AI

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Review

A Bibliometric Analysis on Artificial Intelligence in the Production Process of Small and Medium Enterprises

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Abstract: Industry 4.0 represents the main paradigm currently bringing great innovation in the field of automation and data exchange among production technologies, according to the principles of interoperability, virtualization, decentralization and production flexibility. The Fourth Industrial Revolution is driven by structural changes in the manufacturing sector, such as the demand for customized products, market volatility and sustainability goals, and the integration of artificial intelligence and Big Data. This work aims to analyze, from a bibliometric point of view of journal papers on Scopus, with no time limitation, the existing literature on the application of AI in SMEs, which are crucial elements in the industrial and economic fabric of many countries. However, the adoption of modern technologies, particularly AI, can be challenging for them, due to the intrinsic structure of this type of enterprise, despite the positive effects obtained in large organizations.

Keywords: Industry 4.0; digital transformation; artificial intelligence; machine learning; neural network; deep learning; SMEs; process; production; pros and cons

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1. Introduction

Industry 4.0 is the current trend of automation and data exchange in manufacturing technologies, allowing businesses to monitor physical processes, create virtual copies of the real world and make decentralized and automated decisions. This industrial revolution leads to the creation of intelligent networks of machines and systems, autonomously controlled value chains and highly flexible production. The fundamental principles of Industry 4.0 include the following:

- Interoperability: Communication and coordination between machines, computers and people, facilitated by the Industrial Internet of Things (IIoT) [1]. IIoT enables SMEs to seamlessly connect and collaborate with partners across the value chain. Moreover, the collected data are the basis for AI training.
- Virtualization: Generating virtual assets using sensory data to replicate the real world, creating Cyber Physical Systems (CPSs) [2] and Digital Twins (DTs) [3], allowing SMEs to create digital models of products and processes for optimization and simulation. Those systems can be driven by AI to achieve further performance.
- Decentralization: Moving systems to the edge of the enterprise, improving scalability through solutions such as Cloud Computing [4] and empowering SMEs with scalable cloud solutions, reducing IT burdens and boosting agility. AI will be pivotal in that, providing in-depth local data analysis.
- Production flexibility: The ability to quickly respond to variable demand and small production batches, supported by technologies such as additive manufacturing [5]

and enabling SMEs to quickly adapt to market changes and offer customized products. AI, with forecasting abilities, can further enhance this characteristic.

- Technical assistance: Using robotics and augmented reality to support customers and employees, improving interoperability and facilitating co-design and training [6]. Equipping SMEs with robotics and augmented reality enhances their efficiency, customer service, and innovation. AI can also provide better insight and suggestions.

The push towards Industry 4.0 is due to three main structural changes in the manufacturing sector: the growing demand for customized products, greater market volatility and the need for environmental sustainability and resource efficiency [7]. However, the transition to Industry 4.0 may encounter cultural resistance and requires a change in mindset [8]. Common mistakes include separating new systems from existing operational realities, lacking adaptability, and waiting for the perfect architecture before implementation. Among the different technologies of Industry 4.0, the one with a comprehensive impact in many different field is artificial intelligence (AI) [9], which refers to the simulation of human intelligence through algorithms and techniques such as machine learning and deep learning, allowing machines to perform complex tasks, such as learning, reasoning, problem solving, natural language understanding, and environmental perception [10]. From a supply chain perspective, AI has a significant impact on improving the forecasting of product demand and the analysis of socioeconomic dynamics. Internally, AI addresses issues such as skills shortages and managing large amounts of data, enhancing business processes and enabling the production of personalized content at scale. However, implementing AI brings risks, such as lack of transparency, inaccurate responses and bias, requiring rigorous control systems and the protection of confidential company data [11]. These challenges become particularly relevant in Small and Medium Enterprises (SMEs) [12]. While AI has shown positive effects in large enterprises, its adoption in SMEs raises significant questions. SMEs, which contribute significantly to the economic system [13], must embrace new technologies to stay competitive, especially during crises such as the pandemic and supply chain disruption [11]. However, many SMEs lack the human, financial and material resources necessary to effectively utilize AI [14]. The understanding and adoption of AI by SMEs depend on managerial decisions and the readiness of employees [15]. Furthermore, SMEs need to carefully assess the costs of transitioning to AI and the potential financial return, as increased revenues from digital services do not always translate into higher profits [16]. For a better understanding of Industry 4.0 in the production sector, Table 1 presents its technologies and their main applications in the production context.

Table 1. Technologies of Industry 4.0 in the production process.

Technology	Explanation	Application in the Production Process
IIoT	A system that allows objects to be visible and accessible via the Internet, enabling remote control and monitoring [1].	Optimizes industrial processes by enabling remote visibility of machines, data processing, feedback control on actuators, and centralized information management via the Cloud [17].
Digital Twin	A Digital Twin is a digital representation of a real-world entity, be it a single object like a machine or an entire business system such as a production line or any process. Its significance lies in the real-time comparison between the actual physical system behavior and its desired state through simulation [3].	Enables benefits such as real-time monitoring for anomaly detection, predictive maintenance, evaluation of hardware and software improvements, optimization of inventory management, personnel training, lifecycle tracking of products, performance analysis, and simulation of production scenarios to enhance efficiency and productivity [18].

Table 1. *Cont.*

Technology	Explanation	Application in the Production Process
CPS	A technology that combines physical components (machines, sensors) with cyber elements (computing systems, digital models) to create a synchronized system [2].	Enables predictive maintenance, leveraging real-time data to detect and address issues swiftly and accurately, facilitating virtual simulation, enhancing DT by continuously updating them with high-quality data from IIoT systems [19].
Robot 4.0	Utilization of autonomous robots to replace human operators in performing repetitive and low-value tasks [6].	Enhances efficiency and effectiveness in manufacturing activities by performing tasks with high precision and speed, thus improving product quality and overall productivity [5].
Virtual Reality	Three-dimensional visualizations of what is developing, thus avoiding the need to resort to constructing physical prototypes that require significant time and often high costs.	Enhances productivity by providing a safer, cost-effective training method that minimizes learning times and allows for repeated practice until full proficiency is achieved, thereby improving overall operational efficiency.
Augmented Reality	A technology that, through devices like smart glasses, helmets, and tablets, allows instructions for operation or diagrams to be displayed directly on the object you are working on, whether it is a product or a machine [20].	Facilitates remote assistance, assembly guidance, real-time inventory management, and collaborative work among distributed teams, thereby optimizing processes and improving overall productivity.
Big Data Analysis	The flow of large volumes of data characterized by high velocity, variety, potential value, and the need for veracity.	Allows for trend analysis, predictive maintenance, quality control enhancement, workforce management improvement, and operational cost optimization in manufacturing processes, thereby enhancing productivity and decision-making [21].
Cloud Computing	A technology that enhances productivity by providing access to shared data over the Internet [4].	Enhances operational efficiency through shared data management, IT cost reduction, resource scalability based on demand, data security, and agile integration of new technologies and services [22].
Edge Computing	A distributed computing model that decentralizes processing and storage activities closer to devices or data sources, moving away from reliance on remote data centres or centralized Cloud Computing. This approach aims to reduce latency, improve communication efficiency, and provide more immediate responses to connected applications and devices [23].	Supports real-time data processing, enhances operational efficiency, and enables timely responses critical for connected applications and devices, thereby optimizing production processes and reducing reliance on distant data centres [24].
Fog Computing	A distributed computing model that brings computing and storage resources closer to devices or data sources to reduce latency and improve efficiency, with a broader scope than edge computing, encompassing a diverse range of distributed computing nodes [25].	Facilitates real-time data processing directly on the production line, alleviating potential data flow bottlenecks and supporting applications sensitive to latency, thereby improving operational efficiency and responsiveness [26].
AI	AI refers to the simulation of human intelligence through various algorithms and techniques, allowing tasks such as learning, reasoning, problem-solving, natural language understanding, and environmental perception to be performed [27].	Enables intelligent automation and prescriptive maintenance, allowing for mass customization and optimizing processes overall [5].

Therefore, Industry 4.0 is profoundly influencing business activities, particularly in the manufacturing sector, revolutionizing production processes and improving skills, cross-functional collaboration and safety in the workplace, as well as business decisions, making them faster and more precise [28]. Customers are experiencing the effects through reduced production times, decreased costs and enhanced customer service [29]. Among emerging technologies, AI plays a vital role in optimizing production. However, while large companies are exploring AI application cases to enhance productivity, SMEs, which constitute a significant portion of the business landscape [13], encounter unique challenges in adopting AI, due to their characteristics. These include common barriers found in other digital technologies, such as lack of awareness, preparation and knowledge, as well as AI-specific challenges like high costs and uncertainty about benefits [13]. Successful AI implementation in SMEs also necessitates the integration of complementary technologies and substantial cultural shifts in business practices, alongside appropriate investments [14]. It is crucial for SMEs to fully understand the potential and risks of AI and be prepared to effectively manage and leverage their data. There is then the need to map the current existing literature to better understand the main research directions and correlations among topics.

The aim of this paper is to study the current existing literature on the topic of AI applied in SMEs and understand the main research areas and the correlations in this field. To successfully perform a careful and deep analysis, the following research questions (RQs) have been posed:

1. What are the current trends about the publications on the application of AI in the production plants of SMEs?
   This first question aims to identify the main research trends and topics related to AI in SME production plants. This information can be useful for identifying research gaps and opportunities, as well as for understanding the current state of the art in this field.
2. What are the main macro topics and how are they related to each other?
   The second research question seeks to understand the relationships between different AI topics and how they are applied in SME production plants. This information can be useful for developing a comprehensive framework for understanding the role of AI in SMEs.
3. What is the evolution of the topics in time and what are the future research directions?
   This last research question aims to identify emerging trends and future research directions in the field of AI and SMEs. This information can be useful for researchers who are looking to contribute to this field, as well as for SMEs that are considering adopting AI technologies.

2. Materials and Methods

2.1. Article Selection

To conduct our research, the first step involved finding the papers to analyze by using the Scopus database, adopting the PRISMA protocol, as illustrated in Figure 1. In this figure, only the results from the Scopus search are presented, on which bibliometric analyses were conducted. Therefore, data related to the eight articles added through snowballing for contextual reasons are not included but are used to provide better context for this analysis.

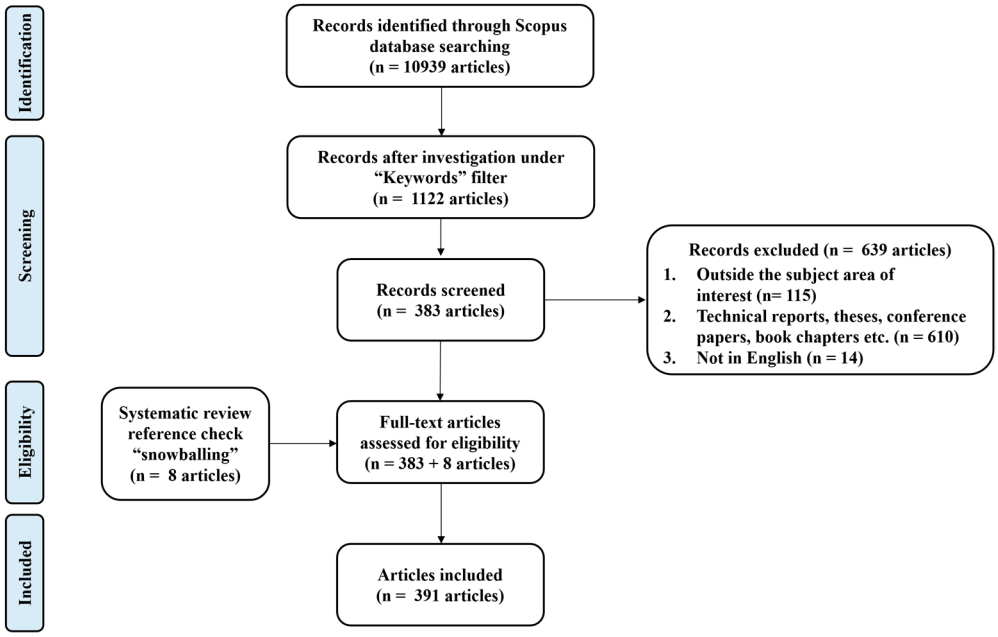


Figure 1. PRISMA protocol.

Our goal is to obtain a clear understanding of the current areas of interest in the fields of Industry 4.0 and AI applied to the production process of SMEs. Accordingly, we defined four strings of keywords, as detailed in Table 2. The search query was constructed using the logical operators "AND" to determine Boolean strings combinations, such as "(string 1) AND (string 2) AND (string 3) AND (string 4)".

Table 2. String of keywords.

String	Explanation
"industry 4.0" OR "digital transformation" OR "CPS" OR "IOT" OR "digital twin" OR "cyber physical system" OR "Big data" OR "Cloud Computing" OR "IIOT" OR "Edge Computing" OR "Fog Computing" OR "Automation" OR "Robot"	Limit the research to the scope of Industry 4.0 and its technologies, capturing the essence of Industry 4.0 from various angles, ensuring the search doesn't miss valuable contributions due to terminological variations or specific focuses.
"Generative AI" OR "Artificial Intelligence" OR "AI" OR "Machine learning" OR "Deep learning" OR "Neural Network"	Aims to comprehensively cover the field of Artificial Intelligence and its related subfields, ensuring that the research captures a broad range of relevant studies focusing on AI and its algorithms.
"Adoption" OR "Integration" OR "Barrier" OR "Benefit" OR "Constrain"	Target research that explores the practical aspects of AI implementation within the context of Industry 4.0, going beyond simply identifying AI applications to focus on the challenges and opportunities associated with their deployment.
"sme" OR "Small and Medium Enterprises" OR "Production" OR "Process" OR "Manufacturing"	Explicitly targets research focused on the adoption of Industry 4.0 technologies, including AI, specifically within SMEs and within their production processes.

The initial search considering the "Article title, Abstract, Keywords" fields resulted in 10,939 documents. To reduce this number, strings 1, 2 and 3 were investigated only in the "Keywords" field, yielding 1122 documents. Additionally, we considered only the

following subject areas: "Computer Science", "Engineering", "Business, Management and Accounting", "Environmental Sciences", "Social Sciences", "Decision Sciences", "Economics, Econometrics and Finance", "Multidisciplinary", "Energy". This reduced the number of records to 1007. Furter, the screening phase of the PRISMA protocol introduced additional eligibility criteria. First, only papers published in journals were selected, reducing the number to 397. Then, by selecting only papers written in English, the final number of papers was 383. These choices were taken to maximize the quality of the content, as the topic of AI is widely studied but only minimally in the domain of SMEs. Therefore, papers in journals have been considered to guarantee the best output of this kind of analysis.

2.2. Content Production

To perform a thorough bibliometric analysis, graphs were created showing the trends in scholarly production over the years, the distribution of articles by subject area, and the distribution of articles by journal, affiliation, country, and funding sponsor. Additionally, to assess the impact of each individual factor on the total number of articles, cumulative analysis is provided for each of these categories. The Pareto diagram is not included for readability reasons.

Lastly, to evaluate the correlation between keywords, VOSviewer (1.6.20) was used. The performed analysis is about the co-occurrence of "all keywords" using the "full counting" method. Only keywords that appear at least 10 times have been considered, resulting in 75. Then, the following keywords were removed: "article", "controlled study", "priority journal". Furthermore, the "Min Strength" of the lines is set to 5.

3. Bibliometric Analysis and Results from Filters

This section presents the results of the bibliometric analysis performed, reviewing the literature on the application of Industry 4.0 and, more specifically, AI, in the production process of SMEs.

3.1. Year

The evolution of the studies published in Figure 2 demonstrates a growing interest in the topic over the years, mainly driven by the novelty of the subject matter and the usefulness of technologies in addressing recent economic crises [30]. Businesses are implementing Industry 4.0 technologies, particularly AI, to respond to market variability, supply chain disruptions, and rising raw material costs [31]. This situation has certainly fuelled the growth of research on these topics.

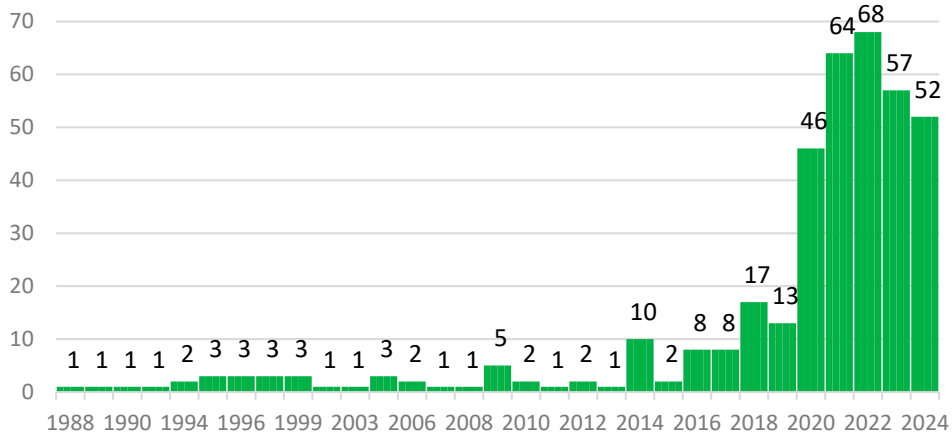


Figure 2. Number of articles per year.

Indeed, to reinforce what was stated earlier, as shown in Table 3, more than 80% of the articles on the topic were written in the last 7 years, with nearly 75% published from the onset of the COVID-19 pandemic (2020) onward.

Table 3. Articles per year.

Year	N° of Art.	% on Tot Art.	Cumulative %
2024	52	13.58%	13.58%
2023	57	14.88%	28.46%
2022	68	17.75%	46.21%
2021	64	16.71%	62.92%
2020	46	12.01%	74.93%
2019	13	3.39%	78.33%
2018	17	4.44%	82.77%
2017 and before	24	17.23%	100.00%

When analyzing the articles over the years, a clear evolution of themes emerges. In earlier years, the focus was primarily on automation, robotics, and traditional simulation. Over time, the introduction of AI shifted attention toward ML and intelligent robots, marking a significant transformation in the field. More recently, the themes have centered around Industry 4.0 and its enabling technologies, such as edge computing, Cloud Computing, and the IIoT, underscoring the growing importance of digital transformation. Finally, it has become evident that AI in production plays a key role in enhancing sustainability.

3.2. Subject Area

Grouping the articles by subject area (SA), as shown in Figure 3, which only displays the subject areas selected by the filters used during the Scopus research, reveals that most of the articles relate to the fields of "Computer Science" and "Engineering". This underlines the importance of engineers and computer scientists [3].

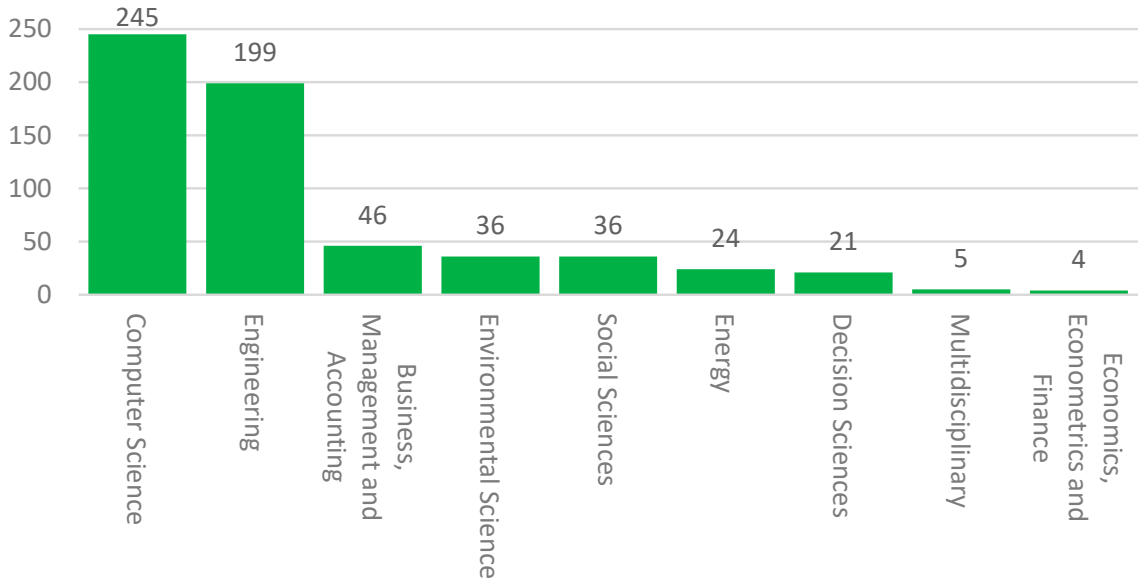


Figure 3. Number of articles per subject area.

As shown in Table 4, which reports all the subject areas, more than 50% of the articles relate to these two categories, which can be considered the A category.

Table 4. Articles per subject area.

Subject Area	N° of Art.	% on Tot Art.	Cumul. % on Art.	Cumul. % on SA
Computer Science	245	28.99%	28.99%	4.35%
Engineering	199	23.55%	52.54%	8.70%
Business, Management and Accounting	46	5.44%	57.99%	13.04%
Mathematics	38	4.50%	62.49%	17.39%
Environmental Science	36	4.26%	66.75%	21.74%
Social Sciences	36	4.26%	71.01%	26.09%
Materials Science	33	3.91%	74.91%	30.43%
Physics and Astronomy	27	3.20%	78.11%	34.78%
Medicine	25	2.96%	81.07%	39.13%
Biochemistry, Genetics and Molecular Biology	24	2.84%	83.91%	43.48%
Energy	24	2.84%	86.75%	47.83%
Decision Sciences	21	2.49%	89.23%	52.17%
Chemistry	20	2.37%	91.60%	56.52%
Neuroscience	13	1.54%	93.14%	60.87%
Psychology	13	1.54%	94.67%	65.22%
Agricultural and Biological Sciences	11	1.30%	95.98%	69.57%
Chemical Engineering	9	1.07%	97.04%	73.91%
Earth and Planetary Sciences	8	0.95%	97.99%	78.26%
Health Professions	6	0.71%	98.70%	82.61%
Others	5	1.30%	100.00%	100.00%
Chemical Engineering	9	1.07%	97.04%	73.91%
Earth and Planetary Sciences	8	0.95%	97.99%	78.26%
Health Professions	6	0.71%	98.70%	82.61%
Others	5	1.30%	100.00%	100.00%

Related to the B category, we find “Business, Management and Accounting”, “Environmental Science”, “Social Science”, “Energy”, “Decision Science”, being more correlated with the application of AI, rather than AI itself.

The last ones are in category C and are “Multidisciplinary” and “Economics, Econometrics and Finance”.

However, applications of Industry 4.0 and AI can also be found in other fields, such as medicine, environmental sciences, social sciences, and accounting. In fact, 80% of the articles are distributed across nine subject areas. In addition, 80% of all the subject areas account for more than 98% of all the articles.

3.3. Publisher

From an initial analysis of Figure 4, which groups the articles by publisher, it is noted that the majority are produced by "Elsevier" and that only three other publishers have more than 20 articles (18.28%).

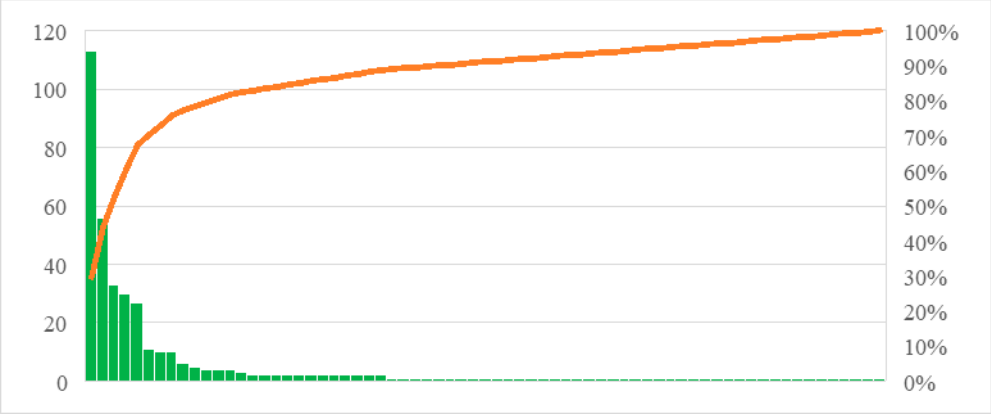


Figure 4. Number of articles per publisher.

Observing Table 5, the previous statement becomes even more evident: Elsevier alone accounts for nearly 30% (29.50%), while the top four publishers alone publish more than 60% of the articles (60.57%), despite representing only a little more than 5% of the total number of publishers (5.80%). Furthermore, 80% of the publications (80.16%) on the topic are produced by just over 31% of the publishers (31.88%).

Table 5. Articles per publisher.

Publisher	N° of Art.	% on Tot Art.	Cumul. % on Art.	Cumul. % on Pub.
Elsevier	113	29.50%	29.50%	1.05%
IEEE	56	14.62%	44.13%	2.11%
Springer	33	8.62%	52.74%	3.16%
MDPI AG	30	7.83%	60.57%	4.21%
Taylor and Francis Ltd.	11	2.87%	63.45%	5.26%
Hindawi Limited	10	2.61%	66.06%	6.32%
Emerald Publishing	10	2.61%	68.67%	7.37%
IGI Global	6	1.57%	70.23%	8.42%
Association for Computing Machinery	5	1.31%	71.54%	9.47%
Inderscience Publishers	4	1.04%	72.58%	10.53%
John Wiley and Sons Ltd.	4	1.04%	73.63%	11.58%
John Wiley and Sons Inc.	4	1.04%	74.67%	12.63%
Routledge	3	0.78%	75.46%	13.68%
Publishers with 2 articles	24	6.26%	81.72%	26.32%
Publishers with 1 article	43	11.22%	92.95%	71.58%
Publisher unknow	27	7.05%	100.00%	100.00%

Finally, the percentage of articles whose publishers have produced only one article or is unknown is also significant.

3.4. Journal Distribution

From the analysis of Figure 5, which lists journals with at least five articles, it is evident that, except for "IEEE Access", which has published 16 articles on the topic, the distribution of articles across other journals is quite spread out, with many journals publishing only a few articles.

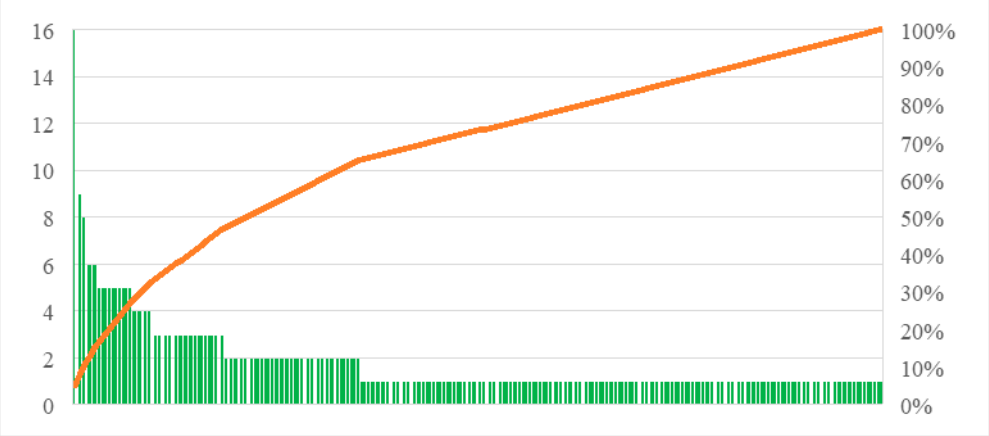


Figure 5. Number of articles per journal distribution.

This is confirmed by the analysis in Table 6, which shows that more than 80% of the journals sampled have published only one or two articles on the topic, and only "IEEE Access" exceeds 5% of the total articles.

Table 6. Articles by journal distribution.

Source Title	N° of Art.	% on Tot Art.	Cumul. % on Art.	Cumul. % on Jour.
IEEE Access	16	5.42%	5.42%	0.63%
Technological Forecasting And Social Change	9	3.05%	8.47%	1.25%
Sensors	8	2.71%	11.19%	1.88%
IEEE Internet Of Things Journal	6	2.03%	13.22%	2.50%
Sustainability Switzerland	6	2.03%	15.25%	3.13%
Computers And Electronics In Agriculture	5	1.69%	16.95%	3.75%
IEEE Transactions On Industrial Informatics	5	1.69%	18.64%	4.38%
Journal Of Cleaner Production	5	1.69%	20.34%	5.00%
Journal Of Industrial Information Integration	5	1.69%	22.03%	5.63%
Journal Of Manufacturing Systems	5	1.69%	23.73%	6.25%
Multimedia Tools And Applications	5	1.69%	25.42%	6.88%
Sensors Switzerland	5	1.69%	27.12%	7.50%
Engineering Applications Of Artificial Intelligence	4	1.36%	28.47%	8.13%
Expert Systems With Applications	4	1.36%	29.83%	8.75%
Neural Computing And Applications	4	1.36%	31.19%	9.38%
Neural Networks	4	1.36%	32.54%	10.00%
Journal with 3 Articles	42	14.24%	46.78%	18.75%
Journal with 2 Articles	54	18.31%	65.09%	35.65%
Journal with 1 Article	103	34.91%	100.00%	100.00%

Furthermore, almost 50% of articles (46.78%) were published by less than 20% of papers (18.75%).

3.5. Affiliation

A similar high distribution is observed when grouping articles by affiliation, as shown in Figure 6, which lists affiliations with more than four published articles.

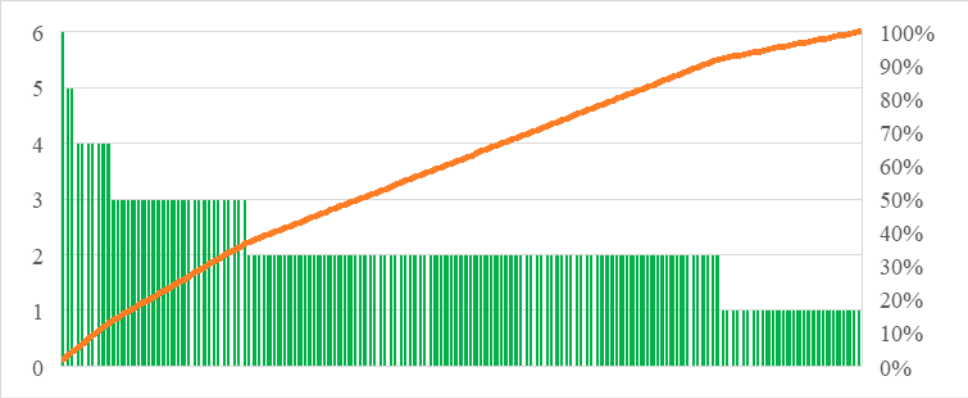


Figure 6. Number of articles per affiliation.

From a more detailed analysis, as shown in Table 7, we confirm what was previously stated. Indeed, just over 23% of the affiliations have produced slightly more than 35% of the publications. Each affiliation within the remaining 76% is associated with 63% of the articles, with each affiliation in this group having produced fewer than three articles on the topic.

Table 7. Articles by affiliation.

Affiliation	Country	N° of Art.	Cumul. % on Art.	Cumul. % on Aff.
Chinese Academy of Sciences	China	6	1.76%	1.76%
Pennsylvania State University	USA	5	1.47%	3.23%
Ministry of Education of the People's Republic of China	China	5	1.47%	4.69%
Swansea University	UK	4	1.17%	5.87%
La Trobe University	Australia	4	1.17%	7.04%
University of Leeds	UK	4	1.17%	8.21%
University of Science and Technology Beijing	China	4	1.17%	9.38%
Xi'an Jiaotong University	China	4	1.17%	10.56%
Hunan University	China	4	1.17%	11.73%
Penn State College of Engineering	USA	4	1.17%	12.90%
Affiliations with 3 Articles	/	81	23.75%	36.65%
Affiliations with 2 Articles	/	186	54.55%	91.20%
Affiliations with 1 Article	/	30	8.80%	100.00%

3.6. Country

Grouping articles by country, as shown in Figure 7, which lists countries with at least six articles, reveals that most articles on the topic are produced in the major global economies: China, USA, India, and the EU. This underscores the current and future importance of the topic.

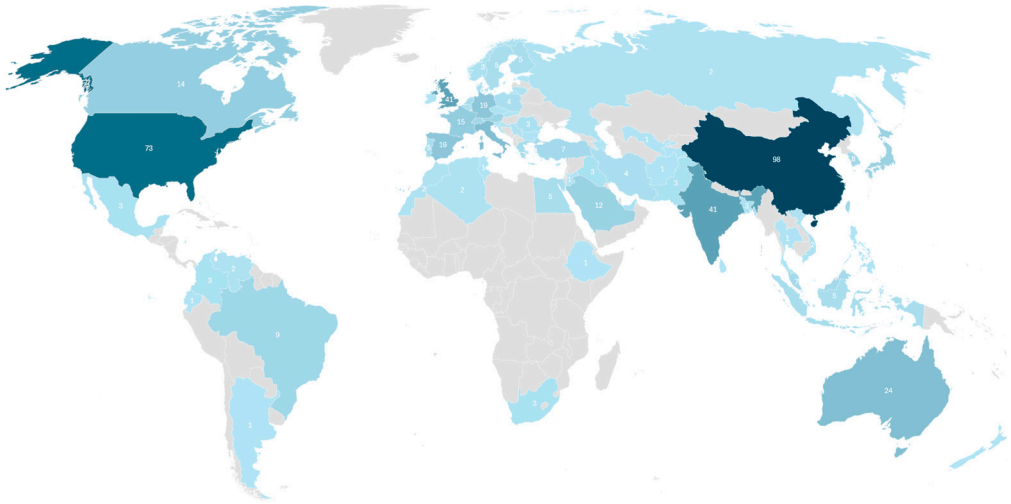


Figure 7. Number of articles per country. The intensity of the color indicates the number of articles.

As further confirmation, observing Table 8 reveals that 30% of the countries that have produced at least one article on the topic account for nearly 80% of all the literature produced. The top 10 countries alone contribute more than 60% of the total production. Based on these countries, it can be seen that Asia is the highest publisher, especially thanks to China and India, shortly followed by Europe, where the papers are distributed among multiple states, and America, with the USA as the leading country.

Table 8. Articles by country.

Country	N° of Art.	% on Tot Art.	Cumul. % on Art.	Cumul. % on Country
China	98	16.61%	16.61%	1.39%
United States	73	12.37%	28.98%	2.78%
India	41	6.95%	35.93%	4.17%
United Kingdom	41	6.95%	42.88%	5.56%
Australia	24	4.07%	46.95%	6.94%
Italy	24	4.07%	51.02%	8.33%
Germany	19	3.22%	54.24%	9.72%
Spain	19	3.22%	57.46%	11.11%
France	15	2.54%	60.00%	12.50%
Canada	14	2.37%	62.37%	13.89%
Japan	12	2.03%	64.41%	15.28%
Saudi Arabia	12	2.03%	66.44%	16.67%
Austria	11	1.86%	68.31%	18.06%
Brazil	9	1.53%	69.83%	19.44%
Switzerland	9	1.53%	71.36%	20.83%
Taiwan	9	1.53%	72.88%	22.22%
South Korea	8	1.36%	74.24%	23.61%
Malaysia	7	1.19%	75.42%	25.00%
Turkey	7	1.19%	76.61%	26.39%
Greece	6	1.02%	77.63%	27.78%
Hong Kong	6	1.02%	78.64%	29.17%
Netherlands	6	1.02%	79.66%	30.56%
Countries with <6 Articles or Undefined	50	20.34%	100.00%	100.00%

3.7. Funding Sponsor

Then, grouping articles by funding sponsor (FS), as shown in Figure 8, which lists funding sponsors with at least four published articles, reveals, once again, a significant distribution of articles, except for the "National Natural Science Foundation of China", which has published 34 articles.

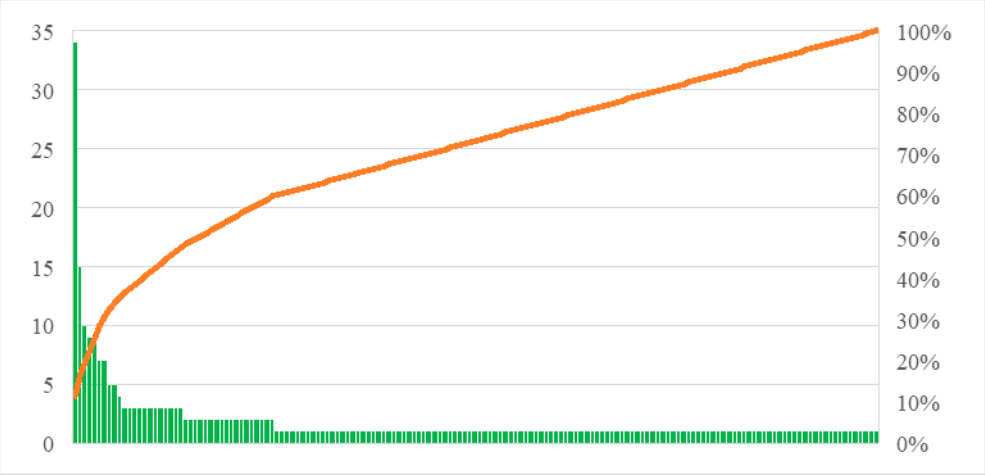


Figure 8. Number of articles per funding sponsor.

This is further confirmed by a more detailed analysis of Table 9, which indicates that 25% of the funding sponsors account for only 34% of the total articles, with 74% of the funding sponsors contributing to 23% of the articles. A high percentage of articles have funding sponsors that are unknown or unspecified.

Table 9. Articles per funding sponsor.

Funding Sponsor	N° of Art.	% on Tot Art.	Cumul. % on Art.	Cumul. % on FS
National Natural Science Foundation of China	34	6.68%	6.68%	0.63%
National Science Foundation	15	2.95%	9.63%	1.25%
National Key Research and Development Program of China	10	1.96%	11.59%	1.88%
European Commission	9	1.77%	13.36%	2.50%
Horizon 2020 Framework Programme	9	1.77%	15.13%	3.13%
Engineering and Physical Sciences Research Council	7	1.38%	16.50%	3.75%
European Regional Development Fund	7	1.38%	17.88%	4.38%
Fundamental Research Funds for the Central Universities	5	0.98%	18.86%	5.00%
National Research Foundation of Korea	5	0.98%	19.84%	5.63%
Japan Society for the Promotion of Science	4	0.79%	20.63%	6.25%
Funding Sponsor with 3 Articles	36	7.07%	27.70%	13.75%
Funding Sponsor with 2 Articles	36	7.07%	34.77%	25.00%
Funding Sponsor with 1 Article	119	23.38%	58.15%	99.37%
Funding Sponsor Undefined	213	41.85%	100.00%	100.00%

4. Keywords Co-Occurrence

4.1. Clusters

From the analysis, five clusters were found. After their analysis, only four were kept, by setting the minimum number of keywords for a cluster to 10, as shown in Figure 9, where they are divided per color by the software. They are reported here in order of the number of keywords.

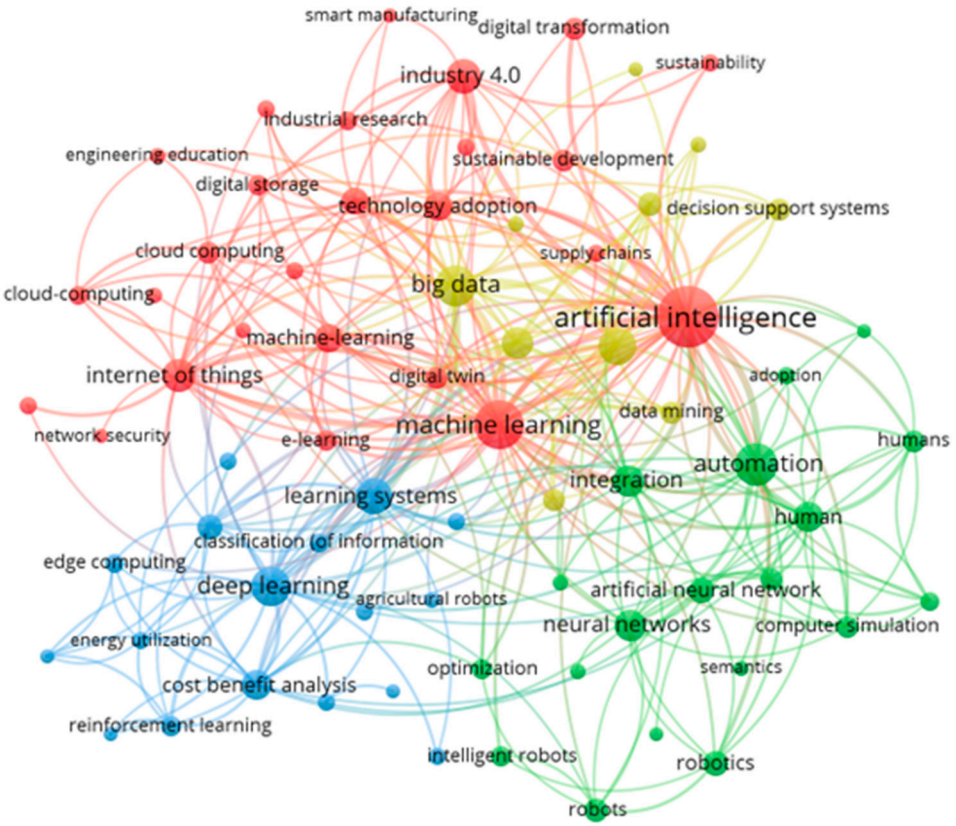


Figure 9. Keywords co-occurrence (source: VOSviewer).

4.1.1. AI in I4.0 Domain (Red)

In this first cluster, there are 26 keywords. The main ones are as follows: "artificial intelligence" (163 occurrences/624 connections/67 links), "machine learning" (163 occurrences/624 connections/70 links), "industry 4.0" (51 occurrences/239 connections/55 links), "internet of things" (48 occurrences/290 connections/59 links).

This cluster mainly refers to AI, in particular machine learning (25 co-occurrences), and its connection among I4.0 (31) and other 4.0 technologies, like IoT (18), Cloud (10) and Digital Twin (11).

The focus on different aspects of companies is as follows:

- On the side, the general I4.0 environment. In fact, there is a group made up of smart manufacturing, Industry 4.0, industrial research, digital transformation, and technology adoption. These generic topics are very strongly connected to AI and machine learning [32].
- Then, another subcluster focuses on the 4.0 technologies, particularly IoT, Cloud, Digital Twin, embedded systems, data analytics, digital storage, blockchain, network security. This group is strongly connected to AI and machine learning [33]. Moreover, IoT and Cloud are strongly connected (14). DT is connected to IoT (5). Data analytics (14) and digital storage (5) are connected to IoT [34].

- A third one is connected to engineering education and e-learning, which are strongly connected to machine learning (6 the first/13 the second). The first is strongly connected to Cloud (11) and the second with AI (5) [33].
- Sustainability (11) and sustainable development (13) are strongly connected to AI [35]. This is expected as the impact on the environment is central nowadays [36].

AI is a key enabler of Industry 4.0 within SMEs, driving automation, optimization, and data-driven decision making across various production processes. Specifically, machine learning empowers SMEs to leverage the vast data generated by Industry 4.0 technologies like IoT and Cloud Computing for improved efficiency and sustainability.

4.1.2. ANN Integration for Optimization (Green)

In the second cluster, there are 19 keywords. The main ones are "automation" (80 occurrences/310 connections/58 links), "integration" (44 occurrences/220 connections/62 links), "neural networks" (46 occurrences/53 connections/55 links), "human" (41 occurrences/229 connections/59 links).

This cluster refers to the usage of ANN to diagnose and optimize processes, with an integration with robots, simulation tools and humans. All the main concepts of this cluster are strongly connected to each other.

Neural networks empower SMEs to automate and optimize production processes, integrating with robots and simulations while still incorporating human expertise.

4.1.3. Deep Learning (Blue)

In the third cluster, there are 17 keywords. The main ones are "deep learning" (68 occurrences/344 connections/66 links), "learning system" (60 occurrences/307 connections/62 links), "cost benefit analysis" (41 occurrences/209 connections/54 links), "learning algorithms" (30 occurrences/196 connections/57 links).

This cluster is focused on deep learning, with the different techniques, used to create intelligent systems, able to learn from data, collected by devices like those of edge computing. These techniques are associated with cost–benefit analysis and energy efficiency [37].

Energy efficiency is linked to energy efficiency utilization, which is strongly correlated with deep learning [38].

There are different models of deep learning, like reinforcement learning and convolutional neural networks [39,40].

For SMEs, deep learning offers powerful tools to create intelligent systems that learn from data, often collected via edge computing, enabling process optimization and automation. Critically, its link to cost–benefit analysis and energy efficiency makes deep learning a particularly attractive option for resource-constrained SMEs seeking both performance improvements and return on investment.

4.1.4. Big Data for Prediction (Yellow)

In this last cluster, there are 10 keywords. The main ones are "big data" (74 occurrences/416 connections/62 links), "data integration" (65 occurrences/325 connections/56 links), "decision making" (45 occurrences/255 connections/67 links), "information management" (25 occurrences/145 connections/43 links).

The last cluster concerns the usage of Big Data for decision making, based on data integration. The main areas of implementation are forecasting and predicting system behaviors.

All the main keywords are strongly connected to each other, showing that this cluster is very well defined.

For SMEs, Big Data analytics, enabled by data integration, provides crucial insights for informed decision making, particularly in forecasting and predicting system behavior. This data-driven approach allows SMEs to optimize operations, improve resource allocation, and gain a competitive edge despite limited resources.

4.2. Correlation Among Keywords

In this subparagraph, the major connection between keywords is reported. For each cluster, the main keywords have been chosen for this kind of analysis. Finally, other important correlations are reported at the end.

4.2.1. AI in I4.0 Domain (Red)

Artificial intelligence, in cluster 1, is strongly connected to all the other clusters, in particular with the following:

- Industry 4.0 (31), machine learning (25), digital transformation (19), Internet of Things (18), sustainable development (13) in cluster 1.
- Automation (41), integration (22), human/humans (21 + 13), robotics (15), computer simulation (10), intelligent robots (10) in cluster 2.
- Learning systems (15), cost benefits analysis (11) in cluster 3.
- Big Data (26), decision making (21), data integration (21), decision support system (18), information management (12) in cluster 4.

Machine learning, in cluster 1, is strongly connected to all the other clusters, in particular with the following:

- Artificial intelligence (25), data analytics (17), Internet of Things (16), e-learning (13), Industry 4.0 (10) in cluster 1.
- Automation (22), human (16), integration (11) in cluster 2.
- Learning systems (27), learning algorithms (17) in cluster 3.
- Big Data (28 + 13), data integration (27 + 11) in cluster 4.

The links above underline how AI and ML are strongly related to automation and robotics. With IoT and other I4.0 technologies, AI can in fact control robots and optimize the facility. The connection with humans and decision making is notable, highlighting how this technology is not meant to substitute people but to support them, providing a better information-based system. Finally, it is worth noting that there is a strong link with other I4.0 technologies, Big Data and data integration. To successfully train artificial intelligence models, the quality and quantity of data are mandatory. Therefore, well-integrated Big Data are a key aspect to bring AI into a production line.

4.2.2. ANN Integration for Optimization (Green)

Automation, in cluster 2, is strongly connected to the other clusters, excluded for cluster 3, in particular with the following:

- Artificial intelligence (41), machine learning (22) in cluster 1.
- Neural network (14) in cluster 2.
- Data integration (13) in cluster 4.

Neural network, in cluster 2, is strongly connected only to its own cluster, in particular with the following:

- Automation (14) in cluster 2.

Once again, AI is related to automation in any form. In fact, both ML and neural network appear.

4.2.3. Deep Learning (Blue)

Deep learning, in cluster 3, is strongly connected to the other clusters, excluding cluster 2, in particular with the following:

- Internet of Things (13) in cluster 1.
- Learning systems (18), reinforcement learning (15), cost–benefit analysis (15) in cluster 3.
- Big Data (17), data integration (15) in cluster 4.

DL is strongly connected to IoT and Big Data, showing the need for quality data collected with other I4.0 technologies.

4.2.4. Big Data for Prediction (Yellow)

Big Data, in cluster 4, is strongly connected to all the other clusters, in particular with the following:

- Machine learning/machine-learning (28 + 13), data analytics (18), Internet of Things (10) in cluster 1.
- Learning systems (17), deep learning (17) in cluster 3.
- Data integration (32), data mining (18), information management (15) in cluster 4.

Here, it is possible to appreciate how Big Data and IoT are connected, supporting the previous statements. Moreover, other notable relations are with data integration and data mining.

4.2.5. Others of Interest

- Data integration and data mining (13).
- Data integration and learning systems (12).
- Internet of Things and learning systems (11).
- Decision making and I4.0 (10).

Finally, from these last connections, the most important is the one between decision making and I4.0, denoting how digital technologies are a key aspect to improve the quality of choices as they are more evidence-based and supported by reliable data.

4.3. Temporal Analysis of Keywords

From the temporal analysis of keywords, shown in Figure 10, it is noted that, in general, the keywords belonging to the "ANN integration for optimization" group refer to less recent years. In particular, "Automation", "Robot/Robotics" and "Computer simulation" were used more often up to 2018. This is a sign that, with the advent of AI, and specifically ML and DL, the focus has shifted toward them.

Proceeding with the years, it is possible to see how the research is evolving toward the integration of AI into the other I4.0 systems and technologies. In fact, cluster 1, "AI in I4.0 domain", and cluster 3, "Deep Learning", are the most recent.

More specifically, it can be noted that older concepts, such as AI and learning systems, integrate well with more recent concepts, such as sustainability and Cloud Computing.

Furthermore, the relationships between AI and automation, such as robotics, and computer simulation have been well known for years. In recent years, new integrations between technologies, such as Big Data, machine learning, IoT, and edge computing, are being explored.

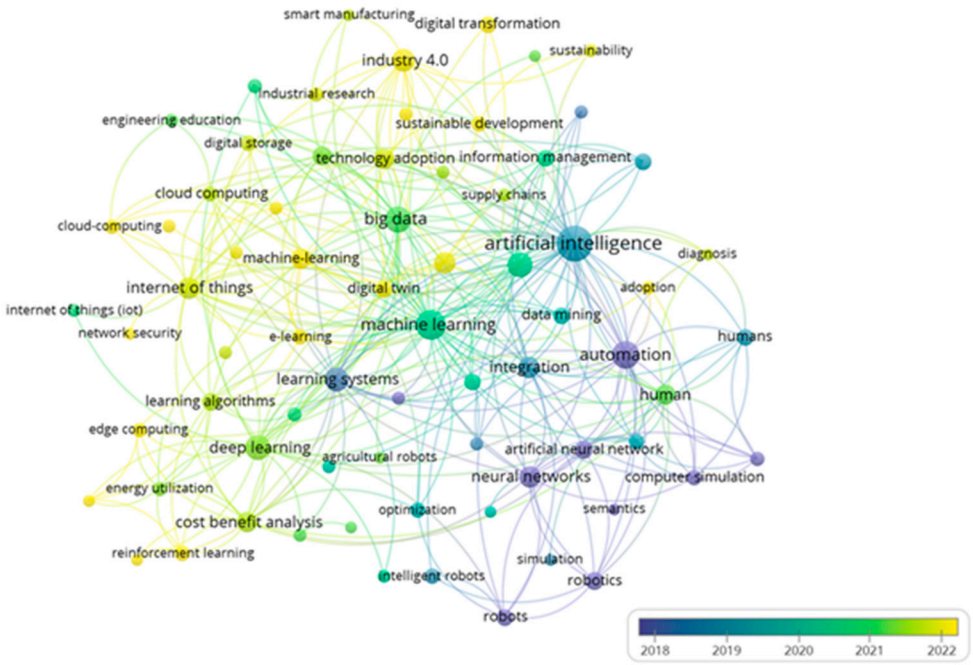


Figure 10. Keyword co-occurrence and timeline.

5. Discussions and Future Work Agenda

5.1. Key Findings

Publication Trends: The analysis of the year showed how the interest of the scientific community has been rising in the last few years in the adoption of AI in SME production systems [41]. In particular, there is a clear cut-off from 2020, from which journal papers more than doubled. In Table 3, it is in fact possible to notice how almost ¾ of the entire papers have been published since then. Another aspect that made the interest grow is the development of LLMs, with ChatGPT (3.5) as the first famous one. The importance of topics like "computer science" and "engineering" underlines the status of technology, which is becoming mature but still requires a lot of studies. In fact, the applications of AI appear a lot less, denoting how concrete solutions are still limited.

Geographic Distribution: For what concerns the geographic distribution, as expected, the highest-publishing countries are China and the US, which are also the places where there are more investments in AI. It is also important to note that Europe has an important publication history, showing how AI is a worldwide topic of interest. Moreover, as Europe is characterized by SMEs as the main kind of companies, studies about their implementation are more focused there and can be expected to grow. In the EU, Italy, Germany, Spain and France are the highest publishers and are characterized by an industrial fabric mainly made of SMEs.

Keyword Correlation: From the keyword analysis, it was found that AI is strongly correlated with the other Industry 4.0 technologies and automation. Is it then clear how the integration of AI with other digital technologies is mandatory to successfully bring new automation to companies.

5.2. Theoretical Implications

Currently, AI is very widely studied [41]. However, only in recent years has there been enough hardware and data to train the model correctly [21]. Future studies should keep working on improving AI accuracy in different fields, showing the value that it can provide. In particular, it is important to carry out studies focused on SMEs. Due to their characteristics, they often have strong limitations due to lack of knowledge and skills about

new technologies [42]. Moreover, management is also often scared about the adoption of I4.0, considering the risk too high [43]. Therefore, integrating AI with other Industry 4.0 technologies like IoT, Big Data, and Cloud is crucial for unlocking its full potential in areas like production optimization, forecasting, and even sustainability, addressing key SME needs and driving future research.

Another tip for a future direction is that AI is becoming mature but still requires a lot of studies. In fact, the field of the application of AI, like "Business, Management and Accounting" and "Environmental Science", appears a lot less, denoting how concrete solutions are still limited. Production is strictly related to business management; therefore, more was expected about this research field, also considering that AI can improve management with optimization and forecasting. The other unexpected missing topic is environmental science, as most of the sustainability papers fall under this, a current major concern for smaller entities. Studying the subject areas in more detail, it is possible to see how AI is very widely applied. Future directions of research will focus on how AI can improve in biology, chemistry, genetics and also in agriculture and energy efficiency. In pharma, AI is used to find new molecules for products and medicines, while in agriculture, it can detect insects and plant diseases [44]. To develop better solutions, AI must be integrated with other I4.0 technologies, in particular IoT, Big Data, and Cloud [45]. This requirement is underlined by the novelty of the keywords concerning this topic, which have been used especially since 2022.

This integration is also important to successfully bring automation into companies. In fact, another research direction is how to enhance automation and robotics with the use of modern technologies, including artificial intelligence [46].

Worth citing is the connection between AI and sustainability in cluster 1 (Red). As this characteristic is more and more required by any company, studies about how this technology can reduce the impact of businesses on the environment will be a very important research direction [47].

Regarding publishers and journals, it is possible to detect a trend toward specialization. In fact, Elsevier accounts for nearly 30% of papers published on AI applied to SME production lines. Considering IEEE, Springer and MDPI reach more than 60%. This trend is visible in journals, too. Almost 50% of papers are in less than 20% or journals, showing how there is a clear specialization trend.

5.3. Practical Implications

The initial information for companies is the need for engineers and computer scientists. In fact, to successfully implement AI, it is mandatory to clearly understand the requirements of the plants and have a deep understanding of how this kind of technology works. Hiring skilled personnel is indeed a fundamental step to successfully incorporate AI and other digital technologies into a company [48,49]. Therefore, to effectively leverage these technologies, SMEs need to invest in both human capital and strategic planning [42].

To reduce the potential resistance to adoption, it is fundamental to start from small projects, able to bring value rapidly [14]. The connection between AI, I4.0, IoT and Cloud suggests how SMEs can start implementing small pilots based on the last two technologies and then scale up to AI. This is important because businesses must have high-quality data to correctly train AI models [42]. Those data are collected by sensors and sent through IoT to the Cloud, where they are available and analyzed [32].

Moreover, as automation and robotics are linked to AI, there is a clear synergy that companies can exploit to improve the results [6]. In fact, smart robots can be more flexible and efficient, reducing the costs and successfully dealing with the production lines of SMEs, usually characterized by small batches and high product variability [15]. However,

implementing AI, especially machine learning, effectively requires significant resources and expertise, which many SMEs lack. Cloud Computing solutions offer a compelling alternative. By leveraging cloud-based AI platforms, SMEs can access the necessary storage, computing power, algorithms, and even pre-trained models without large upfront investments in infrastructure or personnel [42].

6. Conclusions

The adoption of AI is studied in many different fields [50–52]. This study provided insight into the production lines of SMEs. Due to their characteristics, this kind of company has different needs and more limitations than large organizations [14]. However, AI can bring great value to them [42]. In particular, there is clear evidence that this technology is strongly related to automation, a trend that is interesting for every company to keep pace with global competition [53]. Moreover, AI is not a tool to be considered on its own. In fact, it must be integrated with the other I4.0 technologies [54]. First, it strongly requires high-quality data in huge quantities, like Big Data [55]. Thus, IoT becomes central to have those data available for training and testing [34]. Furthermore, Cloud obtains a strategic role as it enables companies to have access to the needed storage and computational power [33]. Also, edge computing comes out as key technology, as AI can be used for local application and not only centralized ones [32]. In this direction, Digital Twin can be embedded with AI systems to optimize the production lines, in both terms of efficiency and effectiveness [41]. Finally, it is important to evaluate in depth what the current existing solutions are, their limitations and the difficulties that SMEs met in their adoption.

With the findings of this study, it is possible to successfully address the research questions, providing the current trends and explanations (RQ1), the macro topics and the interrelations (RQ2), and the future research direction that literature should take to keep closing the gap between AI potential and real applications (RQ3). In fact, it was found that AI offers SMEs a range of powerful tools to address their specific challenges and improve their operations:

- Enhanced Automation: AI-powered robots and automated systems can handle repetitive tasks, freeing up human workers for more complex and creative activities.
- Improved Quality Control: AI algorithms can analyze vast amounts of production data to identify defects and anomalies in real time, leading to higher product quality and reduced waste.
- Predictive Maintenance: AI can predict equipment failures before they occur, allowing SMEs to schedule maintenance proactively and avoid costly downtime.
- Optimized Resource Allocation: AI can analyze production data to optimize the use of resources like energy, materials, and personnel, leading to cost savings and improved efficiency.
- Data-Driven Decision Making: AI can analyze data from various sources to provide SMEs with valuable insights for making informed decisions about production planning and inventory management.
- Personalized Customer Experiences: AI-powered chatbots and recommendation systems can help SMEs provide personalized customer service and tailor their products and services to individual customer needs.
- New Product Development: AI can assist in the design and development of new products by analyzing market trends and customer preferences, leading to faster innovation cycles.

By strategically implementing AI solutions, SMEs can overcome some of their traditional limitations and unlock significant growth potential.

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