reveal significant clusters and interconnections among topics related to both Quality 4.0 and Industry 4.0, illustrating the multidisciplinary nature of this research area. This bibliometric analysis not only identifies the most influential works and authors but also highlights the evolving trends and focal points within the literature.

Furthermore, the application of the Methodi Ordinatio methodology adds an additional layer of rigor to the literature review process. This methodology integrates impact factor, citation count, and publication year to rank the scientific papers, ensuring that the most influential and relevant studies are prioritized early in the research process. By providing a quantitative classification of the literature, Methodi Ordinatio helps to identify pivotal studies that have shaped the field of Quality 4.0. This approach is particularly useful for new researchers, offering them a clear understanding of the field's structure and the key contributions that have driven its development.

Despite the analysis, the study identifies a notable gap in the existing literature concerning the specific skills and competencies needed for quality management in the context of Industry 4.0. The keyword analyses reveal a conspicuous absence of terms directly related to professional skills and competencies, highlighting an area that requires further exploration. This gap underscores the need for future research to delve deeper into the professional profiles required to meet the demands of Industry 4.0. Addressing this gap presents an opportunity to develop more targeted and comprehensive understanding of the competencies necessary for quality professionals in this new industrial era.

The implications of these findings for practice are profound. There is a clear need for innovative educational programs at various levels to equip future professionals with the necessary skills for Industry 4.0. Lifelong learning and workplace training strategies should be emphasized to ensure continuous skill development and adaptability to technological advancements. Companies must also adapt their organizational strategies to incorporate the technological and cultural changes brought about by Industry 4.0. This includes fostering an environment that supports continuous learning and the integration of advanced technologies into quality management practices.

Moreover, as the role of human-machine interaction becomes more prominent in Industry 4.0, organizations need to develop frameworks that place humans at the center of quality management processes. Enhancing the interface between human skills and technological capabilities is crucial for achieving higher efficiency and effectiveness in quality management. This involves not only training professionals to use advanced technologies but also fostering a culture of innovation and adaptability.

A further aspect emerging from the literature concerns the evolving identity of the quality professional. Instead of operating mainly as inspectors, these professionals increasingly act as data-driven strategists and facilitators. Evidence from Kannan and Garad (2021) shows that quality roles now require technical abilities such as interpreting large volumes of process data, working with digital tools, and understanding information-security risks. In parallel, Flores, Xu, and Lu (2020) present how Human Capital 4.0 reshapes workforce expectations by combining digital literacy, analytical reasoning, and new forms of human–technology interaction. As a result, the quality function becomes more integrative and human-centered, with professionals expected to navigate complex data environments while coordinating cross-functional collaboration and supporting organizational adaptation.

The discussion around Industry 4.0 often brings up a rather practical point: the skills required in this context depend heavily on how people are educated and trained. Several companies still mention difficulties in preparing their teams for routines that involve digital systems, which suggests that the training currently offered does not always match the technological environment they are trying to adopt (Faria et al., 2017). These competencies are not limited to technical abilities, but also involve methodological, social, and personal dimensions essential for decision-making in data-rich contexts (Sallati, Bertazzi, and Schützer, 2019). However, these digital competencies related to digital literacy, analytical reasoning, and more integrated interaction with technology do not tend to emerge naturally from traditional, lecture-oriented teaching (Flores, Xu and Lu, 2020). Learning factories and virtual production environments have been recognized as effective mechanisms for connecting theoretical instruction with realistic industrial scenarios (Abele et al., 2015; Tisch and Metternich, 2017). As manufacturing shifts toward digitally mediated workflows, education must evolve accordingly, preparing future quality professionals to operate in hybrid physical-digital settings and to interpret complex system behaviors rather than relying solely on traditional inspection routines (Umeda et al., 2019; Liljaniemi and Paavilainen, 2020). When these elements are viewed together, a recurring idea emerges, preparing quality professionals for Industry 4.0 benefits when theoretical content is combined with practical exposure to digital tools and situations that resemble real work, rather than relying mainly on conventional instruction.

Practical studies identified in the review also help to show how Industry 4.0 tools have been finding space in day-to-day quality activities. One example appears in Vukicevic et al. (2019), who describe the use of a vision-based system to carry out the dimensional inspection of extruded rubber profiles in the automotive sector. The authors report gains in consistency and a decrease in manual effort, which is still common in many inspection routines. A different application is presented by Bucur, Armbrust and Hungerländer (2021). Working with vibroacoustic data from mechanical assemblies, they applied heuristic optimization to support predictive actions and were able to markedly reduce scrap levels by almost half in the case studied. Although these studies focus on different processes, both show that the movement toward Quality 4.0 is already materializing in practice, with digital inspection, analytics, and predictive logic gradually expanding the way quality is carried out on the shop floor. To consolidate these findings and provide a clearer view of how literature positions Quality 4.0 in terms of competencies, technologies, and practical implications, Table 6 summarizes the main insights identified across the reviewed publications.

Table 6 – Overview of Competencies Required for Quality Management in Industry 4.0

Dimension	Main Insights from the reviewed articles	Observed Implications	Sources
Competencies	• Handling data and extracting what really matters; • Problem-solving associated with structured methods; • Communication and adaptability.	Quality work is moving away from pure inspection toward tasks that require more interpretation and coordination.	Kannan & Garad (2021); Flores et al. (2020); Babatunde (2020)
Industry 4.0-related abilities	• Some skills depend on the digital tools used (CPS/IoT, AR/MR, digital twins, automated inspection); • Learning curves vary by tool.	Professionals need to know what the tools produce and how this helps reliability or early detection.	Peruzzini & Pellicciari (2017); Krugh & Mears (2018); Longo et al. (2019); Munoz et al. (2019)
Human–technology interaction	• Human resource capital; • Mix of digital literacy and situational awareness.	Quality decisions rely more on interpreting system outputs than on manual inspection alone.	Di Nardo et al. (2020); Taylor et al. (2020); Flores et al. (2020)
Skills found in applications	• Reading digital signals (e.g., vibroacoustic); • Setting automated inspection routines; • Understanding heuristic models used in some studies.	More consistent inspection, earlier detection of issues, and reduction of scrap.	Vukicevic et al. (2019); Bucur et al. (2021)
Organizational skills	• Updated TQM thinking and digital-transformation work; • Big data and AI linked to decision-making.	Connects daily quality tasks with the organization's digital strategies.	Chiarini (2020); Babatunde (2020); Yadav et al. (2021)

Source: The Authors (2021).

5 CONCLUSION

This study reviewed how Industry 4.0 has been affecting quality management and what this shift means for the competencies expected from professionals in the field. The use of VOSViewer together with the Methodi Ordinatio helped organize a literature base that was otherwise very dispersed, making it possible to see more clearly which themes and authors have been shaping the debate. The review also shows that competencies usually treated separately in the literature tend to form a more coherent group when viewed through the lens of Quality 4.0, especially when technical, methodological, social, and personal aspects are related to the types of digital tools and work practices now common in industry.

One practical contribution of the study is that the competency groups summarized in Table 6 give a more concrete picture of what quality professionals are expected to handle in data-rich environments. This includes not only analytical tasks but also the ability to work across human-technology interfaces and to coordinate activities in settings where digital and physical elements overlap.

Another point emerging from the review is that the development of these competencies depends heavily on how organizations and educational programs prepare their professionals. Much of the literature notes that traditional training does not always reflect digital work routines, which helps explain the difficulties reported by companies adopting Industry 4.0 tools.

Regarding future work, some directions follow naturally from the gaps identified. Empirical studies could examine how these competencies appear in practice in different industrial sectors, or how organizations support their development over time. There is also room for studies that test training approaches or models for assessing the competencies mapped in the review. Sectors such as services or smaller firms also offer further opportunities for investigation.

Overall, the points discussed here outline how quality management is changing and provide a basis for future investigations into the competencies required in digital production environments.

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