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Research trends and trajectories in quality management in the age of Industry 4.0 – the current state of knowledge

1. Introduction

There has been a major shift towards automation and digitization in all business processes, related to the development of Industry 4.0 (Clancy et al. 2023). Digitalization can help reduce uncertainty in business processes and manage environmental complexity. Specifically, it can contribute to cost reduction, improved organisational efficiency and performance, increased output quantity and quality, decreased lead time, enhance customer responsiveness, competitiveness, business growth sustainability, smoother information flow and better customisation capabilities (Margherita et al. 2022; Broday 2022; Mtotywa 2022; Agarwal et al. 2022; Antony et al. 2023; Sureeyatanapas et al. 2023; Psomas et al. 2023). Additionally, tasks performed by people become automated, almost entirely eliminating human participation (de Souza et al. 2022).

To gain competitive advantage, companies must adapt to environmental changes and address current challenges in deploying Industry 4.0 (Csiki et al. 2023; de Souza et al. 2022; Majernik et al. 2023). This also includes the area of quality management. Technological advances and increased environmental turbulence require a transition in quality management (Mtotywa 2022). Although the Industry 4.0 concept has recently gained significant attention from academics and practitioners, it remains relatively a new area of research requiring further in-depth study, particularly within the field of quality management. Specifically, research on Quality 4.0 has gained traction in the last few years, driven by technological advances linked with Industry 4.0 technologies, as well as the COVID-19 pandemic,

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which changed the face of society and the workplace (Mtotywa 2022). For example, authors have called for an exploration of how Industry 4.0 technologies support workers' engagement in soft total quality management practices for organisational performance or how Industry 4.0 impact organisational performance indicators (Yadav et al. 2020; Margherita et al. 2022).

Given the lack of recognition of the developmental trajectories of scientific research themes on quality management in the context of Industry 4.0, a research gap was identified in this field. For example, it is not clear what is the current state of knowledge on quality management in the age of Industry 4.0: How has the research area developed over a time? Are there distinct phases, trends, or turning points? What are the future research directions and trajectories?

Additionally, the emergence of a new area for research in quality management, related to the development of up-to-date technologies connected with digitalization, requires further exploitation through intensive research and description. According to Kumar et al., there is a need for research in this area, because research on Quality 4.0, in the larger context of Industry 4.0, is still in its nascent stage (Kumar et al. 2022). There is also a need for tools that facilitate management in the context of Industry 4.0 (Montoya-Quintero et al. 2022). Antony et al. also emphasised that Quality 4.0 is still an understudied area (an emerging and nascent area) and there is a lack of studies in terms of understanding the effect of Quality 4.0 on other quality management tools and methodologies or on quality costs or on financial performance (Antony et al. 2023).

A strong, dynamic increase in the number of publications that have been recently published on Industry 4.0 in a context of different areas, can also be observed. However, there is still a lack of studies specifically on quality management field in the age of Industry 4.0. According to Yildirim et al. the lack of the accumulated theoretical approaches or applications means that today organisations have to follow intuitive methods where the digitalization ideas emerge from "a black box", rather than analysing the actual needs of the organisation's strategies and processes (Yildirim et al. 2022). Therefore, this field requires detailed examination. Although new studies have been recently published, they were not included in previous publications and literature reviews. Consequently, they could deliver new relevant research results and therefore should be taken into consideration promptly. There are also publications where the authors are aware that their studies are only a beginning of research and their results can be used to deepen knowledge in further studies. For example, Ferrigno et al. collected the dataset through Scopus and indicated that other databases, such as Web of Science, can be used to deepen the focus of quantitative bibliometric analysis (Ferrigno et al. 2023). As a consequence, the following questions arise: What is the current state of knowledge on quality management in the age of Industry 4.0? What are the

main themes and trends in this field? What are the future research directions and trajectories?

To address this gap in the literature, this study provide an overview of relevant themes on quality management in the age of Industry 4.0, trace research themes' evolution and evaluate the state of knowledge on this topic. Especially, it indicates trends and trajectories in current quality management field. The study is based on articles published in two leading databases: Web of Science (WoS) and Scopus, in field of quality management and Industry 4.0, published up to the end of 2023, using literature review methodology based on bibliometric analysis, especially word co-occurrence analysis and longitudinal thematic map analysis, aiming to answer the following main questions: (1) How did scientific production on quality management in Industry 4.0 grow in recent years? (2) What main themes in literature on quality management in age of Industry 4.0 did emerge till the end of 2023? (3) How did these themes evolve through the studied period? (4) What are the future research directions (trajectories)?

The paper is structured as follows. In Section 2 theoretical background regarding quality management and its evolution is presented; Industry 4.0 and technologies specific to changing ages; and the interactions between them. Section 3 includes an overview of the research methodology indicating the applied research strategy and research protocol with data gathering procedure. Section 4 provides detailed description of research results. It includes results of the analysis of the most relevant sources of publications, the most relevant authors, and also a word cloud analysis, as well as a co-word network analysis to trace the most relevant themes, trends, documents, and asses thematic evolution over time. First part of this section deals with the base research results, the second one enlarges previous results to broader view. The final Section 5 includes conclusions of this publication, research limitations and future research directions.

2. Theoretical background

2.1. Quality management

The quality management field has been studied for more than 100 years (Hamid et al. 2019). Observing its development, the concept of quality has clearly changed over time, with the focus initially being on the quality control process. Inspections were therefore the primary interest of practitioners and researchers aiming to detect a defect or deficiency in the product, which later evolved into eliminating the cause of the defects (Park et al. 2019; Park et al. 2017; Mtotywa 2022). Over time, quality control was replaced by quality assurance.

Subsequently, Total Quality Management (TQM) emerged as a phenomenon in the 1980s and has continued to evolve to this day.

TQM refers to a quality-focused management method based on the engagement of all employees, aiming for long-term success by prioritising the customer and offering benefits to the organisation and society, and is a recognised, sustainable application for competitive advantage (Mtotywa 2022).

In fact, it has recently entered a new breakthrough stage, related to digitalization development (Quality 4.0). According to Park et al. there are four stages of quality development with different goals and strategies (Park et al. 2017; Park et al. 2019). The changes in quality goals are as follows: quality control (QC), quality assurance (QA) and quality management (QM), management quality (MQ) and quality responsibility (QR). Additionally, there are quality strategies aligned with these quality goals, which can be described as follows: inspection, audit standard, innovation, open quality. In particular, the importance of the last stage is underlined by authors in the field. It shows that the recent research focus should be aimed to clarify the responsibility (or accountability) of quality (Park et al. 2017; Park et al. 2019).

Although enterprises can use different tools to deal with some problems more properly, a lot of difficulties from the past still exist and require new solutions (e.g. customer satisfaction). This explains the demand for new technologies and attempts to implement them also in the quality management field. Therefore, academics and practitioners have recently developed a new quality concept called Quality 4.0. This new concept emerged in response to a changing environment, particularly due to advancements in technology, with the previous understanding of quality concept being modified and aligned with the challenges and requirements brought by Industry 4.0. Therefore, Quality 4.0 is in the spotlight of many researchers and their publications in leading international journals (e.g., Bandeira da Silva et al. 2023; Broday 2022; Carvalho et al. 2021b; Jakovic et al. 2023; Khourshed et al. 2023; Kumar at al. 2022; Maganga et al. 2023a, 2023b, 2023c; Sony et al. 2020; Sony et al. 2021; Thekkoote 2022; Wawak et al. 2023; Yadav et al. 2021).

This relatively new concept refers to the digitalization process that aims to cover almost all areas of modern enterprises functioning in the contemporary environment, including the quality management field. In fact, the impact of digitalization process on quality management is crucial to the competitive advantage of each enterprise. Chiarini emphasizes that Quality 4.0 refers to the digitalization of quality of design, quality of conformance and quality of performance using modern technologies (Chiarini 2020). Moreover, he notes that it focuses on connectedness, intelligence and automation to improve performance and timely data-driven decision-making, engaging all stakeholders and providing greater

transparency (Jamkhaneh et al. 2022a). Maganga et al. add that Quality 4.0 refers to a modern quality management approach that uses Industry 4.0 technologies, integration and digitalization (Maganga et al. 2023a).

Broday notices that it is time for Quality 4.0 or the concept of Digital Quality Management (DQM), which was introduced by Romero et al. in 2018 (Broday 2022). DQM refers to cyber-physical production assets through intelligent products, operators and machines and aims to provide information in real time according to pre-defined quality standards, alerting users to deviations that make the process generate non-compliance. This alignment allows companies to achieve higher quality, lower costs and decrease lead times (Broday 2022). In turn, according to de Souza et al., it is time for the new concept of TQM 4.0 as a way of adapting quality management in Industry 4.0 (de Souza et al. 2022). Although literature on Quality 4.0 phenomena is still evolving, researchers emphasise that it is mostly conceptual in nature, requiring further research (Prashar 2023ab).

2.2. Industry 4.0

To better understand the concept of the fourth industrial revolution (also called Industry 4.0 or 4IR), it is necessary to understand how industry has evolved from Industry 1.0 to Industry 4.0 and what the characteristics of each are. The four stages of the industrial revolution are aligned with different periods of time and production strategies (Park et al. 2019; Broday 2022). Industry 1.0 is connected with the age of steam; Industry 2.0 with the age of electricity, Industry 3.0 with age the of information and Industry 4.0 with cyber physical systems. Each era brings different challenges and responds to them in different ways. The question is: How have the key motor elements changed over time?

Mechanical manufacturing systems were the corresponding production strategies in the age of steam, meaning that machine production was crucial at that time. The next challenge was mass production, which was made possible by the discovery of electricity. After that, ICT systems and automation development was possible and led to a focus on lean production. Nowadays, the development of cyber physical systems has changed the rules on the market and is driving mass customization (Park et al. 2019). Significantly, the concept of Industry 4.0 was introduced in 2011 in Germany, as an initiative by the German Government to increase competitiveness through the use of innovative tools and technologies (Kumar et al. 2022). Since that time international journals have published several scientific studies on Industry 4.0, although an increase in interest in the quality management field in the age of Industry 4.0 has only been evident for the last few years (Mtotywa 2022).

According to Maganga et al. the Industry 4.0 involves multiple technologies: the Internet of things (IoT), machine learning (ML), artificial intelligence (AI), mixed reality (MR), virtual reality (VR), connected enterprise, augmented reality (AR), 3D printing, cloud storage, cloud computing, quantum computing, smart sensors, virtual factory, horizontal and vertical systems integration, autonomous robots, big data analytics, etc. (Maganga et al. 2023a). These new technologies have had a crucial impact on the corporate world and have dramatically changed previous approaches to business operations. The goal of Industry 4.0 is to transform industrial manufacturing through digitalization and exploit the potential of new technologies (Zulfiqar et al. 2023).

2.3. Quality management and Industry 4.0

In recent years, Industry 4.0 has become one of the most discussed topics by academics and professionals. Subsequently, the Quality 4.0 concept was created in the field of quality management in response to emerging environment changes that profoundly affected enterprise processes. In fact, with the technological advances and the advent of the Industry 4.0, the focus on quality shifted toward Quality 4.0 (Mtotywa 2022).

The use of new technologies appropriate to the current era is not an easy process, but rather a huge challenge at all times. Technological changes affect various segments of the economy and provide new modifications in business processes and become a source of new solutions. Therefore, the quality management field has changed dramatically over time and changes in priorities for improvements in processes and products can be traced. This refers to the changing understanding of quality and its evolution from Quality 1.0 to Quality 4.0 paralleling the development of industry.

Initially, quality was focused on craftsmanship, raw material, functionality and the understanding of quality was less standardized, and more subjective (Frick et al. 2023). In the mass production age, the concept of quality included consistency and uniformity in mass-produced goods and began a more systematized and standardized approach to quality. Consequentially, the interest moved from the defect detection process to proactive quality assurance, continuous process improvement and Total Quality Management (TQM). Afterwards, the shift was towards total customer satisfaction and experience — even exceeding customer expectations — along with innovation, waste reduction and efficiency improvement simultaneously. Finally, in the current age of digital transformation, the quality management field is focused on using advanced technologies to predict customer needs and personalize experiences on a large scale. It includes continuous monitoring, predictive analytics and real-time adjustments (Frick et al. 2023).

Broday indicates that Quality 4.0 refers to, inter alia, the digitalization of quality management, which aims to improve the culture, organization, skills and leadership of organization (Broday 2022).

All this means that the adoption of Industry 4.0 technologies may affect the quality management field in different ways and with varying degrees of intensity. They may allow enterprises to make current processes more efficient and accurate but also may lead to a reshaping of their business models through the process of implementation of innovations (Ferrigno et al. 2023). For example, the extremely fast development of artificial intelligence and its utilisation in business stands out from other new challenges, e.g. Chat GPT, as a free-to-use AI system, has only been available since 2022. Artificial intelligence (AI) and machine learning are used to define the product inspection strategy or regarding validation, they are utilized to reflect beneficial effects on industrial operations (Jokovic et al. 2023; Mtotywa 2022).

3. Methodology

A literature review methodology, based on bibliometric analysis, is believed to represent an appropriate solution to achieve the aims of this study. Thus to answer the research questions posed, a literature review engaging bibliometric analysis was conducted. As mentioned above, the selected methodology includes several detailed approaches such as: "an annual scientific production analysis", "a word cloud analysis" and "a co-word network analysis", to analyse the research field in depth.

According to Snyder, a literature review, as a research method, is more relevant than ever and can broadly be described as a more or less systematic way of collecting and synthesizing previous research (Snyder 2019). In particular, a systematic literature review is used for an exhaustive search of the past and current published papers on a research topic. In fact, bibliometric analyses are increasingly employed in literature reviews due to the technological development of tools that can support broader, detailed analysis of publications. Consequently, it creates new study opportunities for researchers, previously unavailable and is an expression of technological development in science. Currently, bibliometric approaches are often used to identify emerging themes versus declining ones in the broader research field.

There are several steps that can be identified in the literature review process. According to Snyder, the process of conducting a literature review involves four phases: (1) designing the review, (2) conducting the review, (3) analysis, and (4) writing up the review (Snyder, 2019). Based on this approach, the literature review methodology process was created and applied in this study (see Figure 1).

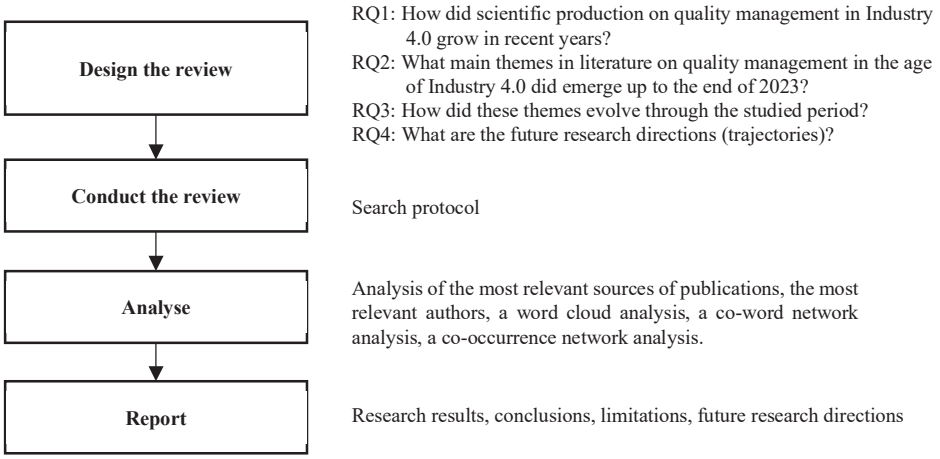

Figure 1. The literature review methodology process applied in this study

Management scholars can use different literature reviews as a research methodology. In particular, they can use approaches such as narrative or integrative reviews; systematic reviews, semi-systematic reviews and meta-analysis or morphological analysis (Snyder 2019; Prashar 2023a). There are many other forms of literature reviews which can combine different approaches or be adaptation of the first one (Snyder 2019; Palmatier 2018). The research strategy, performed in this study, was based on bibliometric review. Especially the open-source R-package called bibliometrix was used. This tool is used by scientists for quantitative research in scientometrics and bibliometrics. The tool was created by Aria and Cuccurullo and provides a set of tools for scientific research especially for science mapping (Aria, Cuccurullo 2017). This bibliometric analysis of scientific literature allowed to perform complete content analysis on the researched topic. The research allowed for the characterization of sources of publications, time of publication, main authors, leading topics, etc.

The research combines results from two sources and therefore consists of two parts. In the first part, the publications included in Web of Science (WoS) database were involved. WoS includes several relevant literature databases supported scientific and scholarly research. Journals in this database are globally recognized by the scientific community as the most essential for publishing and include the most relevant research results, thus this was the reason for the selection of this database. To build the research sample, papers from the WoS database were selected. Initially the research was based on three main keywords:

"quality management", "industry 4" and "fourth industrial revolution". Due to the large number of results, the search was limited to two combinations of keywords. Keywords involved in this research were combine with each other as follows: "quality management" AND "industry 4", "quality management" AND "fourth industrial revolution". Subsequently, the following exclusion criteria were incorporated: only two WoS Categories (Management, Business), English language only, and only article, proceeding paper and review article document types. Then the results were reviewed and duplicate documents were removed. Next, abstracts of these papers were reviewed to ensure the analysis focused on the field of quality management in Industry 4.0 and on this basis articles suitable for bibliometric analysis were identified.

In the second part, the research was expanded and previous results were confronted with the results coming from a search of a second database, SCOPUS. Scopus provides a comprehensive overview of worldwide research output in different fields and includes scientific journals, books, and conference proceedings. The reason for searching documents in the second database was a desire to widen the research results and confront them with a broader view. The searches on the databases ware done in the fourth quarter of 2023 year and updated in January 2024. The whole incorporated search protocol can be seen in Figure 2.

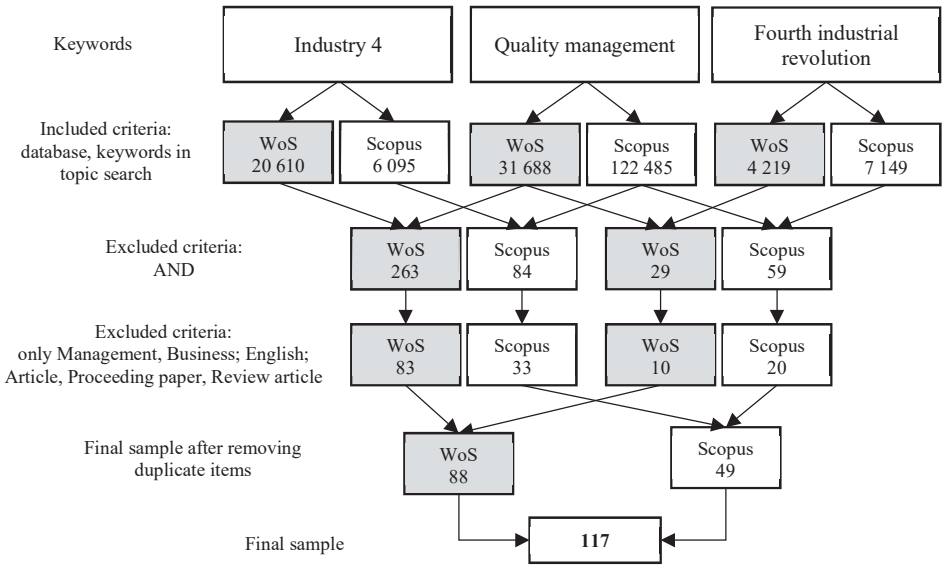

Figure 2. Web of Science and Scopus search protocol

Appendix 1 presents a list of publications selected for the study and sorted by date. Afterwards the papers were loaded into the bibliometrix tool and the content analysis was carried out. This means that the final samples, with selected papers, were evaluated and the results of this assessment are presented in the next section of this paper. Additionally, the presentation of research results was divided into three particular subject subsections: research results review (4.1); research results of word cloud analysis (4.2); research results of co-word network analysis (4.3). Each subsection contains results based on both databases.

4. Research results

4.1. Research results review based on Web of Science and Scopus

Based on three main keywords: "quality management", "industry 4" and "the fourth industrial revolution" and through the combination of these keywords, 88 papers were selected from the WoS database and 49 papers from Scopus database. Table 1 present the results of the descriptive analysis of selected publications from both databases.

Table 1

Results review from WoS and Scopus databases

Description	WoS results	Scopus results
Documents	88	49
Timespan	2017–2023	2016–2023
Document types	article (53), article; early access (13), article, proceedings paper (2), proceedings paper (9), review (10), review; early access (1)	article (32), conference paper (11), review (6)
Average citations per doc	13.88	13.39
Sources (journals, books, etc)	36	25
Authors	221	142
Authors of single-authored docs	8	6
Co-authors per doc	2.86	3.18
International co-authorships [%]	28.41	26.53
References	5026	–
Author's keywords	325	168

The analysis of the data obtained from WoS shows that all documents were dated from 2017 to 2023, although there was no time limit applied in the research. The year 2011 is considered to be a starting point for Industry 4.0, thus it is surprising that no publications linking it to quality management were found from earlier than 2017. It was expected that the first publications would have appeared shortly after 2011 or within the first few years. This means that the concept of Industry 4.0 slowly entered the area of interest of quality management researchers. Interestingly, substantial growth of number of articles can be observed from 2022, approximately ten years after the term Industry 4.0 was first introduced, and is constantly growing. Figure 3 presents annual scientific production.

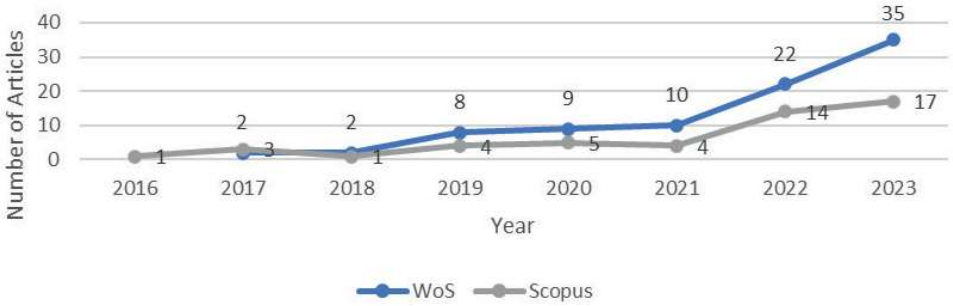

Figure 3. Annual scientific production

Similarly to the results from WoS, data from Scopus indicates that all papers were published between 2016 and 2023 and the number of publications increased substantially in 2022. This confirms that interest in the literature on quality management topic in the context of Industry 4.0 emerged relatively recently (since 2017 in WoS, since 2016 in Scopus) and indicates a great potential that is still not being fully exploited.

Research results also indicate that among gathered documents there are different types of publication. Most of them are articles (WoS – 66, Scopus – 32), but there are also proceeding papers (WoS – 11, Scopus – 11) and reviews (WoS – 11, Scopus – 6). Average citations per document is 13,88 in WoS and 13,39 in Scopus.

All of the selected documents come from 36 different sources, but only ten have published more than one paper (see Figure 4). Among them are many well-known in quality management scientific world international journals which published articles on researched topics.

In WoS, the most relevant source is the *TQM Journal* (with 21 articles). At the top are also: *Total Quality Management and Business Excellence* (with 10 articles)

and International Journal of Quality and Service Sciences (with nine articles). These journals are among the most relevant sources examining the relationship between quality management and Industry 4.0. In Scopus, all of the selected papers were published in 25 different sources (e.g., journals, proceedings), in total. Only seven of them published more than one selected document. Surprisingly, the most relevant source was Proceedings on Engineering Science (10 articles). Although the Scopus database also contains other journals typical for the quality management research field, they turned out to be far behind. This is probably due to greater interest in proceedings, on the one hand, and the topic of Industry 4.0, on the other. Other important sources were: *Total Quality Management and Business Excellence* (five articles), *International Journal of Quality and Reliability Management* (four articles), *International Journal of Quality and Service Sciences* (four articles), Proceedings of the International Conference on Industrial Engineering and Operations Management (three articles) and *TQM Journal* (three articles).

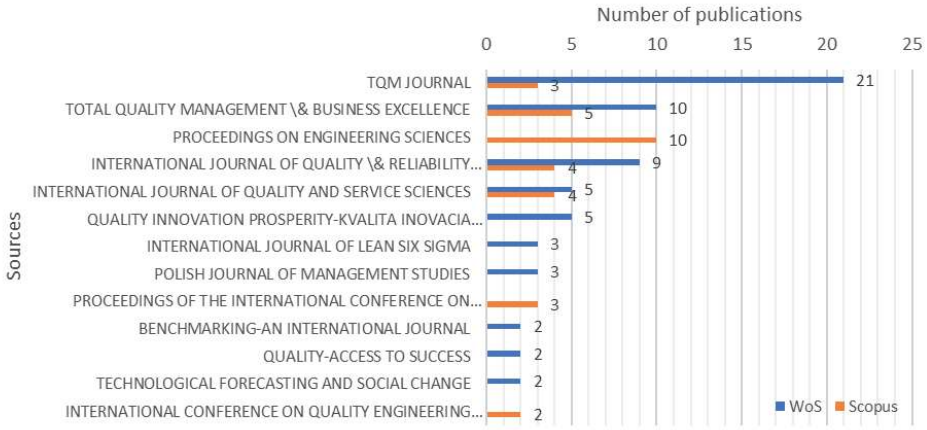

Figure 4. Most relevant sources

Additionally, it is worth noting that the publication dynamics of three leading international journals indexed in WoS are notably high and clearly distinguishable from other sources (see Figure 5).

In contrast to the research results based on the WoS database, Scopus indicates that the production dynamic of leading sources is not so high, apart from Proceedings on Engineering Science, with greater growth in 2023 (Fig. 6).

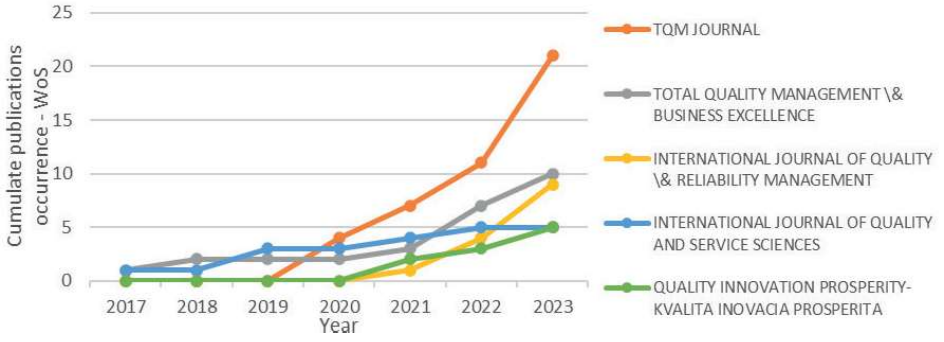

Figure 5. Source growth of publications – WoS

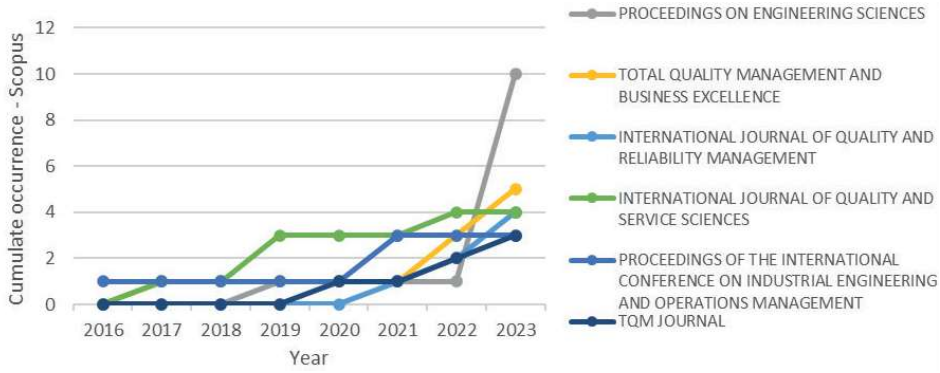

Figure 6. Source growth of publications – Scopus

There are 221 people involved in authorship of 88 selected documents from WoS database. It means that there are 2,86 co-authors per document (circa 28% is international co-authorships). Among them, eight individuals appear as the authors of sole-authored publications. In the Scopus database, 142 authors of selected publications were identified which indicates 3,18 authors per document, with six sole-authored documents and nearly 27% of the international co-authorships.

In WoS, the most relevant corresponding author's countries are: India and United Kingdom. Research based on WoS shows that Antony (with six publications), Sony (with four publications) and Maganga, Sampaio and Taifa (with three publications) have the highest productivity during the researched period (Fig. 7). In Scopus, the analysis indicates that Savelyeva and Sozinowa are the

most relevant authors (four publications). Thus, the highest productivity in the Scopus database during the researched period was an author with four publication, which is similar to previous result (in WoS it was six), but no author appears in both databases at the same time. Eight authors published two papers and the other only one paper.

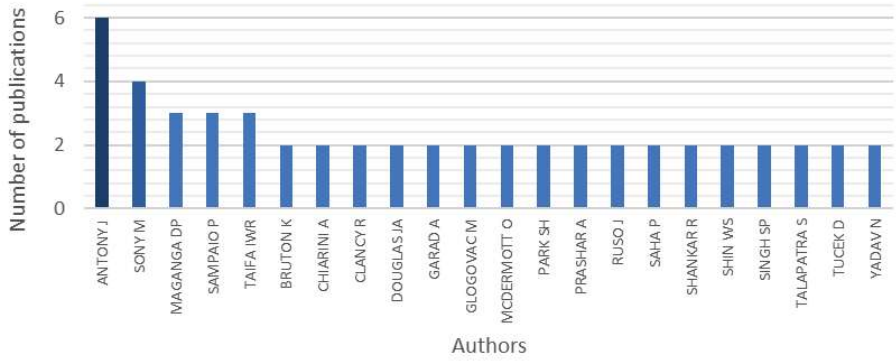

Figure 7. Most relevant authors

In addition, authors of researched publications from WoS database used 5026 references in total and provided 325 author's keywords. In comparison, authors provided 168 author keywords in Scopus.

4.2. Research results of word cloud analysis

The word cloud analysis was carried out after a short review of the most important data from selected documents, in order to detect the most used keywords in the selected documents. Word cloud is a classic text visualization technique and is widely applied in many situations in facilitating semantic understanding (Yang et al. 2020). In this case, word cloud analysis was used to highlight the most prevalent words in representative journals in the researched field.

Figure 8 presents the word cloud with the main keywords provided by the authors in selected documents. It presents collected data as a cloud where the words which are used most frequently are increased in size. It helps to quickly highlight keywords that came into focus in the selected documents. The bigger the word appears, the more often it is mentioned and this keyword is more significant than others.

In the research results from WoS, the biggest words are: "implementation", "quality management", "impact" and "framework", but there also appear

keywords such as: "industry 4.0", "industry", "big data", "total quality management", "performance", "big data analytics", "artificial-intelligence". The word size is proportional to word occurrence. It means, that the word cloud indicates important themes in selected documents and illustrates farness between significant themes in the middle of the word cloud and other themes outside. In this case, a relationship between quality management and other concepts related to Industry 4.0 can be observed, that is distinctive and relevant in this field.

a)

b)

Figure 8. Word clouds comparison – WoS (a) and Scopus (b)

Interestingly, the word cloud from selected documents from the Scopus database differs from previous one from WoS. In this case, the word cloud analysis shows that the most important and the most recent themes are Industry 4.0 and quality management. They are centrally located and are the largest words in the word cloud, therefore they are highly visible. Table 2 presents detailed data about the most frequent words used by the authors of selected documents in the WoS and Scopus databases.

Table 2

Most frequent words comparison

	Words	Occurrences	Words	Occurrences
WoS	implementation	19	industry	8
	quality management	16	firm performance, technologies	7
	impact	15	context, design, integration, sustainability, tqm	6
	framework	14	big data analytics, culture, total quality management	5

Table 2 cont.

	Words	Occur-rences	Words	Occur-rences
WoS	systems	13	analytics, barriers, business performance, challenges, maturity, methodology, organizations, system	4
	future, innovation	12		
	big data, performance	11	artificial-intelligence, iot, adoption, companies, knowledge, knowledge management, lean production, opportunities, servitization, technology, tools	3
	management, model	10		
	industry 4 0	9		
Scopus	industry 4 0	13	construction industry, customer satisfaction, information management, inspection, internet of things, management quality, project management, quality assurance, quality improvement, sustainable development, total quality management	2
	quality management	7		
	design/methodology/ approach, quality 4 0	4		
	artificial intelligence, competition, industrial research, industrial revolutions, literature reviews, quality control, surveys	3		

More information about thematic interest in a particular scientific field can provide also detailed co-word analysis presented below.

4.3. Research results of co-word network analysis

Co-word analysis uses the most important words or keywords of the documents to study the conceptual structure of a research field (Cobo et al. 2011). It can be used to quantify and visualize the thematic evolution of a scientific field. The results of co-word analysis include the results of the co-occurrence network analysis, the thematic map analysis, and the longitudinal thematic map analysis based on data derived from both of databases.

4.3.1. Co-occurrence network analysis

Figure 9 presents results of co-occurrence network analysis for keywords from selected documents based on the WoS database.

The co-word network analysis indicates nine clusters in total. Each colour represents a cluster of word (a "topic"). There are three relevant areas of topic

connections that noticeably stand out from the rest. They are focused on keywords such as: "implementation", "performance", "future", etc. (the first cluster shown in red); "impact", "framework", "innovation", "industry 4.0", etc. (the second cluster shown in blue) and quality management, systems, big data, etc. (the third cluster shown in green). The remaining clusters are: adoption, opportunities (the fourth cluster); methodology, environment (the fifth cluster); capabilities, dynamic (the sixth cluster); context, barriers (the seventh cluster); technology (the eighth cluster) and conceptual framework (the ninth cluster). In the context of this research, clusters, pointed as second and third, are significant. Keywords such as: "quality management", "systems", "big data", "management", "industry", "technologies", "sustainability", "analytics", "artificial-intelligence", "IOT" (Internet of Things), "lean production" are close to each other because a large proportion of selected articles merge them together. The same applies to keywords such as: "impact", "framework", "innovation", "Industry 4.0", "firm performance", "integration", "big data analytics", "total quality management", "system", "knowledge", "knowledge management", "servitization", "tools".

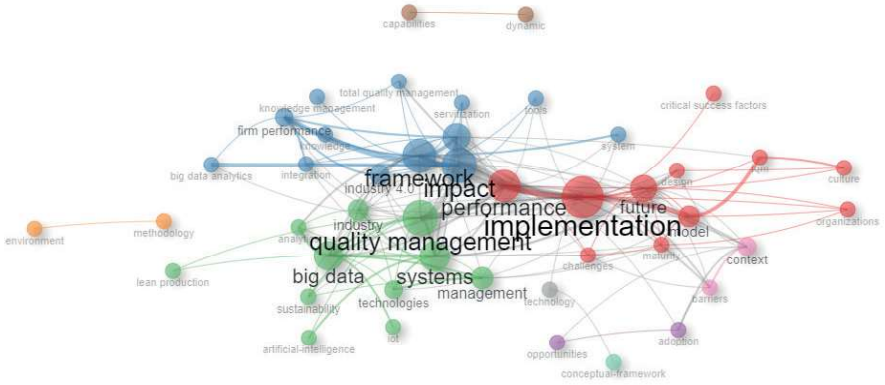

Figure 9. Co-occurrence network – based on WoS database

Similar to the research results based on WoS database, the results of co-word analysis based on Scopus database revealed several clusters, with two of them the largest. Figure 10 presents more detailed information on that analysis.

In total, co-word analysis confirmed the existence of four clusters containing the following main themes. The first cluster (blue cluster) includes: "Industry 4.0", "quality management", "Quality 4.0", "artificial intelligence", "competition", "literature reviews", "quality control", "customer satisfaction", "inspection", "internet of things", "management quality", "quality assurance", "quality improvement", "sustainable development. "

Figure 10. Co-occurrence network – based on Scopus database

Interesting is that the edge size between themes is the same apart from: (1) "quality management and Industry 4.0", (2) "Quality 4.0 and Industry 4.0", (3) "quality management and artificial intelligence", (4) "Industry 4.0 and design/methodology/approach". Due to the strength of the edges highlighting the co-occurrence of related themes, the four relationships identified could be indications for further research interest. The second cluster (the green cluster) merges such themes as: "industrial revolution", "total quality management", "industrial research and design/methodology/approach". The third focuses on construction industry and surveys. The final isolated cluster refers to information management and project management and does not possess any relationship with other themes.

Additionally, due to the fact that each identified cluster ("topic"/"theme") in this analysis can be represented on a plot, a particular plot known as Thematic map is presented below (Cobo et al. 2011). Consequentially, the thematic map was created by using centrality and density as the main measures, helping to shed new light on the results.

4.3.2. Thematic map analysis

A thematic map, known also as strategic diagram, is a two-dimensional space built by plotting themes according to different measures extracted using a post network analysis (Cobo et al. 2011). It highlights different topics of a given domain applying two different criteria: centrality and density. Centrality is understood as a measure of the topic's relevance and density is understood as a measure of the topic's development (Cobo et al. 2011). Figure 11 and Figure 12 present the results of the analysis performed.

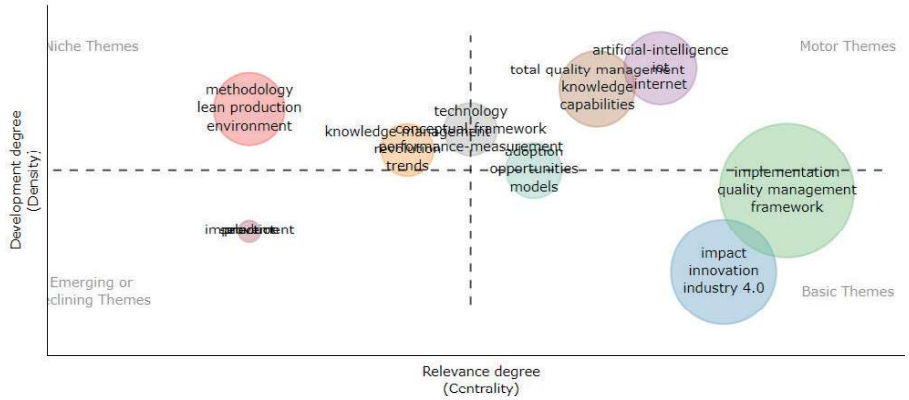

Figure 11. Thematic map based on WoS

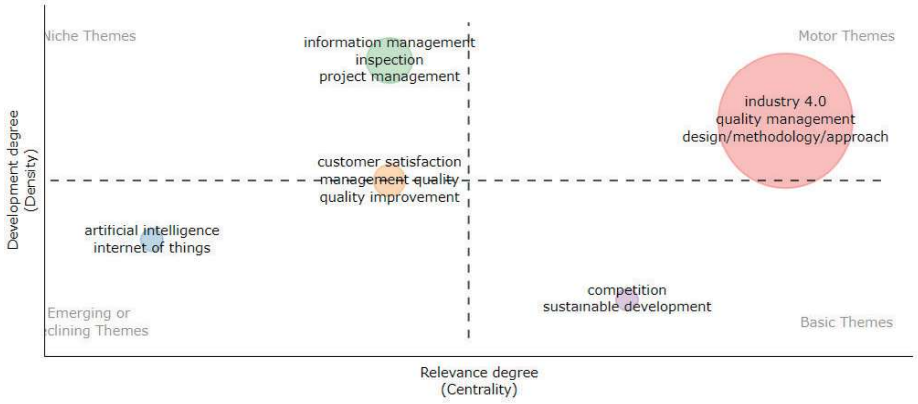

Figure 12. Thematic map based on Scopus

Each bubble represents a different cluster. The bubble size is proportional to the cluster word occurrences. There are four different domains presented in Figure 10 and Figure 11, and they are termed as follows: niche themes (highly developed and isolated themes), emerging or declining themes, basic and transversal themes, and motor themes. There are several clusters in each domain in both figures. In Figure 11, significantly relevant clusters are in the two domains on the right side of the chart. They are the driving force in contemporary research topics. Two clusters in the field of basic themes are the largest. They include concept such as: "quality management" and "Industry 4.0". Basic themes signifies that there is a great potential for further development in these areas. These concepts can be

widely known and extensively used by both academics and researchers in the foreseeable future and over time they may become motor themes. On the other hand, concepts such as: "total quality management", "knowledge", "Artificial-Intelligence (AI)", "Internet of Things", "Internet" currently occur as motor themes. This means that a significant portion of publications are actually focused around these themes, representing current topics of interest.

Figure 12 provides a detailed analysis highlighting the appearance of specific cluster with artificial-intelligence and internet of things which settled in the emerging themes field. Although the results derived from the Web of Science database emphasize the existence of a similar cluster, the results from Scopus shows that it appeared in an another field — as a motor theme. It signifies that this is a current science trend and the themes of AI and IoT will most certainly be the subject of interest of contemporary scientists in the quality management field in the foreseeable future. Secondly, it confirmed that the themes of quality management and Industry 4.0 are not the only motor themes, but also that customer satisfaction or quality improvement themes still should not be forgotten due to them emerging as emerging themes. There is a constant need for performing further research in these areas in context of developing technologies.

Sustainable development theme represented as a small bubble in the basic themes field also seems to be interesting. This shows the potential for further development of this theme although the bubble size, which is proportional to the cluster word occurrences, is not large. In addition, the sustainable theme was also recognised and noticed by researcher in publications from Web of Science. For example, the sustainable theme belongs to the biggest cluster on the thematic map in the domain of basic themes. This points to the fact that sustainable development as a theme might be advisable in future research, including in the quality management context.

4.3.3. Longitudinal thematic map analysis

The next step of this analysis was to trace topic evolution based on data from both WoS and Scopus databases and using a longitudinal thematic map analysis. To achieve this goal, the entire time span (2017–2023) in the WoS database was divided into different time slices. This allowed for studying and plotting the topic evolution. Based on the annual production of selected documents two breakthrough years were identified: 2020 and 2022. The first one is related to the beginning of the increase in the number of selected publications and at the same time the outbreak of the COVID-19 pandemic, and the second one is related to another observed dynamic increase in the production of selected publications. Using these two cutting points, three thematic maps with corresponding clusters can be observed (see Figure 13).

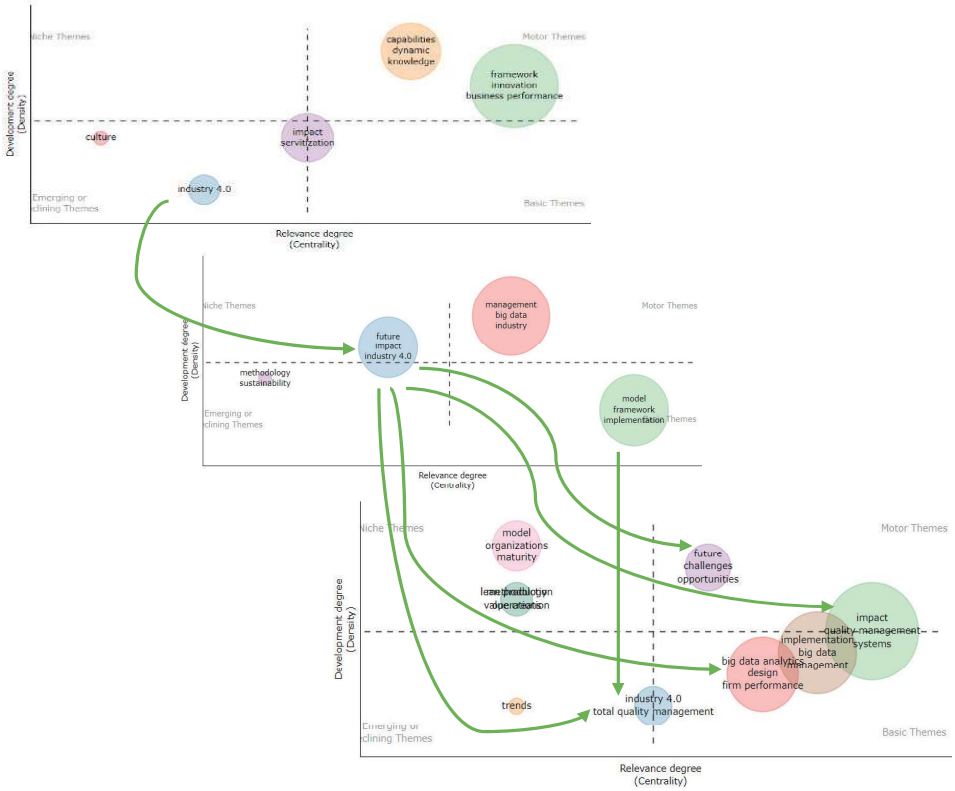

Figure 13. Thematic evolution – three time slices based on WoS database

The results of these three maps analysis shows the research trajectories in quality management and Industry 4.0. Most of all, the trace of evolution indicates that before 2020 year, the concept of Industry 4.0 in selected documents from WoS appeared as an emerging topic rather than something exploited on a broad scale. Then, between 2020 and 2022, the interest increased and slowly begun leaning towards leading, mainstream themes area. And finally, after 2022, it reached the basic themes field.

It is important to emphasize that the tendency of Industry 4.0 topic to divide into several themes can be observed. Significantly, visible is a split the one emerging cluster, identified in second time slice, into four other clusters, identified in the last time slice. It can be observed that it emerged between 2020 and 2022, and it concerned three main themes: future, impact and Industry 4.0. Subsequently, it split into four other clusters. Two of them are directly connected with leading

identified topics (future and impact) and the next two are the results of the further Industry 4.0 theme's split. Interestingly, all of them became fast a basic themes or even motor theme in the third time slice.

As mentioned before, the first theme, specified as "future", became a basis for creation of a new cluster in the last time slice with such themes as: "future", "challenges", "opportunities", etc. The second theme, namely "impact", created a foundation for the biggest cluster at the last thematic map and appeared as the new cluster between basic and motor themes. It means that theme's relevance and theme's development were relatively at a noticeably high level at that time. The next theme of mentioned cluster refers to "Industry 4.0". In this case, thematic evolution proved to be even more sophisticated and extensive. As a result, two clusters were established. The first one with themes such as: "Industry 4.0", "total quality management", etc. and the second one with the following themes: "big data analytics", "design", "firm performance", etc. It should be emphasised that their creation was related to other previous leading themes as well.

Looking at the distribution of publications per year in the Scopus database, however, a burst in publications occurred in 2021. Therefore, the whole collection of publications was only divided into two time slices setting one cutting point in 2021. This allowed us to plot, trace and study the topic evolution using a longitudinal thematic map analysis. On this basis, two thematic maps with corresponding clusters were created (Fig. 14).

Detailed analysis of the data indicated that before 2021 topics such as: "artificial intelligence", "Internet of Things", "quality", "digital transformation", "Quality 4.0" were niche themes rather than motor themes or basic themes. After 2021 this changed significantly. The digital competitiveness and total quality management topics became motor themes in publications from the Scopus database. Industry 4.0, Quality 4.0, quality management and sustainability topics appeared as basic themes. Additionally, total quality management topic that before 2021 occurred as emerging or declining theme (the left lower quadrant of the thematic map) evolved after 2021 and split into several themes directly connected with digitalization and Industry 4.0. It is worth emphasizing that at the same time there was a clear shift towards basic and motor themes. This means that there was a breakthrough in the development of TQM. The concept was renewed in the context of ongoing digitalization and gained importance again among researchers.

This aligns with results of conducted thematic evolution analysis based on data from WoS where quality management theme was rediscovered by researchers and faced many new challenges in the new contemporary context of Industry 4.0. Therefore, it is a good opportunity and also a great challenge for the researchers to develop and find new solutions incorporating an expansion of Industry 4.0 new technologies in quality management field and to move it forward.

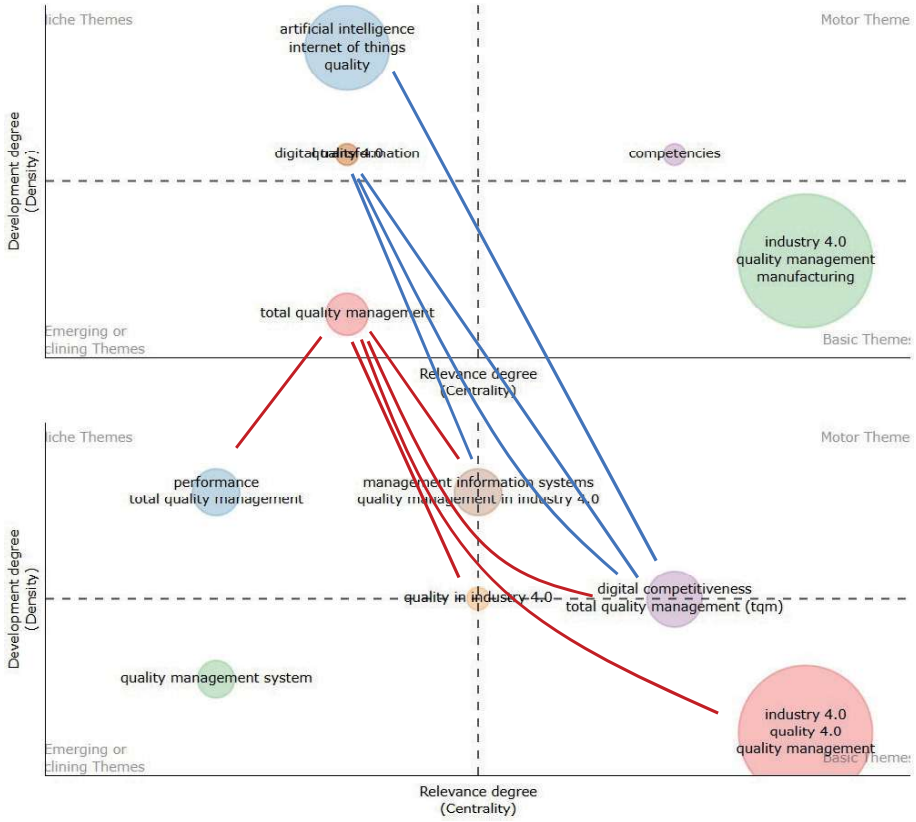

Figure 14. Thematic evolution – two time slices based on Scopus database

Furthermore, total quality management topic began to be linked to the performance topic and appeared as niche theme. Interestingly, the quality management systems appeared among the emerging topics. This may directly refer to the high level of the development (density) of the management information systems topic. This may also be linked to the search for effectiveness and efficiency in management using standardized management systems.

Research trajectories discovered in the analysis of thematic evolution can also be presented in a different way. Noticeably, they highlight the tendencies of some themes to split into other themes, but also to merge together. For instance, in WoS (see Figure 15) the cluster with Industry 4.0 and total quality management, etc. is based on two other previous clusters with themes such as: "future", "impact", "industry", "on the one hand and model", "framework", "implementation", etc., on the other.

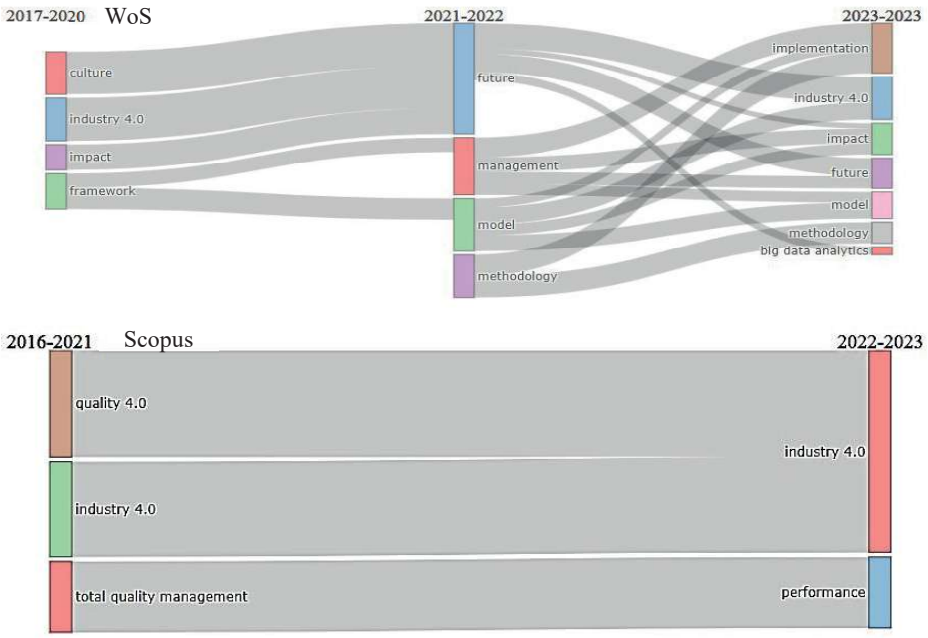

Figure 15. Thematic evolution – research trajectories based on WoS and Scopus databases

The results show also that the "future" theme seems to have been crucial during the years 2021 and 2022 and can be easily related to the COVID-19 pandemic situation at that time. Concerns about the future have become a leading topic for many researchers from various specialties. At the same time, this theme became a source for contemporary fields of interests and research topics such as Industry 4.0 or big data analytics. Results based on the Scopus data indicated that the quality 4.0 and Industry 4.0 themes merged together and the total quality management theme developed gradually into a more complex form enriched with the performance theme. Figure 14 presents all of the research trajectories identified.

Co-word network analysis may be supplemented by an analysis of the intellectual structure and social structure of the scientific research field. For example, co-citation analysis can be used to analyse the intellectual structure of a scientific research field (Cobo et al. 2011). However, due to the limited scope and length of this publication (i.e., the limited number of research questions addressed), the results of this particular analysis have not been included. Nonetheless, the findings did indicate the presence of two distinct and relevant clusters related to the themes of Quality 4.0 and Industry 4.0 (i.e. Zonnenshain et al. 2020; Gunasekaran et al. 2019).

The social structure of the scientific field was analysed with the use of collaboration network analysis. Generally, this can be performed by using different units of analysis in the author's affiliations: co-institution, co-university, or co-country (Cobo 2011). The results, by using the author's affiliations (co-country), indicate that the international dimension of this research is broad and wide. Nine clusters were identified with one standing out from the rest. It pointed to significant international collaboration among authors coming from India, United Kingdom, Ireland, South Africa, United Arab Emirates, Bangladesh, Namibia and the Netherlands. The detailed analysis also confirmed a close collaboration between e.g. M. Sony and J. Antony (Sony et al. 2020; Sony et al. 2021; Antony et al. 2022; Antony et al. 2023), which was reflected in the close collaboration between Liverpool John Moores University and Heriot–Watt University (Edinburgh, UK).

5. Conclusions, future research directions and research limitations

In this paper, a number of research questions were investigated. The first research question referred to scientific production on quality management in the age of Industry 4.0. The research results showed that a significant growth in the number of articles is observable from 2022, which was more than 10 years after the concept of Industry 4.0 was introduced in 2011. Interestingly, this production dynamic is constantly growing, and in last two years it increased dramatically and was at really high level compared to previous years. This provides the opportunity to gain a broader insight into areas of research interest, recent findings and further developments. The fact that all the publications selected for the study were dated from 2016 regarding Scopus database and from 2017 regarding Web of Science database was also surprising. This may confirm why there is currently a relatively high amount of interest in the literature in the results of the study on quality management in the age of Industry 4.0 (as in an unexplored field).

The second and third research question concerned the main themes that had emerged by the end of 2023 in literature on quality management in the age of Industry 4.0 as well as their evolution throughout the studied period. The research helped identify the number of themes from the published articles representing different stages of development in the literature.

The results showed that motor themes are directly linked with the theme of quality management and Industry 4.0. The research helped identify the following motor themes: "quality management", "Industry 4.0 and design/methodology/approach theme"; "the management, big data and industry theme"; and "the

future, challenges and opportunities theme". This is a promising and broad area of research that has begun to be strongly exploited by researchers and is reflected in the literature. There are also three relevant basic themes as: quality management, impact and system theme; implementation, big data and management theme; and big data analytics, design and firm performance theme. Artificial-Intelligence (AI), Internet of Things (IoT), sustainable development as well as customer satisfaction and quality improvements themes are included in the emerging themes. Finally, inspections and project management themes were identified as niche themes.

The evolution of different themes shows that in recent years it was possible to trace a tendency of some themes to split into other themes and also other to merge together. Especially, the results from the WoS database show themes which appeared as basic clusters of topics. For example, it led to the emergence of clusters such as: big data analysis theme in a context of design and firm performance theme or implementation theme with links to big data and management themes or impact theme connected with quality management and systems themes. These fields of interest were identified as basic themes. Additionally, the analysis performed on data from the Scopus database showed that there is one more field of interest, i.e. the sustainable development theme with competition that were identified as basic themes, as well. However, in turn, the results from the WoS database indicate that this theme is still an emerging field. Thus, there is no doubt that the sustainable theme has been recognised by researchers and has great potential for further development. Sustainable development as a theme should also be used in future research in the quality management context.

Artificial-Intelligence (AI) and Internet of Things (IoT) were identified as other emerging themes and it is expected that these new fruitful science trends will increase in importance in the quality management context in the coming years. Interestingly, the research results show that there are also some topics which may potentially become emerging themes, noticeably the customer satisfaction and quality improvements themes. Evolution analysis showed that the quality management theme was rediscovered by researchers and faces many new challenges in the context of Industry 4.0. New research gaps have emerged and fresh evidence and approaches are needed. Therefore, it is both a good opportunity and great challenge for researchers to develop and to find new solutions incorporating the expansion of new Industry 4.0 technologies in the quality management context. This includes customer satisfaction field or quality improvements. These are not new fields of interest but they have been enriched with new opportunities which can improve the quality management field and the whole organization.

The last research question referred to future research directions and trajectories. Figure 16 presents emerging trends and future research directions in quality management in the age of Industry 4.0.

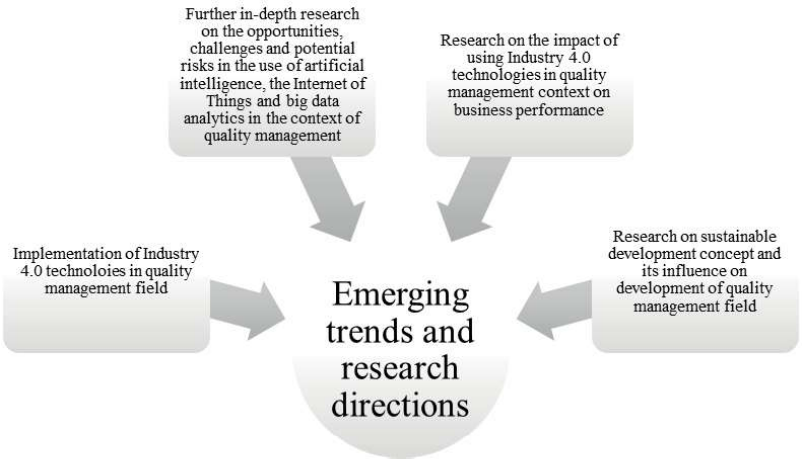

Figure 16. Emerging trends and research directions in quality management in the age of Industry 4.0

Based on the research results, the following emerging trends and future research directions can be indicated: (1) further research should concern the implementation of Industry 4.0 technologies in the quality management field, including basic and also more sophisticated available solutions; (2) using Artificial-Intelligence, Internet of Things and big data analytics in the quality management context requires further in-depth study with an indication of opportunities, challenges and potentially threats; (3) further research should also concern the impact of using Industry 4.0 technologies in the quality management context on business performance (4) additionally, further research should concern the sustainable development concept and its influence on the development of the quality management field.

This study is subject to the following four main limitations.

First, due to the large number of results, the search was limited to two specific combinations of keywords. Keywords involved to this research were combined with each other as follows: "quality management" AND "industry 4", "quality management" AND "fourth industrial revolution".

Secondly, the scientific literature included in the study is derived from two databases, namely Web of Science and Scopus. Therefore, the conducted research could be extended to include data from other databases, which may contribute to a more in-depth bibliometric analysis.

Moreover, several exclusion criteria were applied in this study, and a number of other publications may not have been included in the analysis. For example,

only papers written in English and limited to the fields of management and business were considered.

Lastly, due to the large scope of the different detailed analyses and the limited volume of publications, not all of the results were presented, i.e. the results of co-citation network analysis and historiographic mapping analysis were excluded from this publication.

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Summary

This study aims to analyse publication activity and identify development directions of scientific research themes in the area of enterprise quality management in the context of Industry 4.0, based on a bibliometric analysis of scientific literature from the Web of Science and Scopus databases up to the end of 2023. The article employs a systematic literature review method. The research included a bibliometric analysis of scientific literature sourced from the Web of Science and Scopus databases. Based on a predefined combination of keywords, a set of articles was selected, which – after initial screening and justified exclusions – was accepted for further analysis. The study enabled the characterization of, among others, publications production, sources of publications, time of publication, main authors and leading topics. Next, a word co-occurrence analysis and longitudinal thematic map analysis were conducted to examine the research field in depth and to identify research trends and trajectories in quality management in the age of Industry 4.0.The conducted research shows that the number of publications on quality management in the context of Industry 4.0 is constantly growing, and the topics are progressively evolving towards issues such as: the Internet of Things (IoT), Artificial Intelligence (AI), Big Data, digitalization. These technologies are seen as key enablers for enterprises to cope with the growing uncertainty and complexity of the business environment and to achieve a competitive advantage. The study indicates that AI, IoT, big data analytics, and sustainable development are among the most rapidly growing and prominent themes in the literature on quality management in the Industry 4.0 context. Identifying research gaps and potential directions for scientific development in the field of quality management may contribute to the creation or improvement of new tools, approaches, and concepts including those based on Industry 4.0 technologies.

JEL codes: L25, L15, M14, O14, Q56

Keywords: *quality management, Industry 4.0, Quality 4.0, Artificial-Intelligence (AI), Internet of Things (IoT), sustainability*

Appendix 1

List of publications selected for the study

Year	References
2016	Eleftheriadis et al. 2016
2017	Park et al. 2017; Schlter et al. 2017; Štofová et al. 2017
2018	Anttila et al. 2018; Demartini et al. 2018; Simion et al., 2018
2019	Beard-Gunter et al. 2019; Garad et al. 2019; Hake et al. 2019; Hamid et al. 2019; Martynov et al. 2019; Liczmanska-Kopcewicz et al. 2019; Park et al. 2019; Ralea et al. 2019; Stefanović et al. 2019; Trinks et al. 2019
2020	Angioni et al. 2020; Asif 2020; Beckers et al. 2020; Chiarini 2020; Ghobakhloo et al. 2020; Kisel'akova et al. 2020; Moldabekova et al. 2020; Skuza 2020; Sony et al. 2020; Vo et al. 2020; Tikhonov et al. 2020; Yadav et al. 2020
2021	Babatunde 2021; Carvalho et al. 2021; Carvalho et al. 2021a; Carvalho et al. 2021b; Corti et al. 2021; Efimova et al. 2021; Okwu et al. 2021; Kannan et al. 2021; Nguyen et al. 2021; Sony et al. 2021; Teplicka et al. 2021; U-Dominic et al. 2021; Vinodh et al. 2021; Yadav et al. 2021
2022	Agarwal et al. 2022, Aichouni et al. 2022; Ali et al. 2022; Balouei Jamkhaneh et al. 2022; Broday E.E. 2022; Clancy et al. 2022; de Souza et al. 2022; Elibal et al. 2022; Glogovac et al. 2022; Gyurak Babelova et al. 2022; Jamkhaneh et al. 2022a; Jamkhaneh et al. 2022b; Jamwal et al. 2022; Johannsen 2022; Kumar et al. 2022; Lardosa Rebelo et al. 2022; Margherita et al. 2022; Milosevic et al. 2022; Montoya-Quintero et al. 2022; Mtotywa 2022; Nasir et al. 2022; Ranjith et al. 2022; Sader et al. 2022; Santhi et al. 2022; Schmied et al. 2022; Silva et al. 2022; Thekkoote 2022; Yildirim et al. 2022; Yu et al. 2022; Zhu et al. 2022
2023	Akhmedova et al. 2023; Alieva et al. 2023; Antony et al. 2023; Ashmarina et al. 2023; Bogoviz et al. 2023; Canbay et al. 2023; Chiarini et al. 2023; Clancy et al. 2023; Csiki et al. 2023; Bandeira da Silva et al. 2023; Ganjavi et al. 2023; Jokovic et al. 2023; Karbekova et al. 2023, Khourshed et al. 2023; Kucinska-Landwojtowicz et al. 2023; Laskurain-Iturbe et al. 2023; Maganga et al. 2023a; Maganga et al. 2023b; Maganga et al. 2023c; Majernik et al. 2023; Mondal et al. 2023; Naidoo et al. 2023; Narkhede et al. 2023; Nayal et al. 2023; Nguyen et al. 2023; Popkova et al. 2023; Prabhu et al. 2023; Prashar 2023a; Prashar 2023b; Psomas et al. 2023; Raj et al. 2023; Saha et al. 2023a; Saha et al. 2023b; Saihi et al. 2023; Sharma et al. 2023; Shrivastav 2023; Singh et al. 2023; Solovyov et al. 2023; Sozinova et al. 2023a; Sozinova et al. 2023b; Sureeyatanapas et al. 2023; Tolmachev et al. 2023; Wang et al. 2023; Wawak et al. 2023; Zulfiqar et al. 2023

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