A bibliometric analysis of the landscape of measuring technology maturity in the enterprise internet of things

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ABSTRACT

The internet of things (IoT) is an emerging technology that has taken great relevance in the current socioeconomic context, especially in the business environment, due to its ability to generate competitive advantages. Its adoption presents challenges, such as understanding the value proposition, staff training, and ensuring connectivity and compatibility. In addition, it is crucial to establish the technological maturity of the IoT in enterprises to determine their current state and take steps to address these challenges. In this study, a bibliometric analysis of 431 articles from different scientific databases was performed using Bibliometrix and VOSviewer tools to determine the current state of the domain. The results indicate that the field is booming, with an annual growth rate of 22.58%. Its conceptual structure is composed of the IoT implemented in different contexts, in conjunction with the influence of sister technologies such as big data and blockchain, suggesting limited specificity in establishing the maturity of the enterprise IoT. Countries such as China and Brazil were found to be at the forefront in the area. A promising aspect is establishing standardized ways to measure technological maturity and provide guidelines for improving internet of things adoption.

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1. INTRODUCTION

The internet of things (IoT) is one of the new technological trends that are revolutionizing society, given its versatility across numerous domains [1], such as healthcare [2] and automation [3]. It has improved customer service quality and enabled businesses to optimize processes, gather information, and analyze data [4]. IoT also offers essential services in the business environment, enabling companies to offer specific services and reduce labor costs [5]. IoT can support technological processes in specific areas, such as smart cities [6] and agriculture [7]. These stances exemplify how IoT has positively impacted diverse fields and indicate its great potential to play a fundamental societal role.

The significance of IoT devices in various domains, particularly in enterprises, underscores the need to acknowledge the multiple challenges associated with their adoption [8]. These challenges encompass comprehending the technology's value proposition and its acceptance by the work team [9], training personnel to implement IoT in their processes [10], establishing security protocols and standards, ensuring device connectivity and compatibility, and having a support team for its use [11]. One specific challenge lies in the adoption of the technology itself. In the context of Industry 4.0, technology maturity indexes have been devised to evaluate the technological readiness of an organization. These indexes aid in identifying the areas of the business that require support and improvements to facilitate technology adoption [12]. By utilizing these indexes, companies can better understand their capabilities and develop a roadmap for adopting new technologies that suit their specific needs and objectives [13]. This, in turn, can translate into increased productivity, profitability, and competitiveness and identify areas for improvement [14].

Additionally, these indexes permit companies to benchmark their performance against competitors and industry standards. Within the domain of the IoT, there has been an acknowledged requirement to develop indexes or measurement models for evaluating the technological maturity of companies [15]. Nevertheless, there needs to be more bibliometric analyses that offer a comprehensive view of the scientific output concerning such measurement tools. This dearth hampers the identification of potential research areas, trends, and scientific collaborations, thereby impeding the progress of enterprise IoT research.

In scientific literature, various bibliometric analyses have been conducted in the general IoT domain. For example, Rejeb *et al.* [16] reviewed the maturity of IoT use in supply chain management and logistics by analyzing 807 journal articles published over two decades. This review uses bibliometric parameters to identify the top journals and authors in this field and critical research areas, such as radio frequency identification (RFID) technology, Industry 4.0 technologies, and reverse logistics. The study provides a better understanding of the current state of IoT in supply and logistics and identifies areas for future research. Another study is [17] explored the relationship between IoT and the circular economy in manufacturing. The study used the PRISMA process and VOSviewer for bibliometric analysis; this work maps the case studies and provides a better understanding of the area. Along these lines, in study [18], the application of IoT in smart cities is analyzed using bibliometric techniques to identify the most relevant articles, authors, journals, countries, and keywords. The study analyzed 1,802 articles from Scopus and utilized VOSviewer to build the co-occurrence network. The results highlighted the significant growth in IoT research and major applications in smart cities, such as smart buildings, transportation, and healthcare. Finally, Other bibliometric studies, such as food safety and precision agriculture, also use bibliometric analyses to examine the research landscape of IoT in these domains and identify critical areas for future research [19], [20].

The main distinction of this bibliometric analysis concerning other similar studies is its focus on determining the conceptual structure of the technology maturity domain in enterprise IoT. This sets it apart from other studies that generalize the concept to include other related technologies like artificial intelligence, big data, and cloud computing, which are the pillars of Industry 4.0 [21]. This is relevant because IoT is a set of hardware devices that must work in synergy with software, which implies unique technical challenges, such as interconnectivity, ubiquity, and scalability. Considering the above, the main objective of this study is to conduct a bibliometric analysis that explores the measurement of technological maturity in enterprise IoT through descriptive and inferential knowledge analysis.

2. MATERIALS AND METHODS

This section explains the methodology for conducting a bibliometric analysis to measure the technological maturity of IoT within companies. It uses descriptive and inferential statistical techniques to examine sources, affiliations, countries, and their relationships [16]. Considering the above, a bibliometric analysis was conducted in the domain of IoT, using the guidelines proposed by Bouzembrak [19] as a reference for analysis specification. Additionally, the bibliometric analysis framework introduced by Donthu [22], which offers guidelines for conducting bibliometric analyses, was employed. Moreover, some aspects of the science mapping workflow methodology [22] were utilized to acquire, scrutinize, and represent the data.

The primary tools used in this study were R-Studio with its Bibliometrix library [22] and VOSviewer [23]. The former provides the instruments to perform a complete bibliometric analysis, while VOSviewer is a software that builds and visualizes bibliometric networks. These tools are widely accepted and fundamental to performing Scientometrics in any area [24]. Finally, this study used R-Studio [25] and Google Sheets to generate the graphs.

2.1. Systematic information collection

A search string was used to obtain systematic information from bibliographic databases as shown in Table 1. This search string was constructed using the PICOC criteria [26], which allows for structuring concepts logically and methodically, thus ensuring complete coverage of all relevant topics. The data were extracted from the scientific databases Scopus and Web of Science (WoS), two reputable databases accepted as repositories of scientific papers in the engineering domain [27]. These databases contain journals from prestigious publishers such as Elsevier, Springer, Taylor & Francis, MDPI, and IEEE. The search string applied in both sources consists of three clearly defined parts to avoid noise from other domains. First, all IoT-related concepts are included. Secondly, concepts linked to indexes or maturity assessment models are searched for, along with several synonyms, to find as many published documents as possible. Finally, the third part of the search string concentrated on the application domain, specifically companies with various purposes, such as manufacturing or technology, and their corresponding synonyms.

Table 1. Search string applied on WOS and Scopus

Search string
("Internet of Things" OR "IoT") AND ("digital maturity" OR "evolution stage" OR "maturity index" OR "Capability maturity index" OR "IoT maturity index" OR "maturity level" OR "technology maturity index" OR "maturity model" OR "readiness assessment" OR "self-assessment" OR "technology adoption" OR "technology readiness level") AND ("Companies" OR "Corporation" OR "Digital companies" OR "Enterprises" OR "Information technology companies" OR "Internet companies" OR "Software companies" OR "Tech companies" OR "Technology company")

2.2. Search execution

A methodical search protocol was developed to ascertain the appropriateness of studies for subsequent analysis. This protocol involved a targeted review of titles, abstracts, and keywords in peer-reviewed journal articles and conference papers published in English. The primary aim of this protocol was to uphold the scholarly and superior quality of the examined literature.

This investigation was not confined to a specific time frame and was conducted in November 2023. This endeavor identified 520 articles spanning from 2007 to 2023. A systematic filtration process was subsequently implemented to evaluate the pertinence of the articles to the designated subject matter. This process was steered by pre-established inclusion and exclusion criteria as shown in Table 2, which centered on examining article titles, abstracts, and keywords.

Documents needing more adequate metadata or outside scope were excluded. Additionally, 73 duplicate items were found and merged, resulting in 431 documents meeting the criteria. The data extraction incorporated supplementary sources, including secondary studies. Bibliometric analysis of the identified articles used Bibliometrix and VOSviewer tools.

Table 2. Inclusion and exclusion criteria used in bibliometric analysis

Inclusion criteria	Exclusion criteria
Scientific studies that assess or determine the degree of maturity in the enterprise IoT domain.	The presented study is a preliminary version that precedes a broader study on the same topic.
The research should provide a specific solution for the enterprise IoT domain.	The publications are duplicates of the same authorship, with similar titles, abstracts, results, or text.

3. RESULTS AND DISCUSSION

Bibliometric analysis highlights critical metrics such as sources, journals, production, affiliations, and existing relationships in the field. This analysis provides a global view of the research area, allowing researchers and practitioners to gauge its current state and identify emerging trends. Examination of bibliometric indicators provides valuable insights into the potential adoption of IoT technology within the business ecosystem, facilitating decision-making and strategic planning.

3.1. General domain information

The bibliometric analysis reveals the scientific production in the company domain as shown in Figure 1 from 2007-2023, with 431 articles evaluated from 263 sources, including journals and conference papers. The mean age of the papers under investigation is approximately 2.8 years, signifying the early research stage in the concerned field. Furthermore, an annual growth rate of 22.58% in the quantity of published papers has been observed, indicating a consistent and escalating interest in the subject matter. This growth rate remains notably higher compared to other domains, such as emerging economies at 8.0% [28] or artificial intelligence in health at 17% [29]. These results imply a prevailing enthusiasm for applying IoT technology in corporate contexts, with a strong resonance within the research community.

The analysis also reveals that the average number of citations per paper in this field is 21.7, indicating the considerable importance of these papers for the scientific community and future research. This value is notably higher than other IoT studies conducted in non-business [30]. Additionally, the data shows that the papers analyzed draw from a vast knowledge base, with a total of 20.136 references utilized. This finding suggests that researchers in this field have access to a broad range of relevant information sources, which could foster further development and innovation in the domain.

Figure 1. General information on the bibliometric analysis in the domain

The keyword distribution analysis shows that 1,407 KeyWords Plus and 1,595 author keywords have been utilized [31]. This indicates a broad spectrum of key terms employed to describe research in the IoT maturity indices applied in the enterprise's domain. These findings aid those interested in researching this area and highlight the diverse terminology used to describe research in this field.

The examination of the 431 scrutinized documents divulges that a cumulative total of 1,454 authors have made contributions to their generation. Among these authors, only 24 have authored papers individually, indicating a pronounced propensity for collaboration within this domain. This observation underscores the field's robust maturation, facilitated by the synergy of researchers possessing discrete domains of expertise working collectively on projects of shared interest [32]. Furthermore, the mean count of co-authors per document is 4.04, emblematic of a robust inclination towards cooperative endeavors amongst scientific practitioners. Through statistical scrutiny, it also becomes evident that 24.83% of collaborative authorships extend across international boundaries, indicative of the primary focus of research within domestic networks. This discernment implies the presence of a restricted number of well-established global partnerships geared toward the advancement of knowledge within this realm.

The inferential analysis reveals a noteworthy surge in the pursuit of integrating IoT maturity mechanisms within corporate settings. This domain is experiencing swift expansion, underscored by many citations and references. The heightened attention and pertinence in this realm can be ascribed to the marked level of collaboration among authors, spanning both domestic and international spheres.

3.2. Annual scientific production in the domain

Figure 2 presents a condensed representation of the yearly scientific output about utilizing IoT maturity indexes within companies. It is evident that such production has gradually surged over time. However, a substantial escalation in the volume of published articles has been observed since 2016, with its highest point in 2022, which speaks of the scientific relevance of the study domain in recent times.

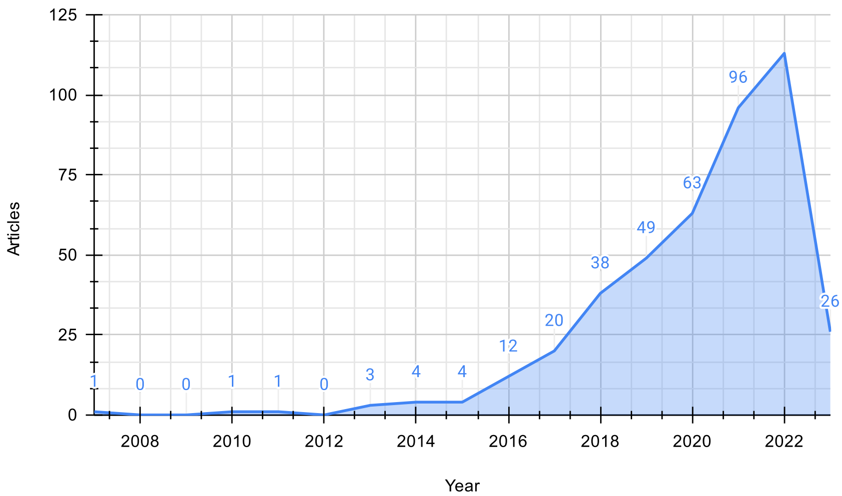

Figure 2. Annual publications in the domain of enterprise IoT

Punctually, between 2007 and 2015, the annual volume of published articles on IoT maturity indices applied in enterprises could have been higher, with an average of fewer than two articles per year. However, a remarkable surge in the number of publications was observed from 2016 onwards. Notably, 12 articles were published in 2016; a steady increase followed this in subsequent years. 2017, there was a significant spike, with 20 articles published, followed by further growth in the subsequent years, namely, 38 in 2018, 49 in 2019, and 63 in 2020. In 2021, a substantial escalation was observed, with 96 articles published, and the trend continued in 2022, with a record-breaking 113 articles published. As of March 2023, 26 articles have already been published, corroborating the growing trend in this field.

The presented data demonstrates a consistent upward trend in utilizing IoT maturity mechanisms within enterprise contexts. Notably, there has been a significant surge in publications on this topic since 2016. This pattern underscores the ongoing evolution of this field, capturing sustained attention from the research community. These observations corroborate earlier IoT research, emphasizing the escalating scholarly interest in the multifaceted dimensions of this technology [33].

3.3. Relevant sources in the domain

Identifying pertinent sources within a specific domain, such as academic journals, holds great significance in comprehending the scientific terrain, facilitating informed decision-making in academia, funding institutions, and formulating policies to enhance technological advancements [22]. Figure 3 presents the primary ten sources that publish articles in the relevant research domain in the present bibliometric analysis. A thorough analysis of the prominent sources publishing research in a particular field can provide valuable insights into the current state of knowledge, emerging trends, and areas that require further exploration. Furthermore, this analysis can assist researchers in identifying reputable and influential journals to disseminate their findings, fostering collaboration and knowledge exchange within the scientific community.

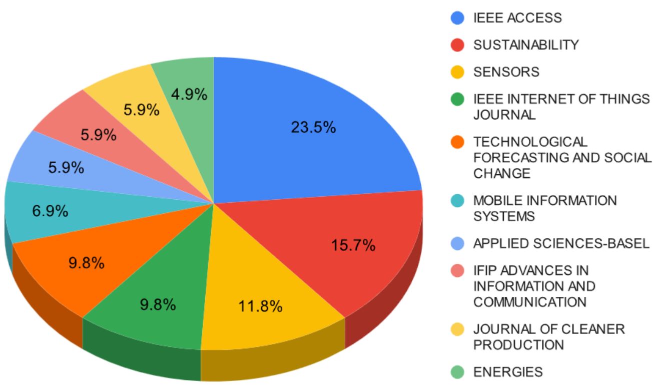

Figure 3. Distribution of bibliographic sources in the domain

The bibliometric analysis indicates that the IEEE Access source exhibits the highest activity level in publishing articles on indices or evaluation models applied to IoT in enterprises, with 24 publications. Sustainability ranks second with 16 articles, followed by Sensors with 12 articles. Other sources have published between 2 and 10 articles, indicating that they are less relevant in this research area. These findings imply that the journals above are vital reference points for empirical IoT research in enterprises and provide valuable information to researchers and practitioners in the industry. Notably, the leading quartet of journals responsible for disseminating the most articles in this domain has received a Q1 ranking within the SCImago Journal Rank [34]. These rankings underscore their scientific caliber and substantial influence on the research community, as gauged by the citation counts garnered by each publication.

3.3.1. Metrics of the leading sources in the domain

Concerning the productivity metrics of journals in the relevant domain of study, Figure 4 presents the H-index, G-index, and M-index, respectively. The H-index is a metric that quantifies the productivity and impact of a journal by considering the number of articles published and the number of citations they receive. The G-index is another metric that considers the distribution of citations among articles and assigns more weight to highly cited articles. The M-index is a variation of the G-index that considers the age of publications and assigns more weight to recent articles [34].

The journal with the highest H, G, and M indices is IEEE Access, with 9, 17, and 1.80 values, respectively. This indicates that the journal has published numerous articles in the field and is a benchmark in this research area. Furthermore, IEEE Access has published some highly cited articles, contributing significantly to its overall impact. This fact illustrates how combining various citations in a short period and publishing multiple articles in the same source with these characteristics establishes IEEE Access as a leading journal in this domain and a benchmark in terms of metrics. Significantly, the total number of citations varies widely among journals, ranging from 30 to 1,116 in all the sources found. Specifically, the International Journal of Production Economics presents the highest number of citations, followed by the Journal of Cleaner Production and Technological Forecasting and Social Change. These journals present low values in the H, G, and M indices, as they have published few relevant articles compared to IEEE Access. This suggests that these articles are isolated cases and that the authors have preferred other sources.

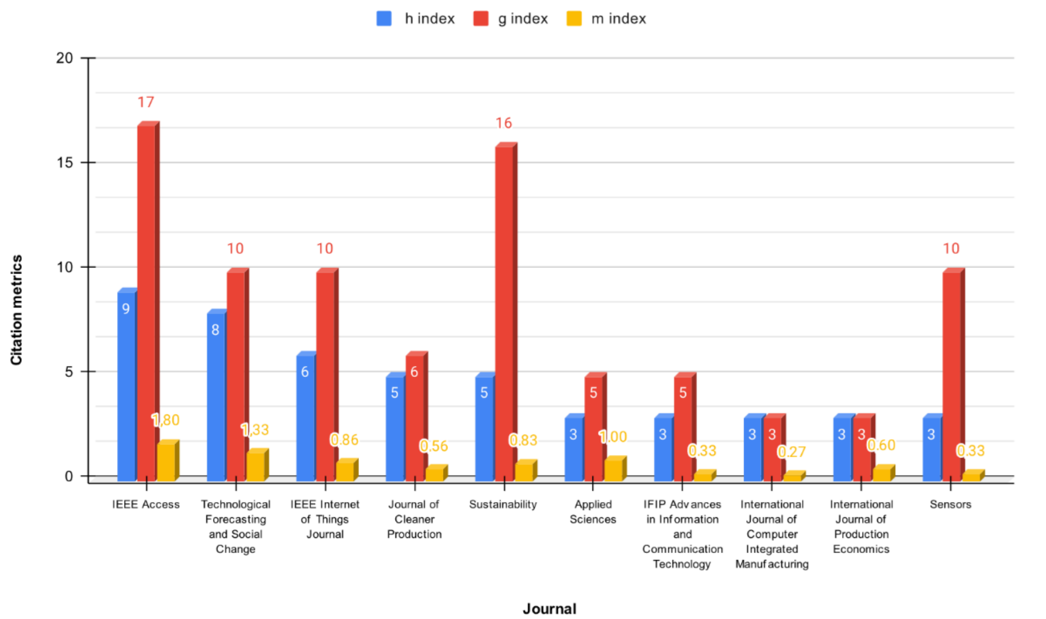

Figure 4. Distribution of productivity metrics for the ten reference journals in the domain

Finally, these journals were published between 2013 and 2021, and most were published after 2015. This relatively short time frame indicates that this field is relatively new and emerging. The fact that the publications are so recent suggests that there are still opportunities for novel contributions and innovative research in the field. As the field continues to evolve, new perspectives, methodologies, and findings may reshape our understanding and advance the current body of knowledge.

3.4. Most productive countries in the domain

Knowing which countries are the most productive concerning IoT maturity indices or evaluation models in enterprises is essential because it provides information on which regions are leading in adopting and utilizing IoT technologies. This information can help companies and organizations decide strategically where to invest infrastructure and resources. It can also provide a benchmark to measure progress and identify areas for improvement. For example, if a country has a high maturity index, other countries can take it as a model of best practices and strategies for success [35]. In addition, knowing the IoT landscape in different countries can also help companies identify potential partners and collaborators. By knowing which regions have the most advanced IoT ecosystems, companies can target their business development efforts and build relationships with key players in those areas.

Figure 5 displays a frequency distribution of scientific articles evaluating IoT technology maturity in enterprises published by researchers from various countries. The data in the figure indicates that China is the foremost contributor in this field, with 369 published articles. South Korea follows closely behind, with 68 articles, and India has 57 articles. The United States ranks fourth with 52 articles, while Brazil, the United Kingdom, and Germany have published 45, 41, and 39 articles, respectively. Italy, France, and Spain round out the top ten, with 31, 23, and 22 articles, respectively.

The data shows that China has firmly established a dominant stance in research concerning the assessment of IoT technology maturity. Its notable lead in article publications eclipses that of other nations. This prevailing trend reflects China's pronounced interest in technological innovation, particularly within the domain of IoT, which is congruent with its affiliations in this domain. Pioneering public policies like the Internet Plus program and the made in China 2025 initiative have contributed to China's preeminent role in IoT. The Internet Plus program is designed to amalgamate cloud computing, extensive data analytics, and IoT across sundry industries. Concurrently, the Made in China 2025 initiative strives to amplify the realms of the industrial internet of things (IIoT) to invigorate advanced technology sectors [36].

In this line, South Korea and India also demonstrate a high level of interest in the research topic, as evidenced by their relatively high publication frequencies. In contrast, developed countries such as Japan, Australia, and Canada exhibit low publication frequencies, suggesting a relatively lower level of interest in this area despite their advanced technological industries. This can be attributed to their focus on other research topics or the inadequate funding and resources allocated to this field of research.

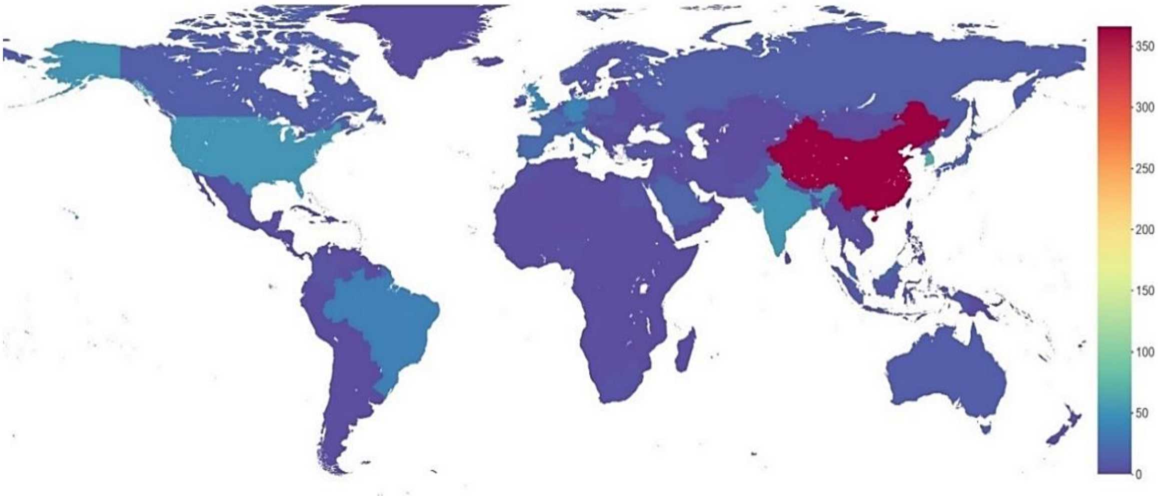

Figure 5. Global distribution of countries publishing in the domain

However, if the analysis is narrowed down to developing or third-world countries, India’s frequency of 57 is relatively high. This suggests that India has progressed in an emerging field despite existing challenges and limitations. The United States, a developed country, has a lower frequency 52. Brazil, a developing country, has a frequency of 45, which is comparatively higher than that of developed countries such as France and Spain. Therefore, some countries, including several third-world countries, contribute significantly to this research. The data also indicate that a country’s status does not necessarily constrain its research output in this domain.

3.4.1. International relations in the domain

Bibliometric analysis is a method used to assess international collaboration by quantifying the number of articles published by corresponding authors from the same country and those with corresponding authors from different countries. In this context, publications authored by individuals from a single country are known as single-country publications (SCP). Conversely, multi-country publications (MCP) are those in which authors from different countries have collaborated, thus representing instances of international collaboration [22].

The analysis findings indicate that China has the highest number of publications measuring the technological maturity of IoT companies, followed by Korea, India, and the United States. This implies that a select group of countries predominantly conducts research in this field, as most publications are authored by researchers from a single country. This observation is supported by Figure 6, which illustrates that China is the leading contributor, with 92 publications authored solely by Chinese researchers, followed by Korea and India, with 27 and 17 publications, respectively. However, these figures account for over 60% of the total output per country, suggesting that the countries above have established robust technological, research, and economic infrastructures and are actively investing in this domain.

In contrast, the number of collaborative publications between authors from different countries is relatively low compared to individual publications. While Brazil is a productive country, its publications are almost equally divided between domestic and international collaborations. Similarly, Saudi Arabia has more collaborative publications than individual publications. Even so, collaborations among the leading producing countries are limited, possibly due to language barriers, divergent research methodologies, financial constraints, or a lack of international research networks [37]. Overall, most of the advancements in the enterprise IoT domain are concentrated in a few countries, highlighting the potential benefits of increasing international collaboration. Such collaboration could facilitate more inclusive and multicultural advancements in research [37].

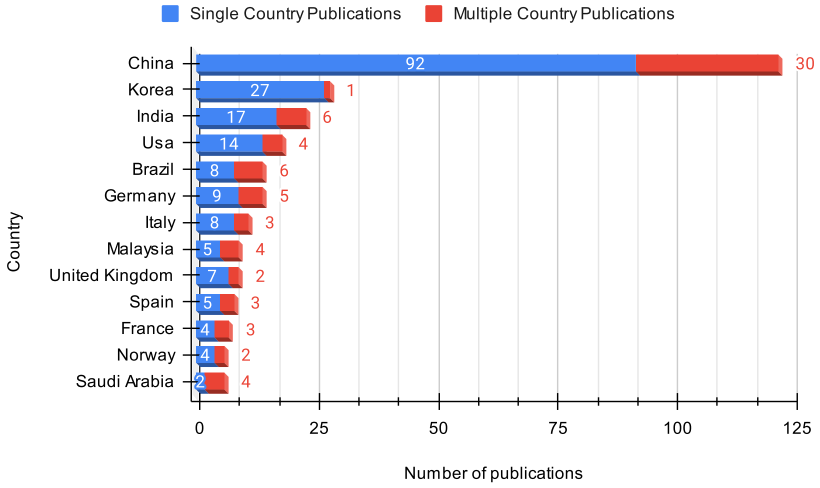

Figure 6. Representation of publications by single- and multi-country authors

3.4.2. Cross-country collaborations-trends

Figure 7 presents data regarding the extent and dynamics of international collaborations in enterprise IoT. The countries have demonstrated significant productivity in this domain, as indicated by the blue shading on the map. The interconnecting red lines represent the networks of cross-regional collaborations, highlighting the global nature of research efforts in this field. These collaborations are crucial for advancing the development of enterprise IoT technologies, as they facilitate sharing knowledge, resources, and expertise across borders.

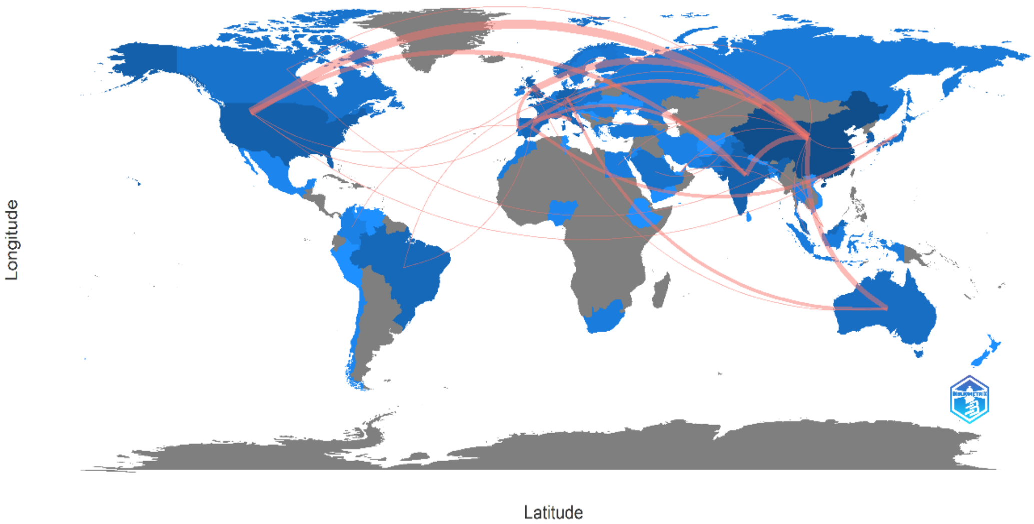

Figure 7. International relationships between countries in the domain of measuring enterprise IoT maturity

China holds the top spot for cross-border collaborations with 61 partnerships in the field, followed by the United Kingdom with 26 collaborations and the United States with 15. This indicates that China is actively engaging in partnerships with other countries in this field, aligning with previous findings that identify it as a leader. The leading collaborators are all developed countries, suggesting room for improvement in the field by integrating developing countries, which could provide researchers with a more inclusive context and a more comprehensive global perspective. Furthermore, the findings reveal the uneven distribution of collaborations among countries, with some countries needing partnerships in this domain while others boast several.

Figure 8 shows a VOSviewer-generated bibliometric network representing collaborative research efforts across countries to evaluate enterprise IoT maturity levels. Boxes represent countries, and connections are colored to indicate relationships among authors, institutions, or groups. Specifically, the green cluster, which comprises China, the United States, England, Russia, South Korea, and Portugal, indicates a high degree of collaboration among these countries, making them critical partners in the IoT domain. Moreover, these countries are the most productive regarding scientific output. The red cluster of Germany, Austria, Denmark, Poland, and Sweden highlights strong collaboration among scientists of geographically close countries. Finally, it observes the yellow cluster, located geographically more distant between components, and where it is evident that the countries present have a low scientific production in the domain.

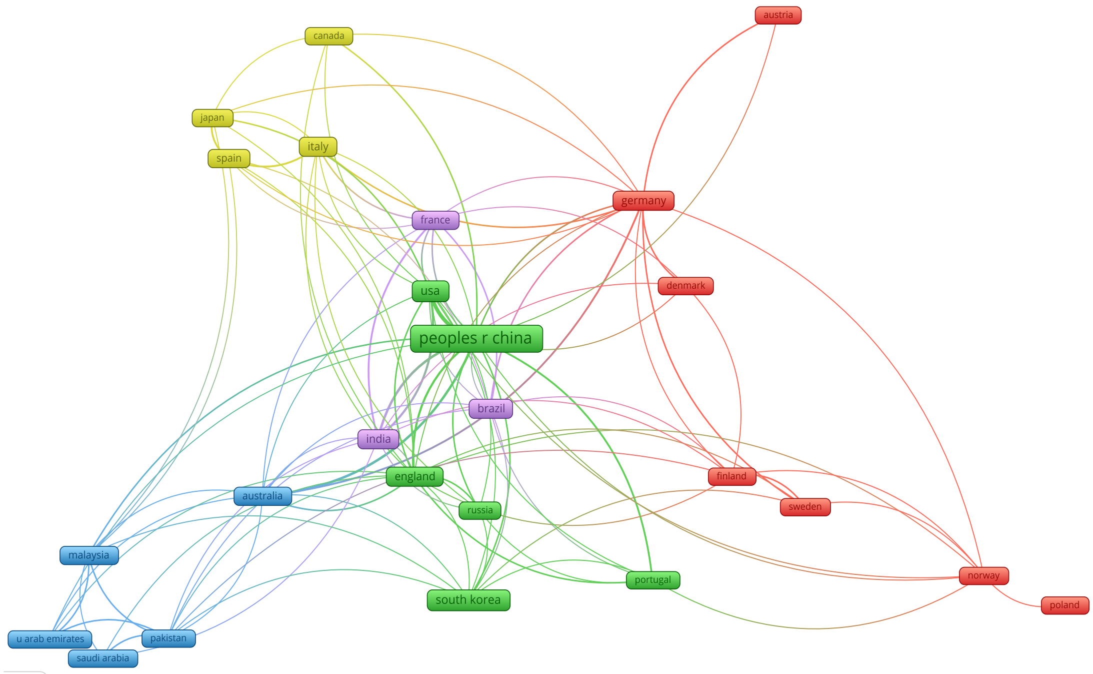

Figure 8. Bibliometric networks concerning country associations using the co-occurrences of the analyzed documents

Establishing international collaborations in the IoT field, especially between neighboring countries, can accelerate the development of models and indices for assessing enterprise IoT maturity. Fostering relationships between countries with different levels of scientific output can advance the knowledge and specificity of research tailored to real-world applications, enabling progress in IoT maturity.

3.4.3. Countries with the highest number of citations

Figure 9 illustrates the total citation counts by country for maturity indices or evaluation models of the IoT in enterprises. The data reveal that China has the highest total citation count, with 1,446, followed by Brazil, with 1,066. This finding indicates that research in this field is relatively more active in these countries. However, when evaluating the average number of citations per article, Brazil has the highest average citation count of 88.80, followed by Hungary with 45.60 and Sweden with 46.80. Research conducted in Brazil and the countries above is of high quality and significantly influences the academic community. Furthermore, it is worth mentioning that while China has the highest total citation count, the average citation count per article (12.30) is relatively lower, indicating that research on maturity indices or enterprise IoT assessment models in China may be frequently cited. However, the average research quality may be lower than in other countries.

Finally, in the bibliometric network referring to country citations as shown in Figure 10, one can see marked relationships between countries; the red cluster shows that the most cited countries are China, Canada, South Korea, Malaysia, and Germany, which is a cluster very similar to that of Figure 9, this shows how consolidated the collaborative network of these countries is. Regarding the other clusters, there is little correlation between their production and their citation, which indicates that there are no consolidated networks among the most producing countries in the domain other than those mentioned above.

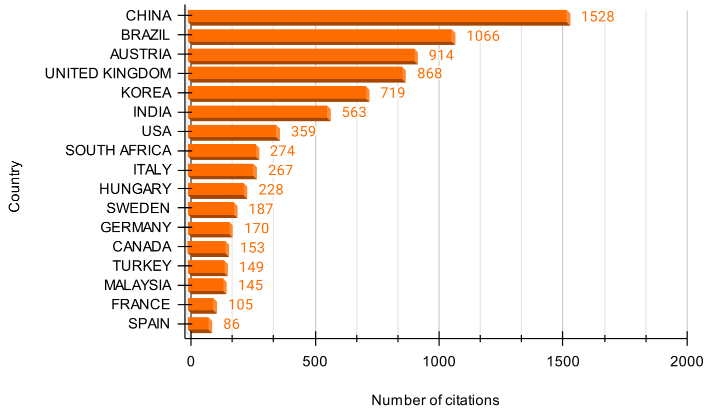

Figure 9. Countries with the highest number of citations in the domain

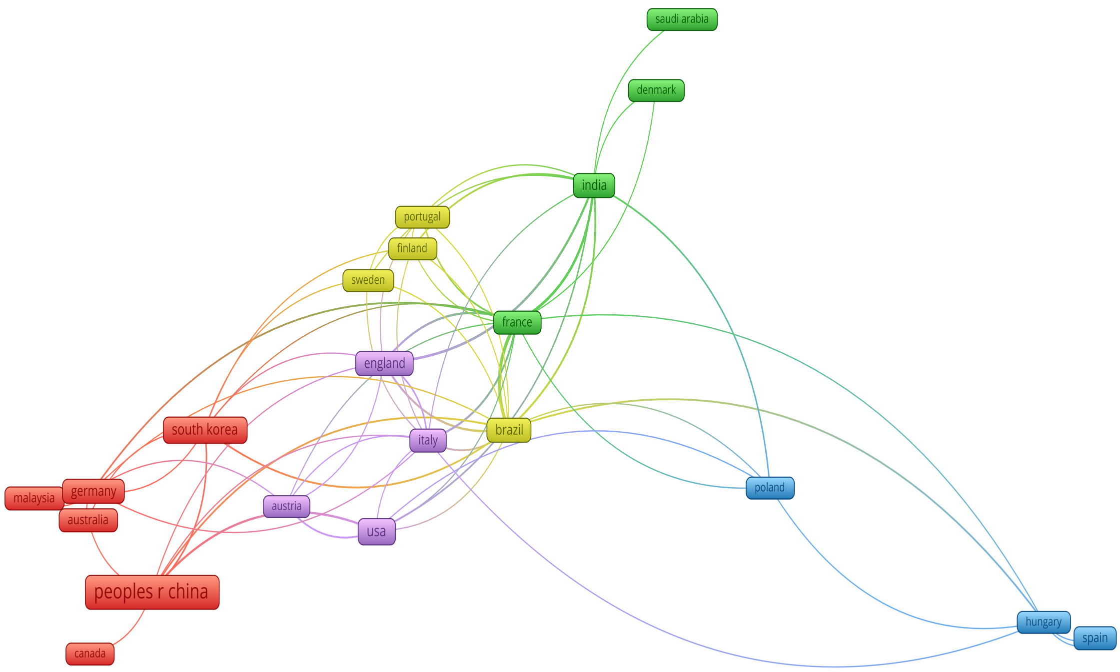

Figure 10. Cross-country bibliometric citation network where five clusters can be evidenced

3.5. The conceptual structure of the domain

The conceptual structure of a domain identifies interrelationships between concepts using keywords and KeyWords Plus. This framework aids in quantitative analysis, intellectual base visualization, and trends in the research field [22]. Regarding the specific research domain under investigation, it has been noted that authors use numerous keywords to define the area and its characteristics in their articles. The term “Internet of Things” is the most used, with 164 occurrences among the various papers. “Industry 4.0” follows closely behind. Surprisingly, blockchain technology, related to IoT in industrialization, holds second place. In fourth place, the term “technology adoption” is one of the focus areas in this article. Figure 11 indicates that many articles do not use identifiers such as “technology adoption” or “maturity models”.

Moreover, only a few mention maturity measurement mechanisms. This suggests that, while there are studies on measuring IoT technology within this area, it may need to be receiving the necessary importance. Alternatively, there may be a few indexes that have been implemented in this domain. Therefore, there is an opportunity for further research. Although maturity measurement indexes for Industry 4.0 are available, they are scarce or nonexistent within the IoT business domain.

Focusing the analysis on the Plus keywords as shown in Figure 12, which are automatically extracted from the titles and abstracts of articles cited by the indexed article using an algorithm to enhance search efficiency in various disciplines [31], the results reveal that "Internet" and "Internet of things" are the Plus keywords with the highest frequency of occurrence in the specific study domain. "Models" and "Adoptions" are also prominent, ranking fourth and sixth near the search. This finding is consistent with the authors' keywords, suggesting that the implementation of models or indexes of technology evaluation in IoT in companies and their conceptual structure need to be developed more. Alternatively, it may be due to the algorithm's inadequate effectiveness in establishing the specific domain of the study, relying instead on generic mechanisms and identifiers to determine the area of interest, as other research indicates that these mechanisms are not sufficiently effective [38]. Adopting the Mesh system, which standardizes indexing and has gained widespread acceptance in the research community, can help accurately establish an indexing exercise.

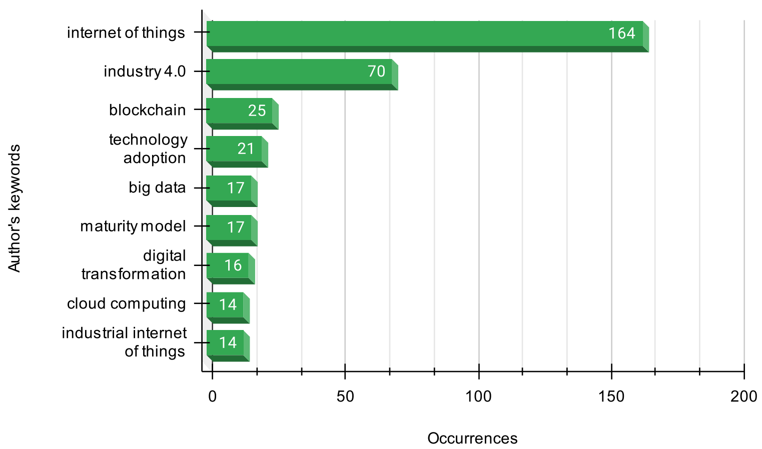

Figure 11. Distribution of keywords used by authors in the domain

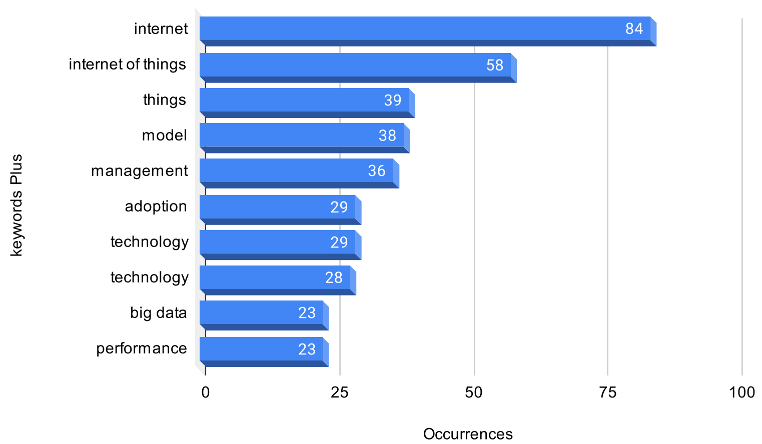

Figure 12. Distribution of KeyWords Plus used in the domain

3.5.1. Interrelationships in the conceptual structure of the domain

Understanding the interrelationships in a domain's conceptual structure is crucial for comprehending its meaning and organization and identifying challenges and structures. It observed five clusters by focusing on author keywords as shown in Figure 13. The green cluster contained terms such as "internet of things", "sustainability", "big data" and "artificial intelligence" These are sister terms and form the core matrix of what Industry 4.0 entails. The red cluster included terms such as "industry 4.0," "digitization," "digital transformation" "digital twins," "optimization," and "enterprises," which are closely related to the meaning and goal of Industry 4.0, i.e., the digital transformation of markets, factories, and organizational structures. The green cluster contained terms describing the scope of the domain search, such as technology adoption, circular economy, and energy efficiency. Finally, the purple cluster comprised "security" and "deep learning," representing key technology trends in Industry 4.0 and IoT.

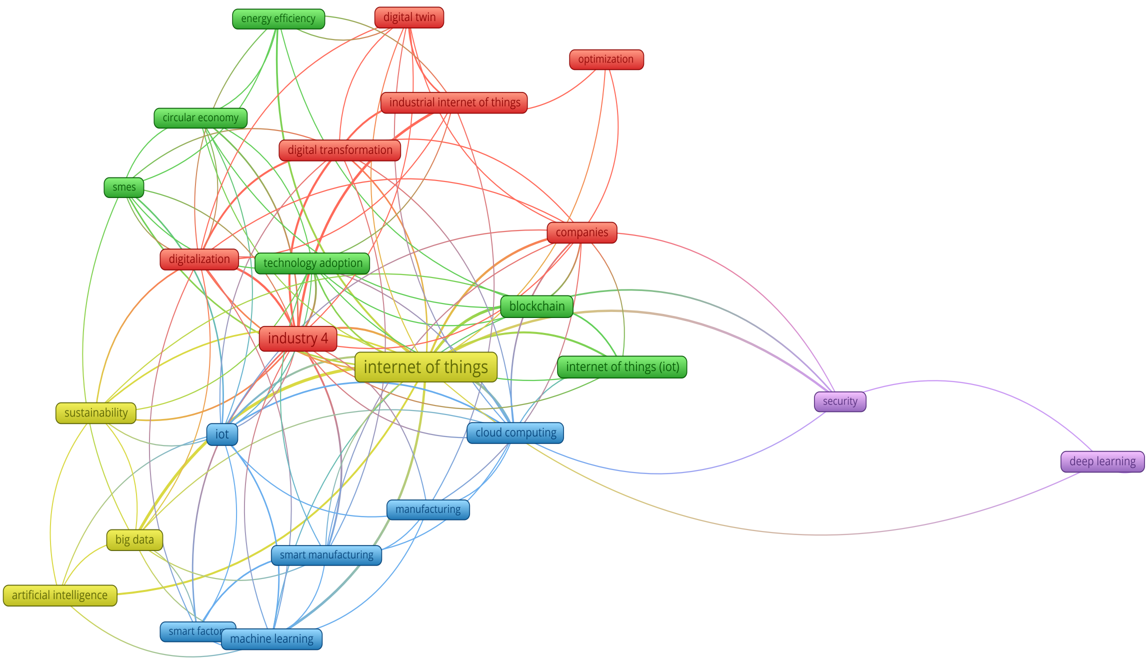

Figure 13. Interrelationships between keywords in the domain

Two well-defined clusters for the keywords generated by the Scopus and WoS databases present a clear distinction. The red cluster represents the first group, primarily composed of terms generated by Scopus, indicating a significant interrelationship between them. On the other hand, the green, blue, and yellow clusters represent keywords generated by the WoS database, highlighting a notable difference in the indexing process compared to Scopus. As shown in Figure 14, the terms that connect all the surrounding items are “Big Data”, “efficiency”, “acceptance of a technology model”, and “innovation”. This pronounced difference between the terms suggests that both scientific databases adopt distinctive indexing procedures. While WoS employs an algorithm based on article titles cited by the article to be indexed, Scopus relies on a data architecture that connects articles based on the similarity of their titles and abstracts [27].

In the context of Industry 4.0, several thematic areas have been identified, including related technologies such as big data, artificial intelligence, and smart manufacturing as shown in Figure 14. Bibliometric analyses reveal no clear focus on the IoT within these areas and that the maturity models and indices developed for Industry 4.0 technologies are applied transversally to all adjacent technologies. In addition, there is a lack of specific studies that address IoT in detail, as indicated by the low correlation between keywords such as "technology adoption", "maturity models", "digital transformation" and IoT. Consequently, the maturity and adoption models used to assess the technological maturity of Industry 4.0 technologies may need to be more generic, which can impede the establishment of precise standards for IoT. This lack of specificity can prevent the comprehensive addressing of all aspects of IoT, including hardware, software, process automation, interaction, and security.

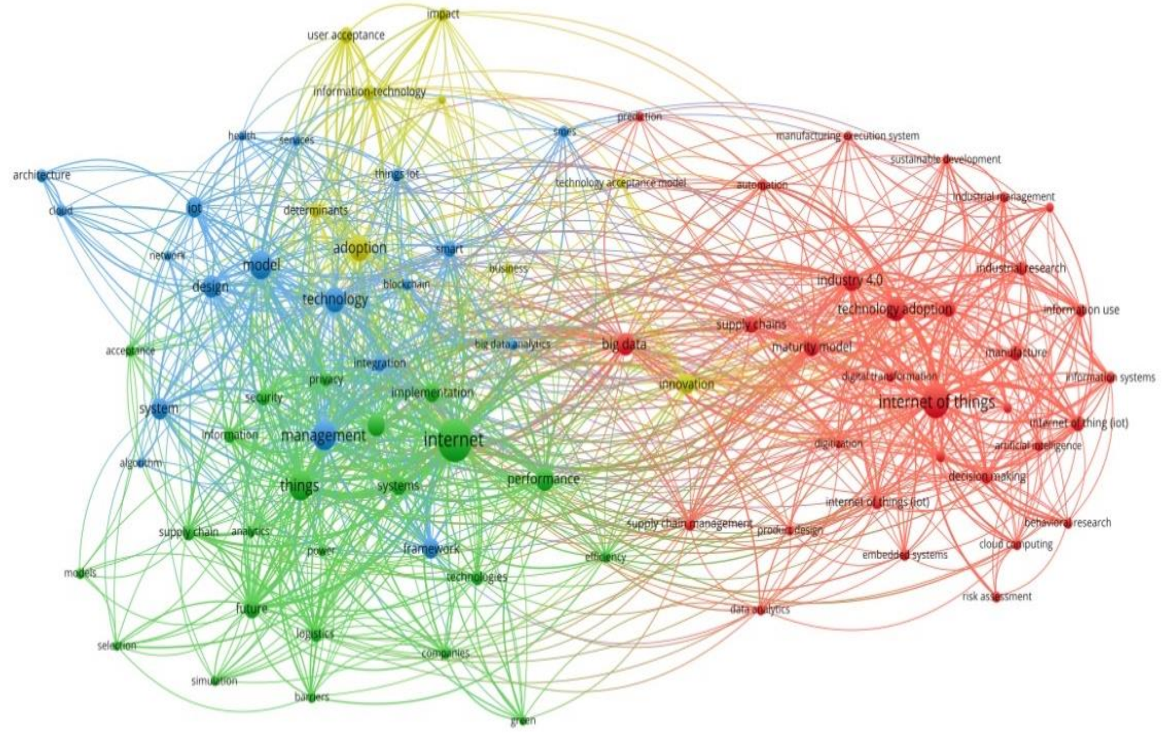

Figure 14. Interrelationships between the keywords of the different databases

Industry 4.0 comprises diverse approaches for measuring technological maturity and evaluating the status of organizations. Some of the established mechanisms include the Acatech Industrie 4.0 Maturity Index [12], the Industry 4.0 index [14], and the Appenfeller/Feldmann maturity model [39], among others. These models offer an extensive evaluation of the technological maturity of all the underlying Industry 4.0 technologies. However, due to their comprehensive nature, these models often need more specificity in assessing individual technologies. This lack of specificity can result in a flawed estimation of the status of a particular technology and may hinder standardization across organizations. Therefore, developing a dedicated maturity index or assessment model for measuring the implementation of the IoT in enterprises may be worthwhile. Such an index could enable organizations to gauge their status and identify areas for improvement in implementing this technology in their workflows.

3.5.2. Thematic map of the domain

A thematic map is a visual display that depicts a research domain's primary topics and themes utilizing co-occurrence analysis. The classification of thematic maps can be based on four categories: driving, niche, emerging or declining, and core topics. This classification is determined by assessing the density and centrality of the topics in the thematic map [40]. Figure 15 displays the relevant keyword terms of the authors' keywords within the domain. These terms are based on their centrality and density in the cluster network. Centrality measures the significance of a topic in shaping a research field, whereas density indicates the degree of advancement of the topic [41].

In measuring enterprise IoT implementation, it is observed that the driving themes are those that structure the field and are well-developed and vital. In this line, it is found that most of the development is focused on Industry 4.0 and its associated technologies, likewise elements such as "supply chain" and "digital twins", which are recurrent in the articles found during the analysis. As for the basic topics, they are those with high centrality and low density. In this case, the "internet of things" is the fundamental element, which is in line with the above, and it is not observed that the implementation of indexes in this domain is so developed, as well as other sister technologies such as blockchain and big data. Likewise, niche topics are those specialized and transversal to research. In this case, words such as digital maturity, IoT adoption, IoT implementation, digitization, and business models are identified, suggesting that emerging topics are not yet widely implemented and are consistent with the analysis of the above bibliometric networks. Finally, emerging or declining topics include agriculture, where specific maturity indices or models are observed for implementation in Industry 4.0 [7], and RFID technology, which plays a crucial role in security and interconnectivity.

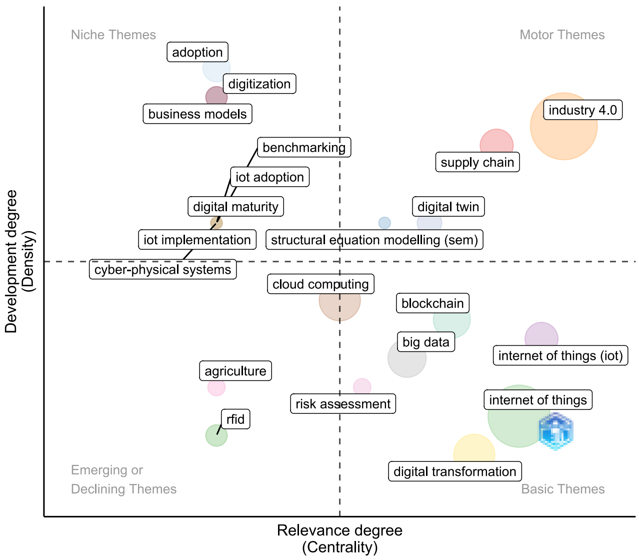

Figure 15. Principal component analysis on the thematic map of the domain to find the central interrelationships

3.6. Discussion

This bibliometric analysis provides valuable insights into the current landscape of technology maturity measurement in the IoT business domain. There is a clear upward trend in research activity in this field, with an annual growth rate in published articles since 2016, indicating a growing academic and industry interest in assessing IoT maturity levels in corporate environments. However, the average age of articles is still only 2.8 years, suggesting that this is an emerging area of research with plenty of room for further exploration.

Analysis of the authors keywords reveals a need for more specificity around the proposed mechanisms in the domain, where most of the focus remains on the broader Industry 4.0 movement and associated technologies such as big data, blockchain, and artificial intelligence. Also, China dominates both citation output and citation impact in this research domain, and promising activity is seen in developing countries such as Brazil and India. This suggests that assessing the evolving role of IoT in the digitization of industry is a priority in all geographies. However, most progress is still concentrated in a handful of leading countries, making international collaboration essential for inclusive progress.

One of the unexpected findings of this study is the low level of international collaboration among researchers in this field, with most publications authored by researchers from a single country. This implies that the leading countries in this field have established technological solid, research, and economic infrastructures and are actively investing in them. The lack of international collaboration could be attributed to the highly specialized nature of the field, making it challenging for researchers from different countries to collaborate effectively, or to the presence of intellectual property concerns that discourage cross-border cooperation.

The conceptual structure indicates that current IoT maturity research integrates implementations in various use cases but needs more specific and standardized frameworks. Opportunities exist to combine software engineering concepts into measurement mechanisms to cover technical nuances around connectivity, scalability, and device interoperability. Despite high-level assessments of Industry 4.0, the enterprise IoT space warrants specific maturity measurement mechanisms that address its unique adoption challenges.

This study adds value to previous studies measuring technology maturity in enterprise IoT by providing a comprehensive and up-to-date overview of the scientific output, significant sources, authors, countries, and keywords in this field. It also identifies this domain's main topics and trends and their interrelationships through thematic maps and bibliometric networks. In addition, it highlights challenges and opportunities for future research, such as the development of a maturity index or specific evaluation model to measure the implementation of IoT in companies, the integration of software engineering concepts, and the promotion of international collaboration.

4. THREATS OF VALIDITY

This study has some limitations that may affect its validity and generalizability. It discusses the main threats to validity and how we attempted to mitigate them. Here is how you might address these issues.

4.1. Selection bias

The selection of articles for the bibliometric analysis was based on a search string that may have yet to capture all the relevant studies in the domain. To reduce this bias, it used the PICOC criteria to construct a comprehensive and logical search string, and it searched two reputable databases (Scopus and WoS) that cover a wide range of journals and conference papers in the engineering field. It also applied rigorous inclusion and exclusion criteria to filter out irrelevant or low-quality studies.

4.2. Data extraction bias

The data extraction process involved manual coding and classification of the articles, which may introduce human errors or inconsistencies. To minimize this bias, it used the Bibliometrix and VOSviewer tools to automate the data processing and analysis, and it followed the guidelines proposed by Bouzembrak *et al.* [19] and Donthu *et al.* [22] for conducting bibliometric analyses. It also cross-checked the results with the original articles to ensure accuracy and validity.

4.3. Interpretation bias

The interpretation of the results may be influenced by the authors' perspectives or assumptions, which may not reflect the actual state of the domain. To mitigate this bias, it used objective and quantitative indicators, such as citation counts, H-index, G-index, and M-index, to measure the productivity and impact of the sources, authors, and countries in the domain. It also used visual tools, such as thematic maps and bibliometric networks, to identify the main topics and trends in the domain and their interrelationships. It also compared our findings with previous studies in the IoT field to validate our conclusions.

5. CONCLUSION AND FUTURE WORK

The present investigation involves a bibliometric analysis of the domain knowledge related to the maturity of the IoT in the business environment. The study utilized the bibliographic databases Scopus and WoS to identify the most significant articles in this field, examining 431 documents. The Bibliometrix and VOSviewer tools were subsequently employed to process the data obtained. The primary outcome of this research is the determination of the knowledge structure within the domain of IoT. It is worth noting that research in this field is relatively recent, and the number of published articles has experienced a significant and consistent increase since 2016, with an annual growth rate of 22.58%. An established collaboration network has been identified among China, the United States, and South Korea. China leads production and collaboration, with its authors making noteworthy contributions that serve as references for other nations. However, it is also noteworthy that developing countries like Brazil and India demonstrate a particular interest in adapting and assessing the maturity of IoT technology for their production processes.

The bibliometric analysis indicates that the conceptual structure of the domain displays a tendency towards thematic diversification, characterized by a multidisciplinary knowledge core that is significantly influenced by the IoT sister technologies, such as big data and blockchain. This implies that the methodologies for measuring enterprise IoT maturity may be restricted and frequently implemented in a cross-cutting approach across all Industry 4.0 technologies, resulting in a lack of specificity and a potential underestimation of the actual maturity state.

Regarding future work, it is recommended that a standardized approach for measuring enterprise IoT maturity be developed and implemented, enabling an analysis of specific features, including connectivity, interoperability, and the proper synergy between hardware and software. Furthermore, it is recommended that this metric should not be confined solely to numerical values but should also include general guidelines and recommendations that assist companies in enhancing their adoption. Additionally, integrating software engineering concepts, such as the capability maturity model integrated for development, could be advantageous for the domain as it provides established propositions to serve as a basis for new initiatives in the IoT domain.

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