Basic Technologies and Models for Implementation of Industry 4.0

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Implementation of Industry 4.0 in the Manufacturing Industry: A Bibliometric Approach

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Abstract: *Industry 4.0 represents the integration of advanced technologies into manufacturing processes with the goal of improving efficiency, productivity and decision-making. However, despite the significant technological opportunities offered by Industry 4.0, there remains a significant gap between these opportunities and their practical implementation in the manufacturing industry. This gap poses a challenge to effectively reaping the benefits of Industry 4.0 and underscores the need for further research and bridging this gap between the technology and its practical application. This study presents a comprehensive analysis of the relevant literature addressing the implementation of Industry 4.0 technologies in manufacturing using a bibliometric approach based on data from the Web of Science Core Collection citation databases. The analysis includes quantitative methods such as direct citation analysis, keyword co-occurrence analysis, co-citation networks, and bibliographic coupling. The aim is to capture the dynamics of published research on the implementation of Industry 4.0, to investigate the intellectual and conceptual structure, and to identify key collaborative research networks. The results contribute to a deeper understanding of the current state and progress of research in this area. The study highlights the importance of continued research, collaboration, and strategic planning to fully realize the benefits of Industry 4.0 technologies in the manufacturing industry.*

Keywords: *Industry 4.0 implementation, Enabling technologies, Manufacturing industry, Bibliometric analysis*

1. Introduction

The term Industry 4.0 was first used in 2011 at the Hannover Messe Industrie trade fair, where it was shown how cyber-physical systems can bring about a paradigm shift in industrial automation [1]. One of the prominent elements of Industry 4.0 in the manufacturing industry is the concept of the smart factory. Smart factories use technologies such as the Internet of Things (IoT), artificial intelligence (AI), Big Data analytics, and robotics to create highly connected and autonomous manufacturing systems [2]. In a smart factory, machines, devices, systems, and people communicate with each other in real-time, enabling

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efficient information sharing and collaborative decision-making. This connectivity enables manufacturers to monitor and control their operations more effectively, optimize workflows, and respond quickly to changing demands or disruptions [3]. Industry 4.0 enabling technologies offer great opportunities to improve automation, flexibility, productivity, and efficiency in the industry [4], [5-7], namely the Industrial Internet of Things (IIoT), cloud computing, Big Data analytics, autonomous robots, simulations/digital twins, additive manufacturing (e.g., 3D printing), augmented reality, cybersecurity, and horizontal and vertical system integration [3], [8, 9]. The transition to Industry 4.0 can have troubling and destabilizing effects, pose significant competitive challenges, and raise legitimate security concerns [10]. Industry 4.0 affects all areas of life and work, in addition to the industrial sector, and has a significant impact on living standards, which is why the topic of Industry 4.0 is attracting a great deal of interest in both academic circles and companies [1], [7].

Previous research has mainly focused on the manufacturing sector when examining the impact of Industry 4.0 [11]. This is understandable, as manufacturing plays a key role in the world's economies and contributes to economic growth. [12, 13]. Today’s manufacturing industry is very diverse and includes various sectors such as automotive, aerospace, electronics, pharmaceuticals, consumer goods, etc. Production in the context of Industry 4.0 is undergoing significant change due to digitalization and the integration of advanced technologies. It continues to evolve rapidly, driven by technological advances, market dynamics, and changing customer expectations.

Manufacturing companies face a challenging manufacturing environment due to globalization, personalization, and market saturation, which translates into increasing quality requirements, shorter product life cycles, and pressure to reduce the cost of manufacturing processes across the value chain [14, 15]. With an increasing focus on innovation, sustainability, and digitalization, manufacturers are striving to remain agile, competitive, and adaptable in a rapidly evolving global environment. However, there are six central design principles for implementing Industry 4.0: interoperability, virtualization, decentralization, real-time capability, service orientation, and modularity [16] [17]. Manufacturing is one of the important sectors that can gain significant benefits by adopting the principles and technologies of Industry 4.0 [4].The expected benefits for production depend on the degree of implementation of Industry 4.0 technologies, with the following benefits most frequently cited: increased productivity, improved product quality, increased flexibility (fluctuating customer requirements, customized products), shortening of the production cycle, energy efficiency, decreased production costs [18][19]. In order to realize these benefits and survive in the market, manufacturers are forced to implement the technologies and principles of Industry 4.0, and in recent years companies are increasingly using technologies related to the concept of Industry 4.0 [20-22]. The transition to Industry 4.0 is a complex and multi-layered process that involves not only technological advances but also strategic considerations. The manufacturing industry is investing more than any other industry in the implementation of Industry 4.0 [23]. The implementation of Industry 4.0 is leading to structural changes in the technological base of manufacturing in countries around the world, such as China, the United States, and European countries, as stronger economies in developed countries invest more in Industry 4.0 [24]. For the successful implementation of Industry 4.0, it is necessary to carry out specific and concrete activities [25], and according to the article [26] digitalization serves as the primary approach to facilitate the implementation of Industry 4.0.

Industry 4.0 technologies are more likely to be adopted by large enterprises, while medium and small enterprises struggle to implement them in production, especially in developing countries [27][28]. On average, less than 20% of large companies are successful in their digital transformation efforts, and the situation is even more difficult for small and medium-sized enterprises (SMEs) [26][29]. Consequently, the transition of manufacturing to Industry 4.0 varies from country to country and is slow, with different challenges and problems [19]. One major problem is the standardization of existing production systems [30]. Since there is no standard definition of Industry 4.0 in the literature [23][31], it is understandable that there are also no standard implementation models [7]. The implementation of Industry 4.0 technologies is a major challenge for many companies because there is no systematic and comprehensive frameworkand models for implementation [32][33].

While there are general guidelines in the literature for implementing Industry 4.0 technologies and transforming manufacturing into a smart factory [34][35], implementation models are less common. The concepts of smart factories, sustainable production, and lean manufacturing in the context of Industry 4.0 are explored in the literature. The literature discusses various aspects of Industry 4.0 basic technologies, concepts, barriers, and opportunities related to Industry 4.0 implementation [36], and maturity and readiness models as key tools for companies to effectively implement Industry 4.0 principles and practices [24]. According to [37], the level of implementation of enabling technologies such as the Internet of Things, cybersecurity systems, and Big Data can be considered very high; Cloud computing, artificial intelligence, simulation, and machine learning can be considered high; the implementation level of intelligent robots, virtual reality, augmented reality, blockchain, cybersecurity, and additive manufacturing can be classified as moderate; and the degree of implementation of digital twins, quantum computing, and edge computing, on the other hand, can be classified as very low.

However, a review of the literature shows that research on implementation models of Industry 4.0 technologies is insufficient. Therefore, this study conducted a comprehensive literature review using bibliometric methods to capture the intellectual, conceptual, and social structure of the research field on the implementation of Industry 4.0 technologies in the manufacturing sector. Although there are articles in the literature on the implementation of Industry 4.0 using a bibliometric approach, it only addresses the implementation of individual technologies, not a comprehensive approach. The bibliometric analysis was performed using software VOSviewer because there is a large number of publications on Industry 4.0 and this number is growing exponentially [38], and it would be difficult to perform the analysis in a conventional way.

There is no doubt that the field of Industry 4.0 is in a constant process of development, which requires continuous monitoring of progress in research [39]. Accordingly, the aim of this study is to describe the current state and progress of research in the implementation of Industry 4.0 in the manufacturing sector and to identify and visualize the conceptual and intellectual structure and the structure of the collaborative network. According to the stated objective of the research, the following research questions (RQ) were defined: RQ1 - What is the trend in publishing articles on the implementation of Industry 4.0 in the manufacturing industry?; RQ2 - Which countries contribute most to research on the implementation of Industry 4.0 in the manufacturing industry in terms of publishing articles and number of citations?; RQ3 - In which research areas are there the most articles on the implementation of Industry 4.0?; RQ4 - Which are the most cited authors, publications and sources in the area of implementing Industry 4.0 in the manufacturing industry?; RQ5 - What is the intellectual and conceptual structure of research on the implementation of Industry 4.0?; RQ6 - How has the research focus in the area of implementing Industry 4.0 in production evolved over time?; RQ7 - What is the macro-level structure of the cooperation network?

The remainder of this article is organized as follows. The second section describes the research methodology. The third section contains the results, followed by related discussion in fourth section. The fifth section provides a conclusion.

2. Research Methodology

In this research, bibliometric analysis was used to reveal the dynamics of published research on the implementation of Industry 4.0 technologies, the intellectual and conceptual structure, and the main collaborative research networks. Bibliometric analysis as a quantitative method is applied to avoid the subjective interpretation of researchers, and the application of these methods is widely used in various research fields because bibliometrics provides a more objective and reliable analysis than other methods [40]. The results of the bibliometric analysis are based on quantitative analysis of citations among published papers, which provides an objective representation of the real situation and identification of the most important research topics [41]. Bibliometric analysis also has some disadvantages, such as the impossibility of long-term predictions [42][43]. Bibliometric tools such as direct citation analysis, keyword co-occurrence analysis, co-citation networks, and bibliographic linkage have been used to identify existing research directions and potential directions for future research.

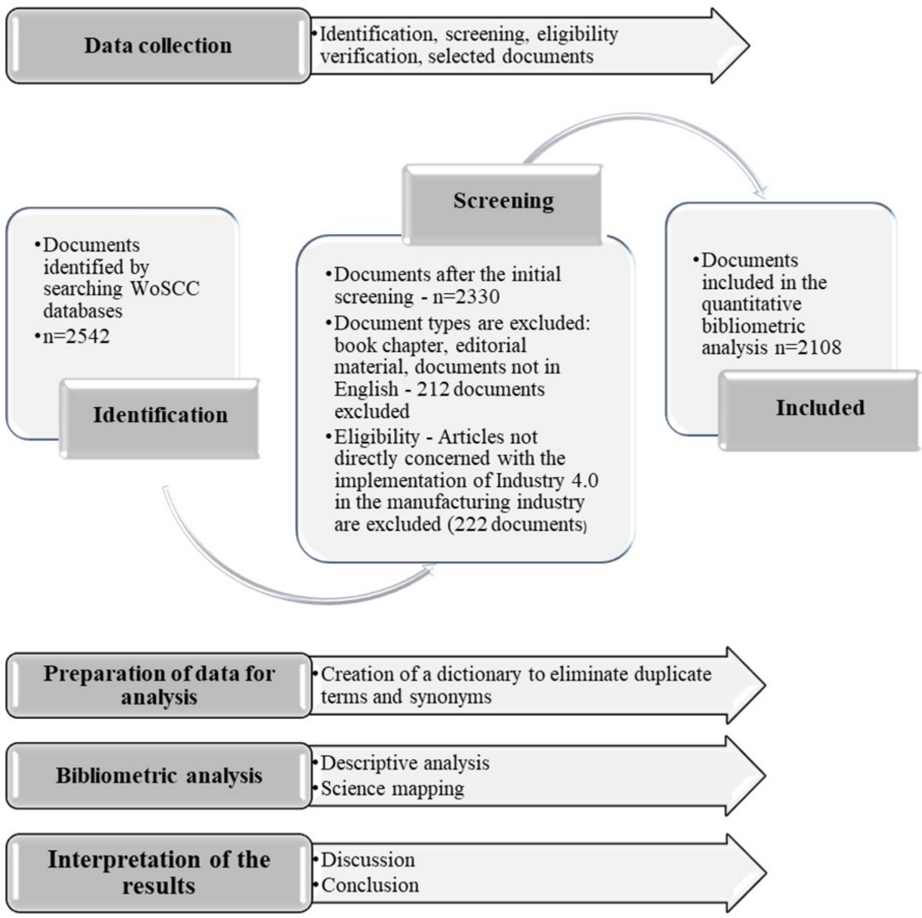

Figure 1. Research methodology

The study was conducted in four phases according to the methodology shown in Figure 1. In the first phase, data were collected from the Web of Science Core Collection citation databases. The PRISMA methodology was used to ensure the quality of data collection and the possibility of replicating the process [44]. The search covered a 10-year period (from 2013 to 2018), and three criteria were used to define the query. The first criterion was related to Industry 4.0, selecting keywords related to Industry 4.0, including the names of several countries' strategies: ''Industry 4.0'', ''Advanced Manufacturing Partnership'', ''Industrial Value-Chain Initiative'', ''Made in China 2025'', ''Future of Manufacturing'', ''Smart Manufacturing'', ''Initiative Industry 4.0'' [45]. The second criterion refers to the implementation of Industry 4.0, using keywords such as ''implement*'', ''model'', ''framework'', ''roadmap'' and ''strateg*''. The research focuses on the manufacturing industry, and the third criterion was defined by the keywords ''manufacturing'', ''production'' and ''manufacturing industry''. Based on the established criteria, a search of the Web of Science Core Collection citation database was conducted with a defined query: (TS=(''Industry 4.0'' OR ''Advanced Manufacturing Partnership'' OR ''Industrial Value-Chain Initiative'' OR ''Made in China 2025'' OR ''Future of Manufacturing'' OR ''Smart Manufacturing'' OR ''Initiative Industry 4.0'') AND TS=(implement* AND (model OR framework OR roadmap OR strateg*)) AND TS=(manufacturing OR production OR ''manufacturing industry'')) .

In the identification phase, 2,542 results were obtained. The sample included only scientific papers, review papers, and conference papers in English. Documents in the form of book chapters, editorial material, and papers in languages other than English were excluded from the collected set of documents. Documents published outside the period from 01/01/2013 to 12/31/2022 were also excluded. This period was chosen in view of the publication of Industry 4.0 initiative and the German economic development strategy in 2013. Screening of the documents when preparing the data for analysis based on the previously described limitations, which are in line with the research objectives and research questions, yielded 2330 results. In the acceptance screening phase, the titles and abstracts of the documents were screened and only papers dealing with models, strategies, and implementation options of Industry 4.0 in the manufacturing industry were selected. In this way, a total of 2108 documents were included in the bibliometric analysis to obtain answers to the research questions. These scientific papers represent the knowledge base (intellectual basis) for the field of Industry 4.0 implementation in the manufacturing industry.

The data were then prepared for bibliometric analysis. The data were cleaned, i.e., a dictionary was created to remove duplicates, i.e., synonyms of terms. In the next phase of the study, bibliometric analysis was performed, namely descriptive bibliometric analysis and science mapping (in which co-occurrence analysis of keywords, citation analysis, co-citation analysis, bibliographic coupling, and social network analysis were performed) to identify the main research topics on the implementation of Industry 4.0 technologies and future research areas, i.e., intellectual structure and research fronts, and collaborative networks at the macro (country) level. VOSviewer software, version 1.6.19 [46], was used as a tool to perform the analysis. VOSviewer is widely used in the scientific community for bibliometric analysis and facilitates the analysis of a large number of publications given the sudden increase in published research. For all types of analyses, data were normalized using a similarity measure called strength of association.In the final stage, the results were analyzed and conclusions were drawn.

3.Bibliometric Analysis

3.1. Descriptive bibliometric analysis

To answer research question RQ1, a descriptive bibliometric analysis was conducted. This analysis includes an analysis of the trend of increase in the number of articles published, an analysis of the greatest contribution to research in the field of Industry 4.0 implementation in terms of number of publications and citations by country, and which are the most influential publications, authors, and sources. Descriptive analysis provides valuable insight into the performance of authors, institutions, or countries in the field. It helps identify publication trends, determine the most prolific and influential authors, identify the most cited publications, identify the most cited sources, and identify the countries with the highest research performance.
Figure 2 shows the trend of the increase in the number of publications on the implementation of Industry 4.0 from the beginning of 2013 to the end of 2022.

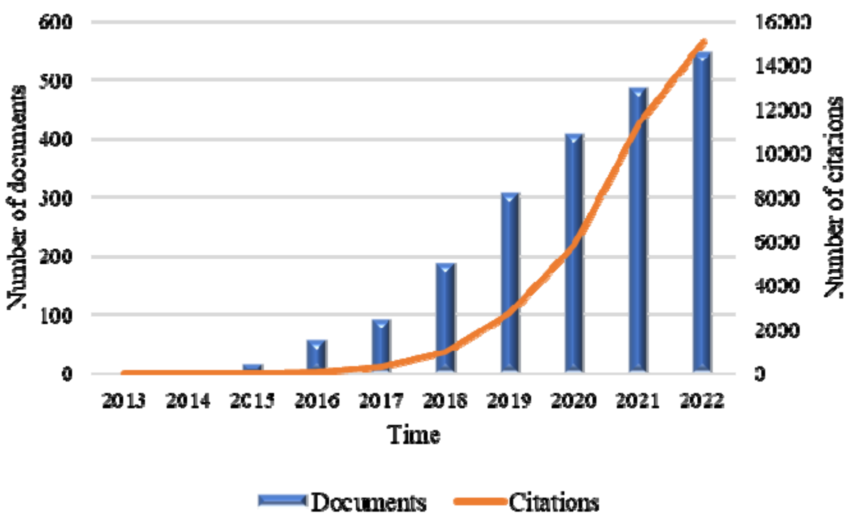

Figure 2. Number of published papers and citations by year, period 2013 - 2022

A steady increase in the number of publications has been observed since 2015, and a stronger increase in the number of publications and number of citations begins in 2018, and this growth trend is maintained until the end of 2022. This shows the growing interest of researchers in research on the implementation of Industry 4.0 in the manufacturing industry.
Figure 3 shows the productivity of different countries in the field of research on the implementation of Industry 4.0 in production (the graph was created in the Microsoft Excel application) as the answer to RQ2. The most productive countries (with more than 100 published papers) are China with 261 papers, Italy with 226 papers, and Germany with 209 papers. They are followed by the United States with 188 publications and India with 186 publications. The United Kingdom, Brazil, France and Spain have published between 135 and 104 papers. Of the countries that have published research on the implementation of Industry 4.0, more than 65% are European countries. Europe is at the forefront of the implementation of Industry 4.0 technologies research. Countries such as Italy, Germany (which initiated the concept of Industry 4.0), United Kingdom and France contributed significantly to the literature on this topic.

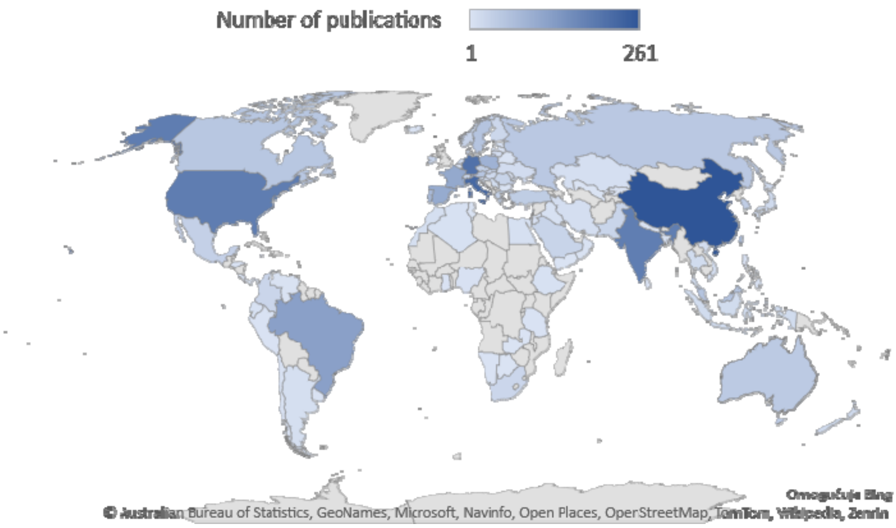

Figure 3.Global distribution of the number of publications on the implementation of Industry 4.0

As answer to RQ3 Figure 4 shows the scientific fields to which the papers from the research sample on the implementation of Industry 4.0 in production can be assigned, based on analytical tools of WoS. The graph shows the research areas to which at least 40 published papers belong. Most of the papers belong to the scientific fields of engineering (1268 papers) and computer science (696 papers),which is understandable since they deal with production and information technologies. In the other scientific fields, there are less than 300 published papers on the implementation of Industry 4.0 in manufacturing for the observed period.

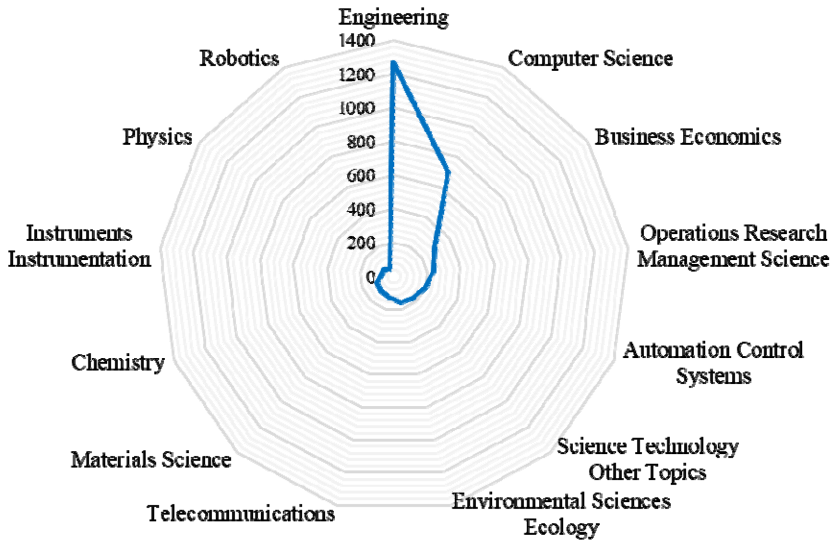

Figure 4. The most represented research areas

Figure 5 shows that most publications relate to manufacturing (26,14%) and industrial engineering (21,96%) (the categories are defined in the Web of Science platform).

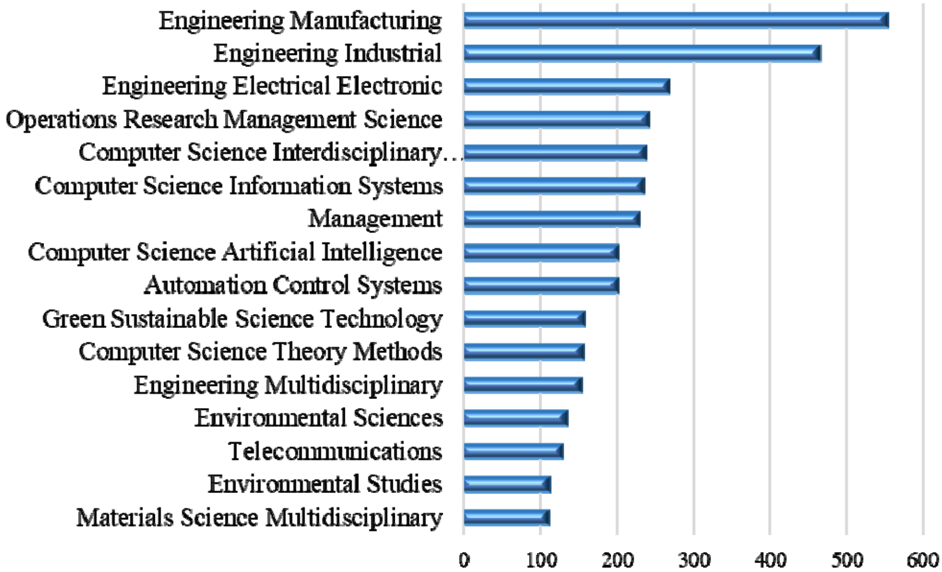

Figure 5.Web of Science categories

The most influential authors, articles and sources, based on the number of citations, were identified by citation analysis, in order to obtain an answer to RQ4. The analysis was performed using VOSviewer software, and the criterion for authors was that the authors had at least 5 publications in the research area and their papers had at least 100 citations. Of the total 6646 authors, 43 authors met this criterion, of which the 10 most influential are listed in Table 1 by number of citations.

Table 1. The most influential authors, based on the number of citations

Authors	Articles	Citations	Total Link Strength
Ayala, Nestor Fabian	5	1635	95
Ghobakhloo, Morteza	10	859	111
Xu, Xun	11	859	51
Pellerin, Robert	6	856	69
Lamouri, Samir	5	854	60
Tao, Fei	8	831	21
Li, Di	6	810	21
Sihn, Wilfried	5	809	39
Tortorella, Guilherme Luz	8	660	70
Zheng, Pai	6	621	36

It is noteworthy that Ayala Nestor Fabian emerges as the most influential author based on the number of citations in the field of Industry 4.0 implementation in the manufacturing industry. This suggests that Ayala's research and contributions have garnered significant attention and recognition within the research community. The most cited article by Ayala, Nestor Fabian in the Web of Science Core Collection, as of 2019, is ‘’Industry 4.0 technologies: Implementation patterns in manufacturing companies’’ [47]. This particular work likely represents a seminal contribution by Ayala, providing valuable insights and analysis on the implementation patterns of Industry 4.0 technologies in manufacturing companies. Ayala’s work ranks eighth in the number of articles published. The second place of Ayala in total number of links indicates a strong connection to other authors in the field and shows how important these citations are.

It is notable that GhobakhlooMorteza holds a significant position in the citation analysis. Ranking second in terms of both the number of citations and the number of articles published suggests that his work has made a substantial impact and has been influential in the field of Industry 4.0 implementation in the manufacturing industry.

Furthermore, having the highest total link strength indicates that GhobakhlooMorteza is highly connected to other authors through citations. This implies that his research has been extensively referenced and acknowledged by other scholars, establishing strong connections and collaborations within the research community.

These findings highlight GhobakhlooMortezas contributions and influence in the field, suggesting his work has significantly influenced and contributed to the body of knowledge on Industry 4.0 implementation in the manufacturing industry.

Table 2 shows the most influential articles by number of citations. The most influential article is above mentioned [47] with the largest number of citations and also the largest number of links.

Table 2. The most influential articles, based on the number of citations

Document	Citations	Links
Frank (2019) [47]	868	7
Wang (2016) [48]	682	4
Dalenogare (2018) [49]	678	7
Kusiak (2018) [50]	562	1
Schumacher (2016) [51]	557	5
Ghobakhloo (2018) [52]	508	5

Table 3 shows the results of a citation analysis conducted to identify the most relevant sources for research on the implementation of Industry 4.0 in the manufacturing industry. The citations analysis in VOS viewer focused on sources that had published at least 10 articles in the field and received at least 1000 citations. Of the 843 sources examined, 10 journals met these criteria.

Table 3. The most influential sources, based on the number of citations

Source	Number of articles	Number of citations	Total link strength
International Journal of Production Economics	21	2537	229
International Journal of Production Research	32	2406	233
Technological Forecasting and Social Change	19	2206	179
Sustainability	87	2012	270
Computers in Industry	29	1640	125
Journal of Manufacturing Technology Management	34	1451	228
Journal of Manufacturing Systems	38	1444	115
Computers & Industrial Engineering	39	1319	117
IEEE Access	35	1147	59
Journal of Cleaner Production	25	1095	157

The Table 3 also lists the strongest links between sources, based on the total link strength. The presence of strong links, as indicated by the total link strength between sources, suggests that these specific sources tend to cite other sources more frequently. This implies a higher level of interconnectivity and scholarly referencing among these journals within the field of Industry 4.0 implementation in the manufacturing industry. Such strong links indicate that these journals are influential in shaping the discourse and knowledge dissemination within the research community, as they reference and build upon the work published in other journals.The International Journal of Production Economics is the most cited journal, but it is not the most productive in terms of the number of articles published, and it does not have the highest total link strength. The most productive journal is Sustainability, which also has the highest total link strength and ranks fourth in terms of number of citations. The journals International Journal of Production Research and Technological Forecasting and Social Change are second and third, respectively, in terms of number of citations.
Overall, the results of this citation analysis provide valuable insight into the influential sources and their relationships to one another in the field of Industry 4.0 implementation in the manufacturing industry.

3.2. Science mapping

Insight into the intellectual and conceptual structure of the research is important to identify key concepts, theories, and frameworks that form the foundation of the research area and to identify areas that have not been adequately explored.

Analyzing the intellectual and conceptual structure of research allows for the discovery of various themes within the research field, the identification of research trends, and current topics in which researchers are showing great interest. In this study, the methods of co-citation analysis and bibliographic coupling were used to identify the intellectual structure and research fronts of research on the implementation of Industry 4.0 technologies, and keyword co-occurrence analysis was used to reveal the conceptual structure. Co-authorship analysis was used to reveal the social network structure, specifically to identify the macro-level international collaborative network.

3.2.1. Intellectual structure of research domain

A.Intellectual base of research

For the purposes of this study, and to answer question RQ5, a co-citation analysis of documents was chosen, the goal of which was to determine the intellectual knowledge base of the research area. In co-citation analysis, the degree of similarity between two documents depends on the number of documents that cite both works. Co-citation analysis provides a simple way to evaluate the relationship between research articles. When two articles are co-cited in the same publication, it indicates a mutual relationship between them. The frequency of co-citations serves as an indicator of similarity between articles, as it indicates how often they are cited together. From the frequency of co-citations, it can be concluded that two articles refer to the same research area [53]. In essence, joint citations provide a link that highlights the interconnectedness and common focus of articles within a given field. In the VOSviewer software, a total of 74196 cited references were identified in the sample of WoSCC. A threshold of at least 20 cited references was chosen, reducing the sample to 286 cited references for the co-citation analysis. The fractal counting method and the number of citations were chosen as the measure for visual representation, and the threshold for the minimum cluster size was set to 5 cited references. Figure 6 shows the network of cited references connected in clusters, i.e., five clusters within the knowledge base: A) red cluster (total 112 cited references) - Digital Transformation in Manufacturing; B) green cluster (total 79 cited references) - Integration of Industry 4.0 Technologies in Manufacturing; C) blue cluster (total 49 cited references) - Enabling Industry 4.0: technologies, systems and strategic implementation; D) yellow cluster (total of 26 cited references) - Technology of digital twins in smart manufacturing; E) purple cluster (total of 20 cited references) - The concept of lean manufacturing in Industry 4.0. It can be seen that the most thematically connected red and blue thematic units.

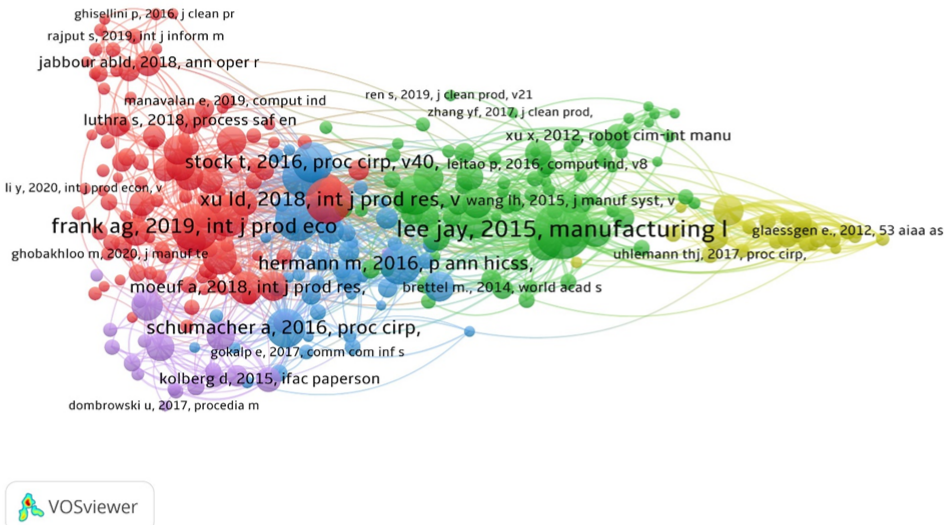

Figure 6. Visualization of the network of cited references - result of co-citation analysis (VOSviewer software)

The red cluster, which contains 112 cited references, refers to digital transformation in manufacturing. Digital transformation means the introduction and integration of digital technologies and processes in manufacturing. It includes digitalization, the use of new technologies, and the transformation of traditional manufacturing into advanced manufacturing systems [47]. It includes concepts such as cyber-physical systems, the Internet of Things (IoT), cloud computing, blockchain technology and other enabling and emerging technologies [54]. It focuses on improving manufacturing performance, industrial integration, interoperability, and enterprise architecture. These concepts and issues are relevant not only in developed countries but also in developing countries, where adopting the principles of Industry 4.0 can promote industrial growth and development [55].
The focus of the green cluster, which contains 79 cited references, is on integrating the enabling technologies and concepts of Industry 4.0 in the manufacturing industry. A prominent aspect of this cluster is cyber-physical systems, which represent the integration of physical and digital components in production processes. This includes the use of sensors, actuators and communication networks that enable real-time monitoring, control and optimization of manufacturing processes. The importance of connectivity, automation, and real-time information exchange to optimize production, improve operational efficiency, and drive innovation has been highlighted. In addition, this cluster emphasizes the importance of sustainability, product lifecycle management, and service orientation in manufacturing.

The blue cluster, which includes 49 cited references, represents comprehensive research on past, present, and future aspects of Industry 4.0, with the goal of thoroughly understanding the current state of knowledge and identifying future research directions in the field [56-59]. In addition, the topic unit addresses the assessment of readiness and maturity of manufacturing companies for Industry 4.0 by developing a maturity model. Such models make it possible to assess the readiness and progress of organizations in adopting Industry 4.0 practices and technologies [51].

The yellow cluster contains a total of 26 cited references, including research on the integration of digital twin technology and the concept of smart manufacturing, and the use of digital twin models to create virtual representations of physical products, processes, and systems in the manufacturing industry. The focus is on the convergence of digital and physical domains for data exchange and communication between virtual and real manufacturing environments [60][61][62][63]. The topic highlights the importance of standardization and interoperability in the implementation of digital twin solutions and smart manufacturing [64].

There are a total of 20 cited references in the purple cluster, and the research focuses on integrating advanced technologies, such as cyber-physical systems and the Internet of Things (IoT), with lean manufacturing principles to promote operational efficiency, productivity, and performance improvement. Lean manufacturing is now considered the most important manufacturing paradigm [65]. The integration of lean manufacturing principles aims to increase productivity and reduce costs in manufacturing organizations [66]. The subject area includes the exploration of concepts and technologies in various contexts, including developing countries.

B. Research Fronts

Research fronts represent the most cited papers of the five-year period, clustered to provide insight into current research priorities and to indicate future research directions [67][68][69]. The bibliographic coupling method was used to identify research fronts. Research results of [70][71] have shown that the bibliographic matching method reveals research fronts more accurately than the co-citation analysis.Bibliographic coupling is a method that provides insight into research trends, research groups, and the dissemination of knowledge within a research field by identifying links between scientific papers based on their citation relationships. It is used to assess the similarity and relatedness of scientific publications based on their common citations. Analyses the citation patterns of articles and determines the degree of overlap between their reference lists. Publications that cite similar works are considered bibliographically related and are assumed to share thematic or conceptual similarities.

The bibliographic coupling analysis was performed for the five-year period from 2018 to 2022. The unit of analysis is a document and only documents with at least 20 citations are included in the analysis, resulting in a sample of 413 scientific articles. In the VOSviewer software, it is specified that 75% of the articles are included in the analysis. As a result, four clusters were formed, which are shown in Figure 7. The names of the research fronts (topics) were determined based on a review of keywords, article titles, and abstracts: A) Red cluster: Smart Manufacturing and Industry 4.0 Technologies Integration; B) Green cluster: Digital Transformation and Business Models; C) Blue cluster: Sustainable Manufacturing and Integration; D) Yellow cluster: Lean Manufacturing and SMEs.

The red cluster includes 179 articles, and research is focused on advancing smart manufacturing. Here, the integration of smart systems such as cyber-physical systems, digital twins, internet of things, big data and blockchain technology is studied to optimize production processes, increase efficiency and minimize environmental impact [72], [73]. Research within this cluster aims to leverage innovative solutions to drive the evolution of manufacturing towards smarter and more technologically advanced processes [52].

The Green Cluster (129 articles) addresses digital transformation in manufacturing [47][49] and explores its profound impact on business models and practices, with a focus on business model innovation for small and medium-sized enterprises (SMEs) [74].It examines the challenges, opportunities, and performance aspects associated with the adoption of digital technologies and explores how they are shaping the future of manufacturing companies and economies [75]. By analyzing the transformative potential of digital change, this cluster aims to facilitate the successful integration of new digital paradigms into manufacturing companies.

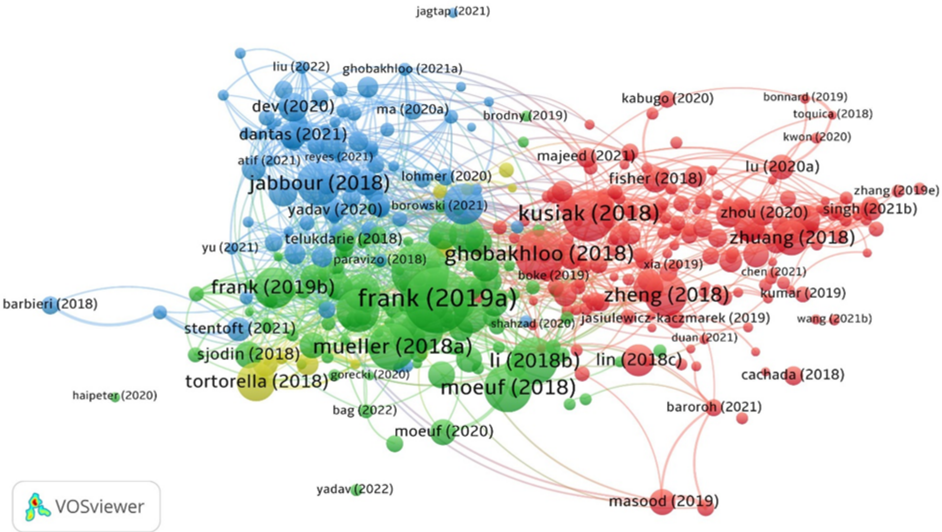

Figure 7.Network visualization of research fronts

The Blue Cluster includes 88 articles and focuses on sustainable manufacturing practices and their integration into the overall operations and supply chains of manufacturing companies. It examines environmental sustainability, circular economy principles, and sustainable supply chain management. By focusing on environmentally sound practices and integrating sustainability principles, this cluster aims to promote long-term profitability and environmental protection in the manufacturing industry [76-78].
The yellow cluster includes 13 papers that address the implementation of lean manufacturing principles in the context of Industry 4.0 [79][80]. This cluster highlights the importance of lean practices for SMEs to thrive and contribute to the overall development of national economies.

Figure 8 shows a map visualizing the density of research fronts based on citation weights. Using a visual representation of network density, it is easy to identify areas of higher density where the network nodes are close together, indicating the most important areas of the network.The greater the number of items in the neighbourhood and the higher the weighting of these elements, the closer the colour of the point is to red. The assumption is made that the research on a particular topic is considered more mature and developed when the density of the corresponding research front is higher [81].

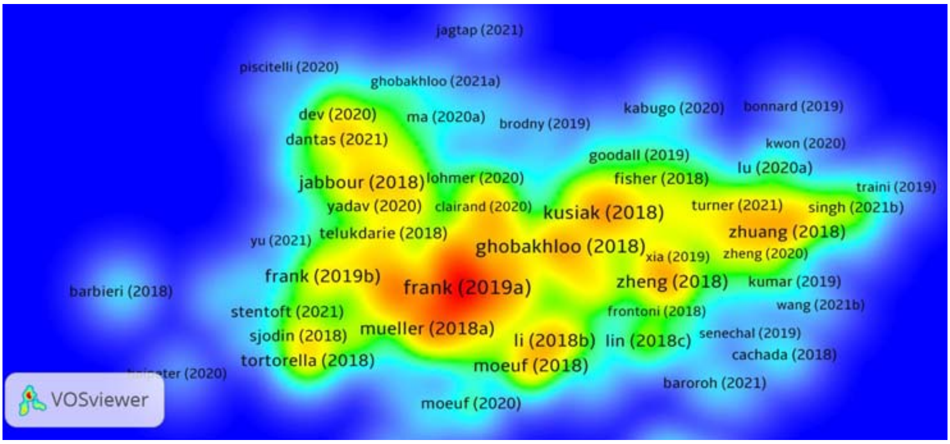

Figure 8. Density visualization of research fronts

In Figure 8, a more intense red colour indicates a higher research density. From the network density visualization, the highest research density is in the area of adoption of Industry 4.0 technologies in manufacturing companies and the associated challenges such as technological complexity, organizational change, workforce skill requirements, and infrastructural constraints. Understanding these challenges can help develop strategies and best practices to overcome them and ensure successful implementation. There is a particular focus on researching strategies that enable small and medium-sized enterprises to effectively use Industry 4.0 technologies and overcome resource constraints. There are some other research areas with a somewhat weaker intensity of red in the density indicator, such asthe integration of Industry 4.0 technologies and environmentally sustainable manufacturing and on the critical success factors of integration; research on digital twins in the context of manufacturing; the opportunities and challenges of adopting and using advanced technologies to promote innovation and efficiency in manufacturing, synergies between sustainable supply chain management, enterprise resource planning, and the potential of Industry 4.0 technologies to promote sustainability and efficiency in supply chain operations. Areas highlighted in green represent marginal research on a particular implementation topic in the context of the manufacturing industry. Research in the areas highlighted in blue, which are older, has no potential for development. Newer researches that are still in the blue highlighted areas are potential new topics that will be developed in the near future, such as research on human-robot collaboration, energy sustainability, human-centered approaches in the context of Industry 4.0, and the future vision of Industry 5.0 to balance technological advancement and human well-being.

The weakness of the dark red areas in the visual representation of density indicates that there is still much room for research on the topic of implementing Industry 4.0 technologies in the manufacturing industry.

3.2.2. Conceptual structure

To establish the conceptual structure of the research about implementation Industry 4.0 technologies in manufacturing, the co-occurrence analysis of terms that occur most frequently in publication was used. The co-occurrence analysis was performed using the VOSviewer software.

Of the total 6248 terms, the terms that occurred at least 10 times were selected for analysis. This reduced the sample for analysis to 161 terms. The default cluster size is set to a minimum of 5 terms in a cluster. The result of the analysis was 4 clusters.The co-occurrence analysis revealed four dominant themes and emerging trends in the field: Cluster 1 (red) - Technology-Driven Transformation; Cluster 2 (green) - Smart Manufacturing and Process Optimization; Cluster 3 (blue) - Industry 4.0 Technologies and Integration; Cluster 4 (yellow) - Technology Adoption and Integration Management.

Figure 9 shows the network visualization of the co-occurrence analysis and Table 2 shows the 30% most common terms from each cluster.

Cluster 1 (red) contains 50 terms covering different aspects and dimensions of this topic. The analysis of the mentioned keywords shows a thematic context covering technology, sustainability and business transformation in the context of manufacturing and supply chain management.

Digital transformation as one of the main themes illustrates the comprehensive process in which organizations adapt to technological change, digitize their business, and transform their operational processes to become more competitive and innovative [82][83]. Supply chain management and sustainability are key elements in today's business environment [84]. Companies are increasingly recognizing the importance of sustainable practices and responsible supply chain management to reduce their environmental impact, including reducing waste, optimizing resources, and promoting circular economy principles [85]. Sustainability also refers to the harmonization of economic, environmental, and social aspects of a business to achieve long-term success [86]. There is a growing interest in integrating the principles of lean manufacturing, which aim to eliminate waste, optimize resources, and improve operational efficiency in the production process, and Industry 4.0 technology [87].Innovation and technology are the main drivers of development in this area. Innovation is key to increasing competitive advantage and ensuring the long-term success of companies in a dynamic business environment [88]. Quality management, productivity, knowledge and skills management, as well as data analytics and predictive analytics also play an important role in achieving excellence in manufacturing and supply chain management [89].

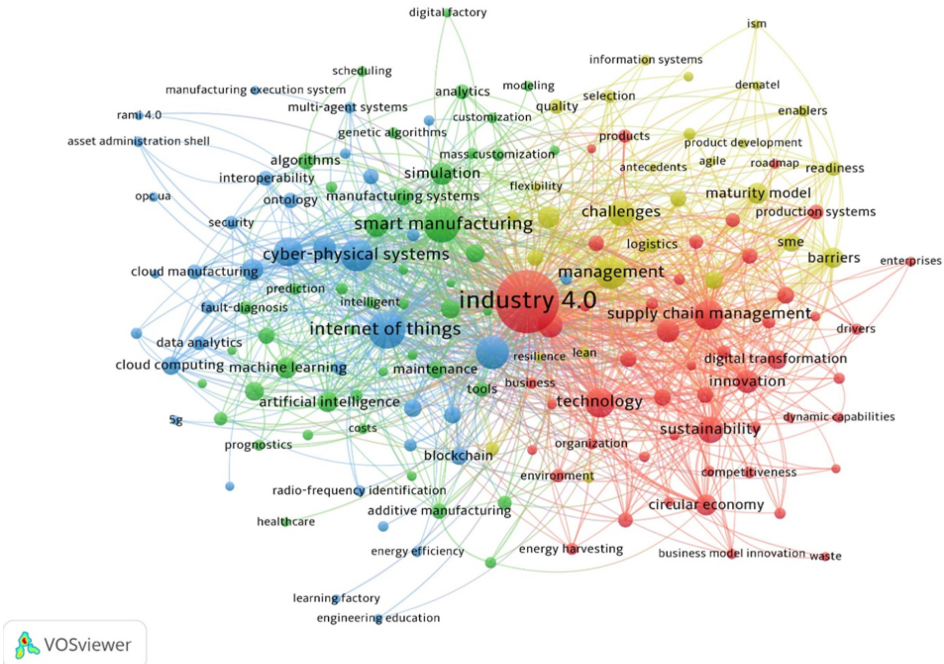

Figure 9. Network visualization of keyword co-occurrence analysis

Quality management of processes, optimization of resources, strategic use of knowledge and information, and decision-making based on data are key factors in achieving operational efficiency and desired business outcomes. All of the above research directions, together with sustainable development, environmental guidelines, and a focus on competitiveness, form an integrated framework for business process transformation and long-term industry success.Cluster 2 (green) includes 46 terms that are thematically related. Smart manufacturing is based on cutting-edge technologies that enable effective real-time engineering decisions by integrating various ICT technologies with existing production technologies [20]. The research trends based on the keywords in this cluster focus on the further development of smart manufacturing processes and technologies. The focus is on optimization, simulation, and machine learning technologies to improve various aspects of manufacturing processes. Predictive maintenance is highlighted as a key area to improve equipment reliability and reduce downtime [90]. Automation and robotics play an important role in optimizing production and achieving higher efficiency. The integration of technologies enables data-driven decision-making and improved production performance.

Table 4. Co-occurrence analysis results - the 30% most common terms from each cluster

Cluster 1	f	Cluster 2	f	Cluster 3	f	Cluster 4	f
industry 4.0	1257	smart manufacturing	311	internet of things	338	management	242
technology	191	optimization	110	big data	248	challenges	145
supply chain management	186	simulation	95	cyber-physical systems	231	integration	86
sustainability	140	machine learning	80	digital twins	174	maturity model	81
manufacturing	120	artificial intelligence	77	smart factory	94	barriers	76
innovation	105	predictive maintenance	66	industrial internet of things	89	sme	59
digitalization	94	industry	62	cloud computing	58	technology adoption	57
circular economy	82	automation	56	services	53	decision making	45
digital transformation	67	manufacturing systems	51	blockchain	48		
lean production	48	maintenance	49	augmented reality	46		
opportunities	46	algorithms	48	intelligent manufacturing systems	40		
knowledge-based systems	44	neural networks	44				
companies	41	additive manufacturing	37				
operations management	40	tools	34				
methodology	38						

f - frequency

The integration of smart manufacturing can play a key role in promoting sustainable development [16]. Mass customization of products and the capabilities of such customization is gaining attention, enabling manufacturers to meet individual customer needs while maintaining profitability. Mass customization and mass personalization enable a wide range of products, ranging from large quantities to one-of-a-kind (unique) products [38]. Quality control, defect detection and diagnosis are important aspects to ensure product reliability and safety [91-93].
Overall, the research trends in this cluster cover a wide range of topics, highlighting the multidisciplinary nature of smart manufacturing and its potential to revolutionize the industry [94]. The focus is on improving productivity,

quality, and sustainability by integrating advanced technologies and innovative approaches.

Cluster 3 (blue) includes 37 keywords that can be used to explore research directions. Exploring the basic technologies of Industry 4.0 provides insights into the key concepts and tools that are shaping advanced manufacturing in today's digital age. Table 2 shows that the basic technologies of Industry 4.0 most frequently mentioned in research are the Internet of Things, Big Data, cyber-physical systems, and digital twins. The Internet of Things (IoT) is a network of physical devices and sensors connected via the Internet to exchange and manage data. The IoT enables the collection of large amounts of data in real-time, which forms the basis for making informed decisions and optimizing production processes [95]. Big Data technology refers to large and complex data sets that are generated during production and require advanced analytics techniques to gain useful insights [96]. Cyber-Physical Systems (CPS) represent the integration of computer and physical components that work together to support and optimize production processes. CPS are the fundamental technological component in the realization of Industry 4.0 [97]. These systems enable monitoring and control of production through sensors, actuators, and control systems with connections to computer systems for analysis and decision-making [98]. Digital twins are virtual replicas of physical objects, processes, or systems that enable real-time simulation, modelling, and analysis. In modern engineering and manufacturing practice, digital twins are mainly used to create accurate virtual representations of objects and simulate operations [99]. These digital models enable a deeper understanding of real objects and processes and support optimization, prediction of failures, and experimentation with new solutions before they are deployed in real production. The concept of a smart factory involves the use of advanced technologies such as IoT, CPS, digital twins, and data analytics to achieve highly automated and flexible production [100]. A smart factory uses digital technologies with the goal of optimizing production processes, increasing efficiency, reducing costs, and increasing competitiveness. However, implementation is extremely complex, and most companies do not have sufficient knowledge of the challenges or the necessary resources for implementation [75]. The Industrial Internet of Things (IIoT) is the application of the IoT concept in an industrial environment. The IIoT enables connectivity and communication between various industrial devices, sensors, and real-time data acquisition systems, opening new opportunities to optimize production processes and improve performance [101].

Cloud computing provides computing resources over the Internet and enables on-demand access to data, applications, and resources 102]. Cloud computing provides the ability to store, process, and analyze large amounts of data and facilitates collaboration, information sharing, and access to advanced data analysis tools. Intelligent manufacturing systems represent the integration of advanced technologies such as AI, machine learning, and automation into production processes. The development and implementation of intelligent manufacturing systems is a complex task that requires the integration of multiple disciplines [103]. In addition, there are other technologies such as blockchain, augmented reality, data analytics, and networks that play an important role in supporting Industry 4.0. Together, these technologies create integrated, connected and intelligent systems that transform traditional manufacturing into a modern digital environment. Consequently, with the increasing adoption of Industry 4.0 technologies, cybersecurity is playing an increasingly important role in securing and protecting systems [104].

Cluster 4 (yellow) is the smallest cluster, highlighted in yellow, and includes 28 terms. The underlying theme that emerges from the key terms is the effective management of technology adoption and integration in organizations, taking into account challenges, barriers, decision-making processes, and information management. The adoption of Industry 4.0 technologies faces both internal and external obstacles that can hinder successful implementation [105]. Internally, companies may encounter challenges such as employee resistance, lack of executive support, limited knowledge about Industry 4.0, and financial constraints [106]. Externally, regulatory compliance issues, data security concerns, low standardization, and the need for significant investment present additional hurdles. Overcoming these internal and external hurdles is critical for companies to effectively transition to Industry 4.0 and reap its benefits. Understanding and overcoming these barriers is key to overcoming difficulties and ensuring an effective transition to Industry 4.0.

Integration plays a key role in this topic, as the concept of Industry 4.0 is based on the integration of information and communication technologies and industrial technology, and is mainly based on building a cyber-physical system (CPS) to realize a digital and smart factory [107].

It requires careful planning, coordination and alignment of the various systems, processes and stakeholders. Effective integration of technologies enables organizations to realize their full potential, improve operational efficiency, foster collaboration, and drive innovation.

An important aspect of this topic is the maturity model, which provides a framework for assessing a company's readiness and ability to implement Industry 4.0 technologies [108]. Maturity models help companies assess their current technology status, identify areas for improvement, and set guidelines for progress. They provide a structured approach to measuring progress and setting goals for achieving higher levels of technology maturity [109].

Within this theme, small and medium-sized enterprises (SMEs) are highlighted in terms of their specific challenges and opportunities in implementing and integrating technology [110]. SMEs often face resource constraints, lack of expertise, and organizational complexity that make technology implementation difficult, and often limit themselves to implementing cloud computing and Internet of Things technologies [74]. However, SMEs can also benefit from innovative solutions tailored to their specific needs.In summary, the underlying theme that emerges from the key concepts relates to the effective management of technology adoption and integration in enterprises, taking into account challenges, barriers, decision-making processes, and information management. This theme highlights the need to address challenges, integrate technologies effectively, assess organizational maturity, overcome barriers, help SMEs make informed decisions, and manage information effectively to achieve successful technology adoption and integration.

3.2.3. Evolution of the research focus

To answer RQ6 and to better understand the research structure and the current temporal dynamics within the research field under consideration, an overlay visualization with the software VOSviewer was used to visualize the progress in the implementation of Industry 4.0 technologies in manufacturing.Figure 10 shows when the frequency of co-occurrence of terms was highest, terms in yellow are more recent, earlier terms are shown from purple to green. From this visualization of the evolution of the theme over time, it can be seen that cluster 4 is an emerging thematic unit, i.e., more than 50% of the keywords in cluster 4 are younger than the other keywords in that cluster, and the highest frequency of occurrence was in 2021.

From the visual representation, it can be seen that the terms Cyber-Physical Systems, Smart Factory, Cloud Computing, Cloud Manufacturing, Simulation, Internet of Things, Industry 4.0, Big Data, Data Analytics, Sensor Networks peaked in the previous period, while newer terms that appear more frequently are Artificial Intelligence, Deep Learning, Blockchain, 5g, Edge Computing, Industry 5.0, human-robot collaboration, supply chain management, technology, drivers, sustainability, circular economy, business model innovation, lean management, technology adoption, asset administration shell, and keywords from cluster 4 (emerging): barriers, readiness, critical success factors, enablers, lean, dematel, flexibility, resilience, ism. A slight shift in researchers' interest from exploring the enabling technologies of Industry 4.0 to implementing the enabling technologies of Industry 4.0 and developing strategies, guidelines, and models for implementation can be seen. The yellow terms also indicate possible future research trends.

Figure 11 shows the density visualization of the co-occurrence analysis, which can be used to analyze the occurrence of potential research and which research areas have reached a certain level of maturity.

The keyword Industry 4.0 is located in a high-density area, which means that the connections of this word with other keywords are extremely strong.

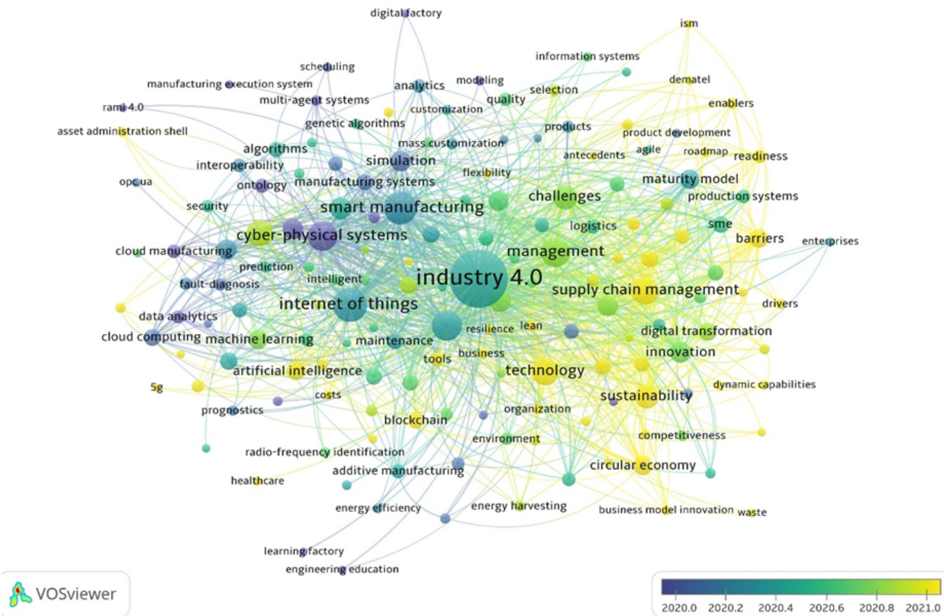

Figure10.Overlay visualization – evolution of research focus

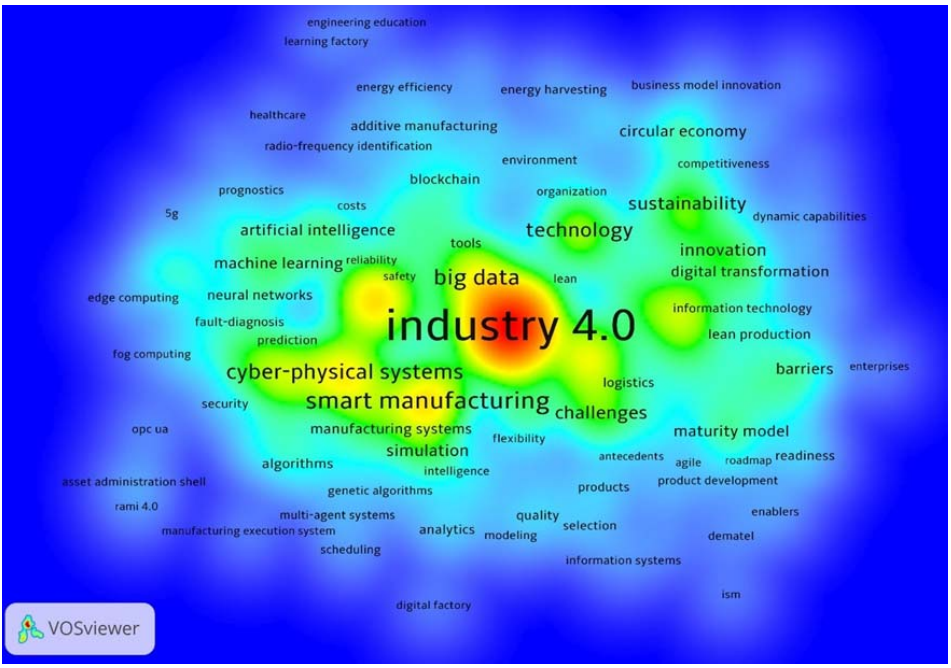

Figure 11. Keyword co-occurrence analysis - density visualization

In the yellow area with lower density are the keywords Internet of Things, smart manufacturing, Big Data and cyber-physical systems.
The keyword Industry 4.0 is located in a high-density area, which means that the connections of this word with other keywords are extremely strong. In the yellow area with lower density are the keywords Internet of Things, smart manufacturing, Big Data and cyber-physical systems. The keywords Industry 4.0 and Big Data are strongly connected according to their position in the graph. From the density visualization, it can be seen that there is only one red area, while many keywords are found in the green and blue areas. This indicates that research into the implementation of Industry 4.0 technologies in manufacturing is still in its infancy and is not mature. Consequently, there is still considerable potential for further exploration and investigation in this area.

3.2.4 Social network structure

The progress of science is the result of the collaboration of numerous scientists, both virtual and physical, who share their discoveries and build on each other's work [111]. In this study, the co-authorship analysis in VOSviewer was used to reveal the social network structure at the macro level, especially at the country level, as answer to RQ7. The analysis of country co-authorship can reveal the degree of communication between countries and the influence of countries in a particular research area. Theanalysis focused on countries with at least 10 publications and 100 citations per country. This narrowed the sample to 47 countries that met this criterion, out of a total of 97 countries considered. The method of fractal counting (the concept of fractional counting aims to mitigate the impact of documents with a large number of authors) and documents as weights were used.
The results of the co-authorship analysis are shown in Table 5 and Figures 12 and 13.

Table 5.Macro co-authorship analysis – an international collaboration

Country	Documents	Citations	Total link strength
Peoples R China	261	7032	116
USA	188	4848	90
Germany	209	4028	89
United Kingdom	153	4199	89
Italy	226	4429	75
India	186	4529	74
Brazil	123	4776	62
France	107	4897	60
Spain	104	1385	54

The table shows the countries with the highest total linkage strength, which means that they achieve the strongest cooperation with other countries (only countries with a total linkage strength of more than 50.00 are shown in the table), namely China, the United States, Germany, the United Kingdom, Italy, India, Brazil, France, and Spain.

Figure 12 shows the structure of the social network, i.e., the structure of international cooperation between countries, in research on the implementation of Industry 4.0 in the manufacturing industry. In Figure 12, it can be seen that the countries are distributed in 5 clusters and that the largest individual linkage strength, i.e., the largest cooperation in terms of co-authorship, is achieved by India and the United Kingdom (14.58) and China and the United Kingdom (13.67), followed by China and the United States with a linkage strength of 13.33, although they are not in the same cluster thematically. Different colours on the map indicate the diversity of research directions, while large nodes represent influential countries. The size of the node represents the productivity of the country (already shown in Figure 3 based on the number of publications). The links between nodes show the collaborative relationships between countries, and the distance between nodes and the thickness of links reflect the degree of collaboration. The thickness of the lines connecting the countries in the network visualization indicates the strength of the link between the countries, i.e., the number of joint publications. The thicker the line, the stronger the cooperation between these countries.

China achieves the greatest international cooperation, has the most publications, the most citations, and the greatest overall strength of connections, although it cooperates with a smaller number of countries than some other countries, such as the United States, Germany, and the United Kingdom.

Figure 13 shows the density visualization of the social network structure, highlighting the countries with the strongest cooperation with other countries (indicated by intense red colour). This visualization is based on the total strength of linkages.

In the area of implementing Industry 4.0 in manufacturing, there was the greatest international collaboration in research, led primarily by China. The following countries, in descending order, also showed significant collaboration: the United States, Germany, the United Kingdom, India, Brazil, and France. In contrast, countries in the yellow to blue range showed weaker collaboration in terms of joint research and publications. In particular, developed countries such as Japan, Canada, Ireland, and the Netherlands are less likely to collaborate with other countries in this area of research. This observation suggests that the field is still in its infancy and that international collaboration has been limited to date.

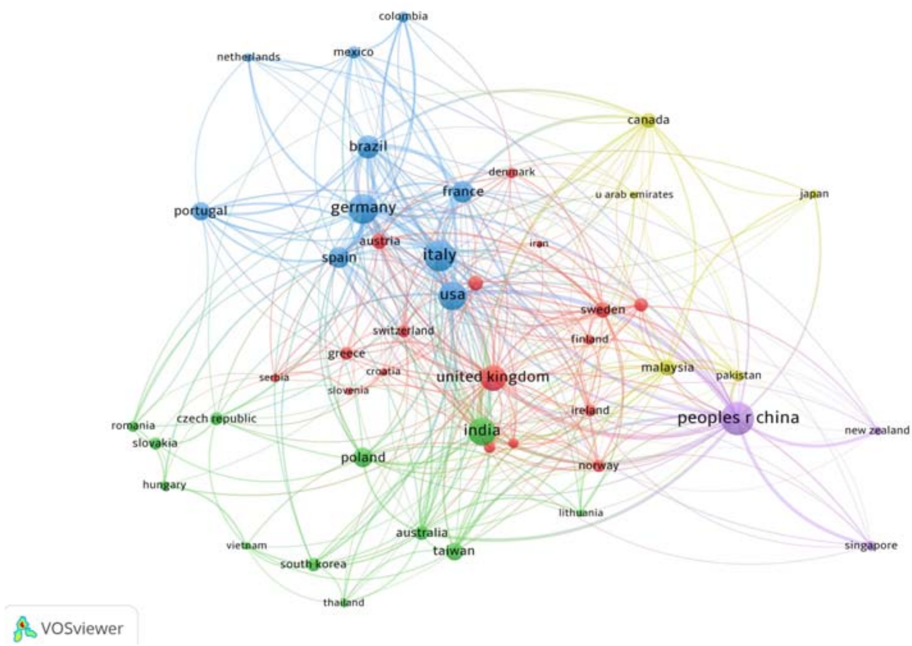

Figure 12. Social network structure

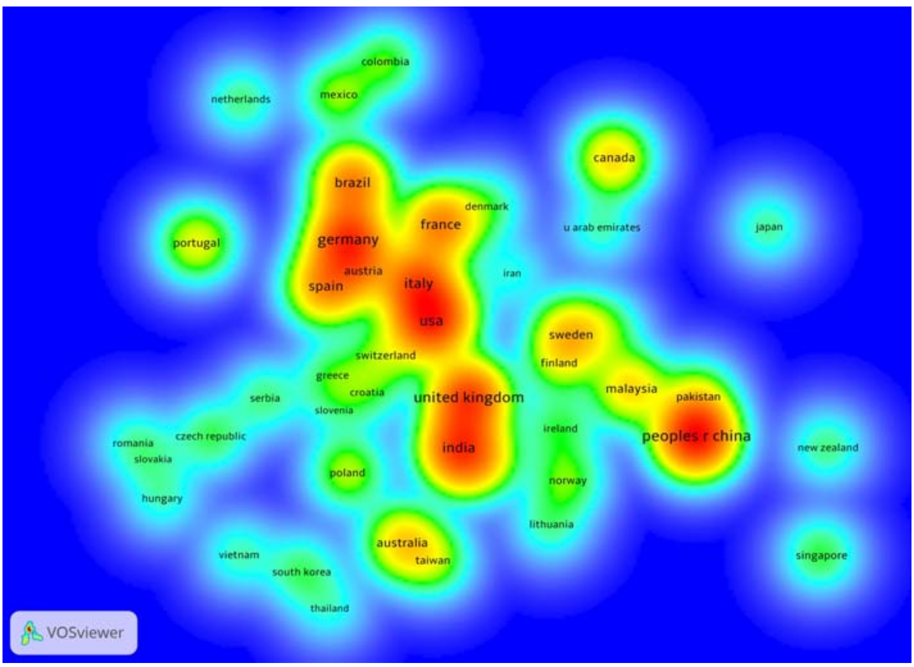

Figure 13. Social network structure – density visualization

4. Discussion

Answers to questions RQ1 through RQ7 were provided using descriptive analysis and scientific mapping.

The trend in publishing articles on the implementation of Industry 4.0 in the manufacturing industry indicates a significant increase in research output over time. A thorough analysis of the publication data shows that the number of articles published each year is increasing, indicating a growing interest and recognition of the importance of Industry 4.0 in the manufacturing industry. This trend underscores the increasing importance and impact of Industry 4.0 technologies in improving manufacturing processes and overall industrial efficiency. In identifying the countries contributing the most to research on the implementation of Industry 4.0 in manufacturing, several countries emerged as leading players. China stands out as a major player with a high number of publications and numerous citations. Following closely behind are the United States, Germany, the United Kingdom, India, Brazil and France. These countries have extensive research activities that demonstrate their commitment to researching and promoting the implementation of Industry 4.0 technologies in manufacturing. Some countries have strategies for Industry 4.0 adoption, but these are general guidelines; research on implementation models is less represented in the literature. Policy-level strategies have been adopted in developed countries that have stronger economies and greater investment opportunities in Industry 4.0. These countries are also more productive in scientific research, so the leading countries are China, Italy, Germany, the United States, India, and the United Kingdom. Developing countries face far greater challenges in implementing Industry 4.0 than developed countries with strong economies, primarily due to problems in investing in Industry 4.0 and other issues faced by both developed and developing countries.

In terms of the scientific disciplines to which the publications from the research sample belong, there is a clear concentration of publications from engineering and computer science, with production engineering and industrial engineering being prominent research areas within these disciplines. This is to be expected, as these disciplines are closely related to manufacturing. This reflects the importance of integrating Industry 4.0 technologies into manufacturing and optimizing industrial processes to improve efficiency and productivity.

As for the most cited authors, publications, and sources in the field of Industry 4.0 implementation in the manufacturing industry, there are some notable contributions, as mentioned earlier. These highly cited authors, publications, and sources identified as a result of the analysis highlight their influence and contribution to the research landscape in the area of Industry 4.0 implementation in manufacturing.

The intellectual research base for the implementation of Industry 4.0 consists of five research directions or clusters. The first cluster addresses a broader perspective of manufacturing transformation, while the second cluster examines specific technologies used in manufacturing to achieve optimization and adaptability and includes contributions published mainly in the formative stages of research on the implementation of Industry 4.0, focusing on cyber-physical systems, the Internet of Things, Big Data, and cloud computing. The third cluster focuses on the technical aspects of implementing Industry 4.0 and developing systems and strategies for successful implementation. This cluster focuses on technical details and challenges related to the implementation of Industry 4.0 principles. The fourth cluster focuses on the application of digital twins to improve production processes, while the fifth cluster explores the convergence between Industry 4.0 and lean manufacturing principles.

Despite their different focuses, all of these clusters contribute to the understanding and practical application of Industry 4.0 in the manufacturing industry.

Based on the bibliometric analysis, four main directions for future research can be derived. The future research directions emphasize ongoing exploration of advanced technologies, sustainability integration, lean manufacturing processes, and optimization techniques for production efficiency and environmental sustainability.

The conceptual structure provides valuable insights into the multidimensional aspects of digital transformation and Industry 4.0 in manufacturing. The findings highlight the importance of technology adoption, sustainability, integration of advanced technologies, effective management practices, and removal of barriers to the successful implementation of Industry 4.0 in the manufacturing industry.

The research used the VOSviewer software to visualize the temporal dynamics and research structure in the field of implementing Industry 4.0 technologies in manufacturing. The overlay visualization showed the emergence of cluster 4 as a thematic entity characterized by newer keywords compared to other clusters, and its maximum frequency of occurrence was observed in 2021. Meanwhile, earlier terms such as Cyber-Physical Systems, Smart Factory, Cloud Computing, and Internet of Things had peaked in earlier time periods.The analysis also showed a shift in research interest from exploring the enabling technologies of Industry 4.0 to their practical implementation. Newer concepts such as artificial intelligence, deep learning, blockchain, 5G, edge computing, asset administration shell, ism, and dematelgained prominence, as did concepts such as Industry 5.0, human-robot collaboration, and supply chain management. This shift shows that the research community is increasingly focused on developing strategies, policies and models for effective implementation. In addition, the presence of yellow terms in the visualization indicates potential future research trends in this area. Standardization and interoperability are essential to the successful implementation of Industry 4.0, and a key enabler for the manufacturing sector is the Asset Administration Shell (AAS) [112]. AAS is an integral part of the Reference Architecture Model for Industry 4.0 (RAMI 4.0) [113] and provides a standardized electronic representation of industrial assets. AAS plays a critical role in realizing the vision of Industry 4.0 by ensuring compatibility and harmonization between different technologies and systems within the industrial domain. AAS (Asset Administration Shell) and DT (Digital Twin) are two intersecting concepts within the realm of Industry 4.0, but while there is overlap between the two, they represent distinct aspects of the digital transformation in industrial processes[114].The presence of AAS (Asset Administration Shell) is evident in both the bibliometric analysis of Cluster 1 - Smart Manufacturing and Industry 4.0 Technologies Integration and the conceptual structure of Cluster 3 - Industry 4.0 Technologies and Integration. However, the science mapping analyses highlight the relatively limited research on the asset management shell model, as shown in the density visualization (as a blue area representing a poorly researched concept). Given the critical importance of interoperability to the successful implementation of Industry 4.0, it is important to increase research efforts in this area. In addition, other potential topics such as ISM (Interpretive Structural Modelling) and DEMATEL (Decision-Making Trial and Evaluation Laboratory), as well as emerging technologies such as artificial intelligence, deep learning, blockchain, 5G, and edge computing, have gained attention in recent research studies and offer further opportunities to explore the implementation of Industry 4.0 technologies in manufacturing.The density visualization of the keyword co-occurrence analysis showed that Industry 4.0 is strongly associated with other keywords, especially Big Data, indicating a strong interrelationship between these concepts. Co-authorship analysis revealed the social network structure of international collaboration in implementing Industry 4.0 in manufacturing. China led in terms of collaboration, followed by the United States, Germany, the United Kingdom, India, Brazil, and France. Developed countries showed limited collaboration, indicating the early stage of international cooperation. China achieved the greatest collaboration despite working with fewer countries. The findings emphasize the need for increased global cooperation in this research field.

5. Conclusion

Given the extensive scientific activity and research that has been conducted in recent years on the topic of Industry 4.0, it is evident that the effective implementation of its principles and technologies in the real manufacturing world remains a major challenge. This discrepancy arises from the gap between the technological capabilities and the practical implementation of their benefits in the manufacturing industry. The manufacturing sector is currently in the process of adopting Industry 4.0, facing obstacles such as outdated infrastructures, security concerns, the need for organizational culture change, and a shortage of skilled workers. Nonetheless, there is growing recognition of the growing momentum in implementing Industry 4.0 and its potential to profoundly impact the manufacturing in the future. This growing awareness has motivated us to conduct an extensive literature review on this topic to examine existing research and gain valuable insights into the implementation of Industry 4.0. Although there are literature analyses on this topic and the application of bibliometric methods in the related literature, to the knowledge of the authors of this study, there is no comprehensive bibliometric approach that addresses the state of research on the implementation of Industry 4.0 and in which comprehensive analyses are applied as in this study.

The bibliometric analysis conducted in this study provided a comprehensive examination of specific patterns, trends, and implications within the research community related to the implementation of Industry 4.0 technology in the manufacturing industry. The study underscores the transformative potential of Industry 4.0 in manufacturing and emphasizes the importance of continuous research, collaboration and strategic planning to fully realize the benefits of these technologies. Industry 4.0 offers manufacturing companies the opportunity to increase productivity, efficiency and competitiveness in a dynamic global environment. By overcoming challenges and leveraging advanced technologies, companies can revolutionize operations and drive innovation, paving the way for long-term success. The findings highlight emerging technologies such as artificial intelligence, deep learning, blockchain, 5G, asset administration shell, highlighting their relevance and potential impact on the implementation of Industry 4.0 in manufacturing. The findings serve as a valuable guide for researchers, policy makers and stakeholders, enabling informed decisions on technology adoption, process optimization and overall digital transformation.

To fully realize the potential of Industry 4.0, it is also important to conduct further research focusing on the integration and interoperability of different technologies and systems in the context of manufacturing.

Further research is needed on how these technologies can work together seamlessly to enable efficient data exchange and collaboration between the various components of the manufacturing ecosystem. By addressing these research gaps, companies can overcome barriers, ensure successful implementation, and realize the full potential of Industry 4.0 in manufacturing. This will lead to advances in productivity, efficiency and competitiveness and shape the future of the manufacturing industry.

The limitation of this study is that it focuses specifically on the implementation of Industry 4.0 technologies in the manufacturing industry only. It does not cover other industries or sectors where Industry 4.0 may have other impacts and challenges. In addition, the analysis is based on data from the Web of Science

Core Collection, which may not include all relevant publications on the topic. The results and conclusions of the study are based on the available data and may be affected by any biases or limitations within the dataset. Despite the limitations, this study provides valuable insights that contribute to a better understanding of the relevant aspects of Industry 4.0 implementation.

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