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Article

Industry 4.0 Risk, Resilience & Adaptability: A Network and Theme-Based Approach

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Abstract

This study aims to achieve an understanding of Industry 4.0 and examine its advantages and drawbacks. The research study offers a thorough literature review on the evolution of technological trends related to Industry 4.0 over the past decade, including an in-depth analysis of its potential to support the entire organizational value chain, thereby augmenting and enhancing the existing supply chain infrastructure of the firm. It is widely recognized that the implementation of Industry 4.0 presents various challenges and inherent limitations. Is it attainable & sustainable? This study is comprehensive, drawing upon a literature review encompassing 15,053 papers up to 2024. The chosen articles are centered around the concept of "Industry 4.0" and its various interpretations. Moreover, to discern emerging themes through an extensive literature review encompassing 15,053 papers, a year-wise topic modelling approach was utilized, employing the BERTopic methodology. The research indicates that engineering and computer science are the predominant disciplines addressing the complexities of Industry 4.0. The findings underscored the complexities encountered in the implementation of I4.0 tools, encompassing adaptability, flexibility, organizational culture, and efficiency. This paper elucidates the diverse technologies linked to Industry 4.0 that have ignited a dialogue in the realms of innovation and technology. The array of technological advancements, including the Internet of Things (IoT) and blockchain, presents significant advantages and sustainability over time. This work will help academics to further research in Industry 4.0 and provide insights into areas where additional research can be conducted.

Keywords: I4.0; big data; digital supply chain management; digital technology tools; 3D printing; digital twins; cyber – physical technology; cloud computing; supply chain management; risk; resilience

1. Introduction

The COVID-19 pandemic foreclosed numerous enterprises globally and influenced countless supply chains (Ketchen and Craighead, 2020). The disruption caused by the pandemic led to a shortage of essential components, impacting global value chains. This led to questioning the narrative of cost-saving and receptiveness of the global supply chain (Wieland, 2020). The Future of Jobs (2020) report has found that COVID-19 has caused the labor market to change faster than expected; by 2025, automation and a new division of labor between humans and machines will disrupt 85 million jobs globally in medium and large businesses across 15 industries and 26 economies (Russo, 2020). Therefore, the complexities in supply chain management (SCM) paved the way for modernizing supply chain practices and systems.

The "Fourth Industrial Revolution" was presented in 1988 to recognize the processes of evolving intentions into innovations (Rostow, 2019). According to the World Economic Forum (2022), Industry

4.0 “refers to the smart and connected production systems designed to sense, predict, and interact with the physical world, so as to make decisions that support production in real time.”

The goal is to recognize the vision of Industry 4.0 for manufacturing systems based on the latest advances in artificial intelligence (Rauch, 2020). However, I4.0 was formalized in 2011 by a German Government Council of scientists and business representatives. I4.0 provides digital solutions to optimize the value chain in industrial systems (Enke et al., 2018). Nevertheless, the notion is condemned for needing a global definition (Heng, 2014; Lasi, Fettke, Kemper, Feld, and Hoffmann, 2014; Oesterreich and Teuteberg, 2016). It is estimated that Germany's initiative to construct Industry 4.0 will contribute up to €78 billion (approximately USD 90.3 billion) to the German GDP by 2025 (Lichtblau et al., 2016).

The devices and processes contain technologies such as the Internet of Things (IoT), Cyber-physical Technology (CPT), autonomous robots, visualization technologies, cloud computing, blockchain technology, big data analytics, additive manufacturing, and digital twins (Liao, Deschamps, Loures, and Ramos, 2017; Tao, Zhang, Liu, and Nee, 2019).

The rapid progression in communication technologies has led to a faster flow of information, marking the beginning of the fourth industrial revolution – “I4.0” (Dalenogare, Benitez, Ayala, & Frank, 2018; Wagire, Rathore, and Jain, 2019). The political regimes of various countries have recognized the importance of modern manufacturing (Reischauer, 2018) and have taken various initiatives to support both private and public companies. Countries such as France, the UK, the US, China, Singapore, South Korea, and Italy have plans for Industry 4.0, focusing on modern manufacturing processes and mobility (Büchi, Cugno, and Castagnoli, 2020). The industry 4.0 market size in China was valued at USD 18.673 billion in 2023 and is projected to reach USD 66.287 billion by 2032. The expansion is driven by increased automation in manufacturing and the rising integration of AI and IoT across industrial sectors (Banerjee, 2022). The Chinese government’s “Made in China 2025” policy aims to make China a leader in smart manufacturing across the automotive and electronic sectors. I4.0 technologies foster sustainability, a cornerstone of the United Nations Sustainable Development Goals (UNSDG) for 2030, by optimizing the use of modern technological tools among manufacturing firms.

The priority for the business sector is to achieve flexibility and remain competitive globally (Leong, Snyder, and Ward, 1990), which in turn influences competitive objectives (Gerwin, 1987). Flexibility signifies an organization’s competitive strategy, vital for growth (Cousens, Szwejcowski, and Sweeney, 2009). This can be leveraged in response to fluctuating conditions or a proactive initiative anticipating forthcoming changes (De Toni and Tonchia, 1998). Flexibility means attaining a competitive advantage in modern manufacturing (Ghadge, Dani, and Kalawsky, 2012).

Technologies in I4.0 are additive and increasingly enhance flexibility in manufacturing. Additive manufacturing technologies efficiently produce products using three-dimensional computer models, eliminating the need for time-consuming and costly tooling development. This quality of additive manufacturing has been recognized as “game changing” (Brennan et al., 2015, p. 1263; MacCarthy, Blome, Olhager, Srai, & Zhao, 2016, p. 1696) and will fundamentally change operational practices (D’Aveni, 2015). Additive manufacturing is utilized for various consumer products and commercial applications (Eyers and Dotchev, 2010).

Firms adopt new technologies due to the benefits of I4.0 (Huang, Talla Chicoma, and Huang, 2019). Hence, adopting I4.0 technologies can assist in achieving and integrating existing processes by adding value throughout the production system (Cimini, Boffelli, Lagorio, Kalchschmidt, and Pinto, 2021; Gamache, Abdul-Nour, and Baril, 2020; Ghobakhloo and Ching, 2019).

There are several challenges to adopting these tools, including legal issues, security compliance, and concerns regarding data privacy. Another critical factor is an organization’s culture, specifically whether it is open to adopting these tools and how quickly it can do so. Proper hands-on training on I4.0 technologies for the workforce is required. The infrastructure required for the adoption of I4.0 technologies is massive. Hence, the research questions addressed in this paper are

RQ1: What is the current theoretical understanding of I4.0?

RQ2: Bibliometric Landscape of Industry 4.0 Research

RQ3: Scholarly Network Structures and Collaboration Patterns

RQ4: Thematic Exploration through Topic Modelling and the evolution of key areas and trends

This paper seeks to elucidate Industry 4.0 and examine the risks linked to the adoption of digital technologies within organizations. The remainder of the paper is organized into five sections. The second section outlines the methodology and keyword selection, subsequently addressing the number of publications, word co-occurrence network, highly cited authors, collaboration networks at the institute and country levels, country-specific publications, and the author network. The third section examines emerging domains within Industry 4.0, informed by an analysis spanning from 2011 to 2024. This subsection analyses the attributes of Industry 4.0, focusing on its openness to change, risk, agility, and resilience. The final section summarizes the discussion, presenting forward-looking insights and emerging themes in Industry 4.0, along with managerial implications and limitations.

2. Methodology

Fink (1998) defines a literature review as a “*systematic, explicit, and reproducible method for identifying, evaluating, and interpreting the existing body of recorded documents*”. This process yields two advantages. Initially, it synthesizes data by recognizing patterns, themes, and issues. Additionally, it aids in identifying the conceptual content of the field (Meredith, 1993). Systematic literature reviews contrast with traditional methods by reducing bias through comprehensive searches of both published and unpublished studies, while also offering a detailed audit trail of the reviewer’s decisions, procedures, and conclusions (Cook, Mulrow, and Haynes, 1997).

An analytical review scheme is necessary for systematically evaluating the contribution of a given body of literature (Ginsberg & Venkatraman, 1985). Systematic reviews enhance the quality of the review process and outcome by employing a transparent and reproducible procedure (Tranfield et al., 2003). However, this methodology is not without its challenges, including the difficulty of synthesizing data from various disciplines, insufficient representation of books, and a large amount of material to review (Pittaway et al., 2004).

The review process consists of three parts: data collection, analysis, and feedback or recommendations arising from the results. Figure 1 explains the stages in the systematic review process.

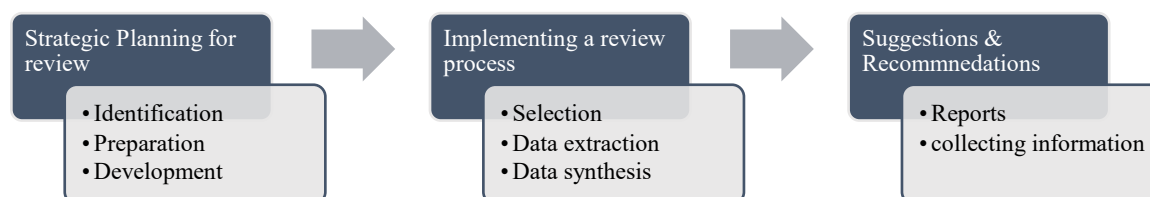


Figure 1. The Systematic Review Process; Source: Modified version from Tranfield et al. (2003).

2.1. Methodology Description and Keyword Selection

This work adheres to the three-step review method established by Tranfield et al. (2003), culminating in recommendations. The initial phase involved delineating the overarching aim of the research and pinpointing essential data sources. The statistics were obtained from the Web of Science database and peer-reviewed articles published in English till December 2024. Following the inception of Industry 4.0 in 2011, the analysis has been performed from that year forward. Investigations into

the impact of Industry 4.0 on supply chain management are scarce (Hofmann & Rüschi, 2017; Partanen & Holmström, 2014). Secondly, the data were refined to include articles and review papers in English on Industry 4.0 up to 2024, yielding a total of 15,053 articles. Furthermore, we have analyzed the data using the BERTopic modelling technique (Figure 2), which employs transformer-based embeddings and clustering to elucidate deeper contextual and semantic relationships within the text. The data has been segmented into nine components: word co-occurrence network, publication count, authors, institutional and national cooperation network, highly cited authors, author network, publications by country, and country collaboration network.

The first is a word co-occurrence network built on 15,053 articles. This strategy is used to investigate the probable relationships between individuals, organizations, concepts, or entities mentioned in research publications. This strategy is based on assessing the frequency of word co-occurrences in the network to detect emergent themes

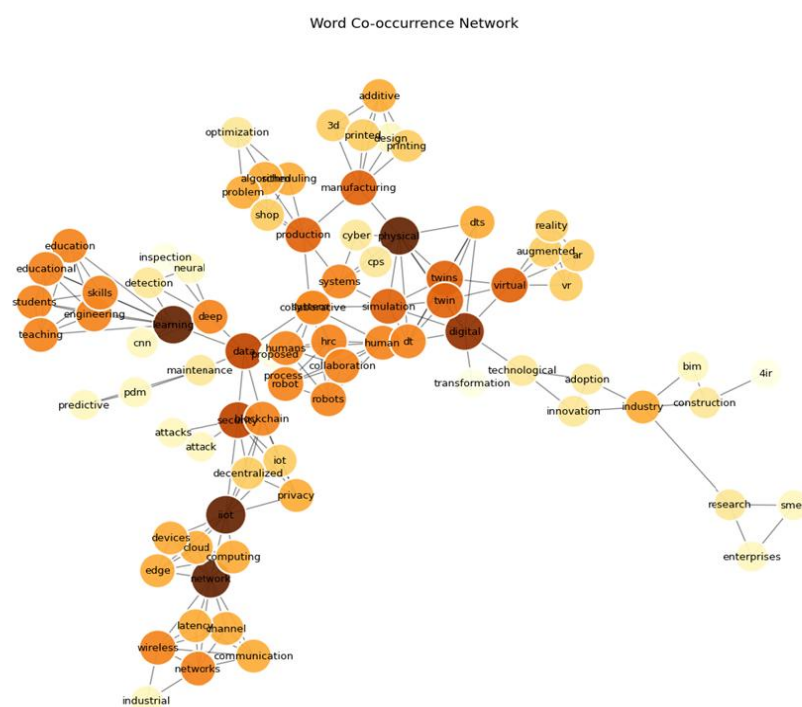


Figure 2. Word Co-occurrence network based on 15,053 articles.

2.2. No. of Publications

Figure 3 depicts the trend of research publications concerning Industry 4.0, highlighting a peak in 2022. The scope of Industry 4.0 extends beyond the manufacturing sector. The digitization of the healthcare industry (Aceto et al., 2020) has facilitated the production of prostheses, implants, and human organs through 3D printing technology. This results in improved healthcare services and enhanced patient satisfaction. Please refer to Appendix A for the leading publications in Industry 4.0.

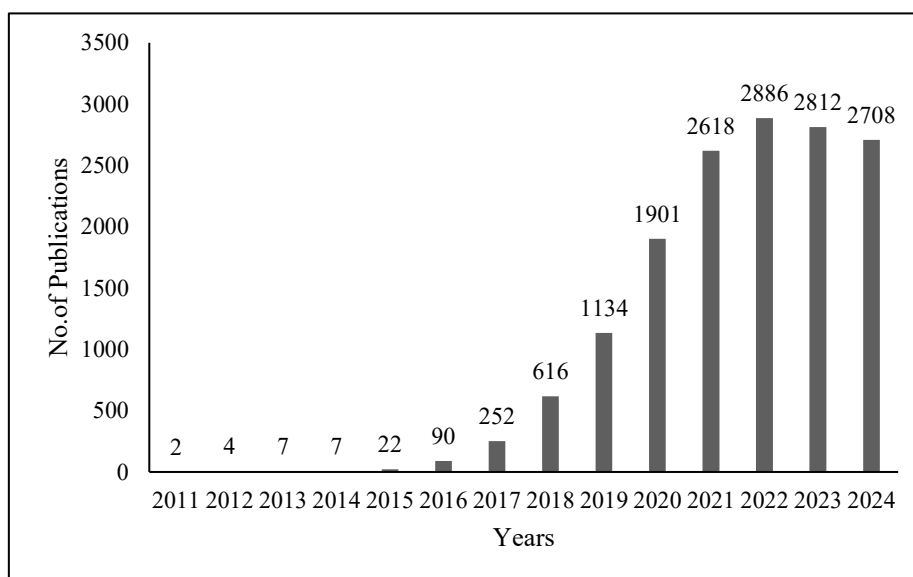


Figure 3. No. of publications on I4.0. Source: Web of Science Database from 2011 – 2024.

Figure 4 procedure exemplifies the way in which businesses and educational institutions work together via the practice of co-authorship. The purpose of these networks is to examine the nature, scope, and impact of cross-institutional and cross-geographic collaborations.

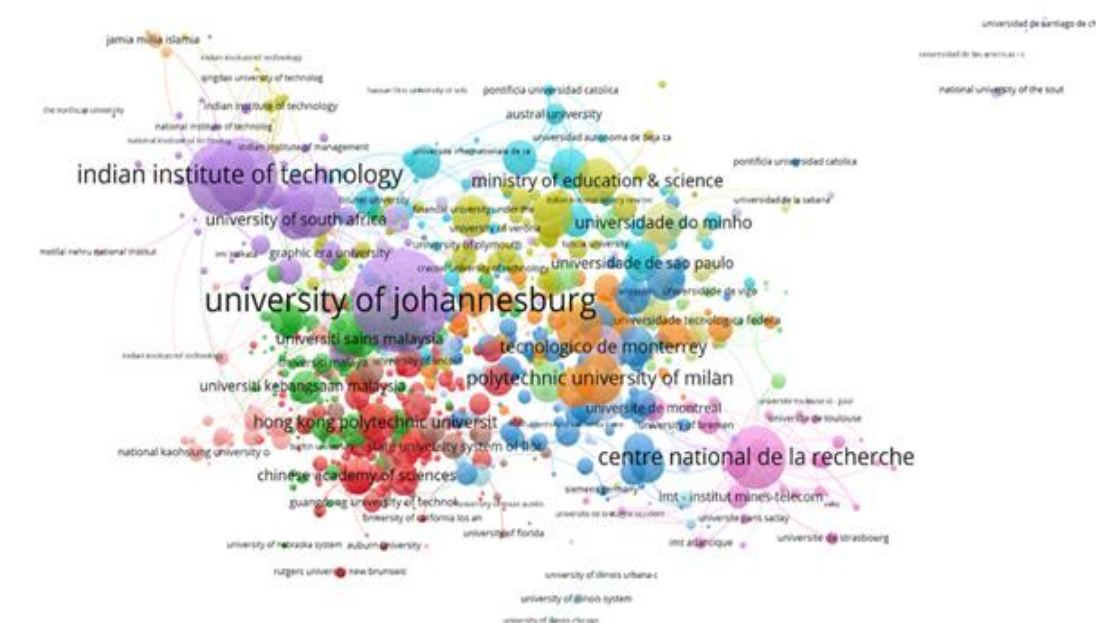


Figure 4. Institute and Country-level Collaborations & Themes from funded projects.

2.3. Highly Cited Authors

Figure 5 illustrates the top authors who have published in the field of Industry 4.0. The top author in I4.0 publications over the last 14 years is Kumar, A., with 76 publications, closely followed by Kumar, S., with 75 publications. Please refer Appendix B for top journals in publication of I4.0. Some articles narrated I4.0 as the digitalization of production processes, limiting its scope to manufacturing plants (Lasi et al., 2014; Strandhagen et al., 2017). It involves implementing 3D printing, data management technologies, modeling, simulation, and virtualization (Kerin & Pham,

2019; Neal et al., 2019). Many studies consider I4.0 the digital transformation of organizational value chains, a paradigm shift across several industries (Ghobakhloo, 2020; Ramakrishna et al., 2020).

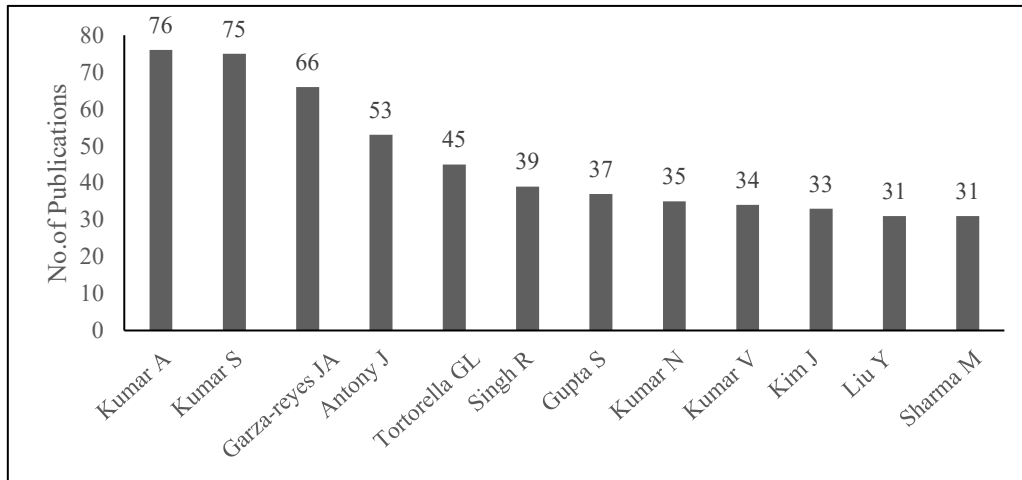


Figure 5. Top Authors in Publications on I4.0 Source: Web of Science Database from 2011 – 2024.

Figure 6 represent a network of 36 authors based on funded projects and collaboration strength, whereas Figure 7 a network of top 100 authors based on collaboration strength.



Figure 6. A network of 36 authors on Funded Projects is based on the Collaboration Strength.

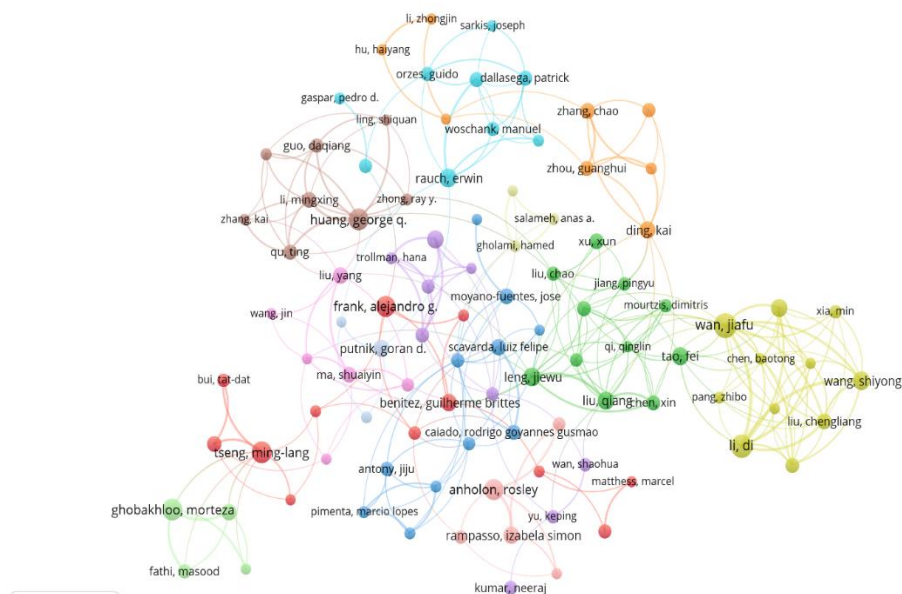


Figure 7. The network of 100 authors is based on the Collaboration strength.

2.4. Country-Wise Publications

Figures 8–10 illustrate Collaboration strength, country-wise research publications and funded project country level of top 50 countries with higher connections on I4.0. The country producing the highest number of publications is the People's Republic of China, with 1,716 publications, followed by India with 1,585, and Italy with 1,363 publications. Surprisingly, the USA stands fourth with 1206 articles. The data in Figure 4 is not the number of publications. It is based on the number of authors. Therefore, the total number of research papers from various countries exceeds 15,053, as one paper can have multiple authors who may be from different countries.

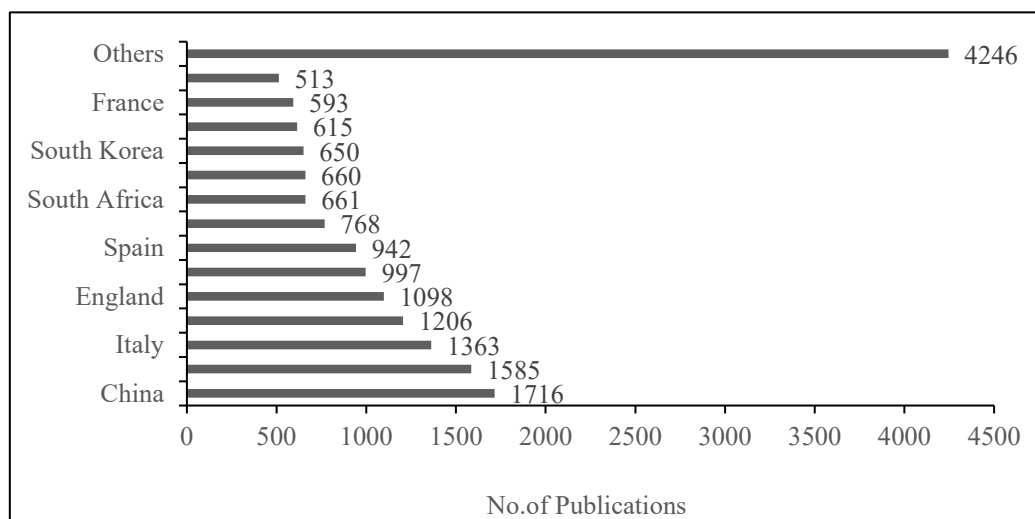


Figure 8. Country-wise Publications on I4.0.

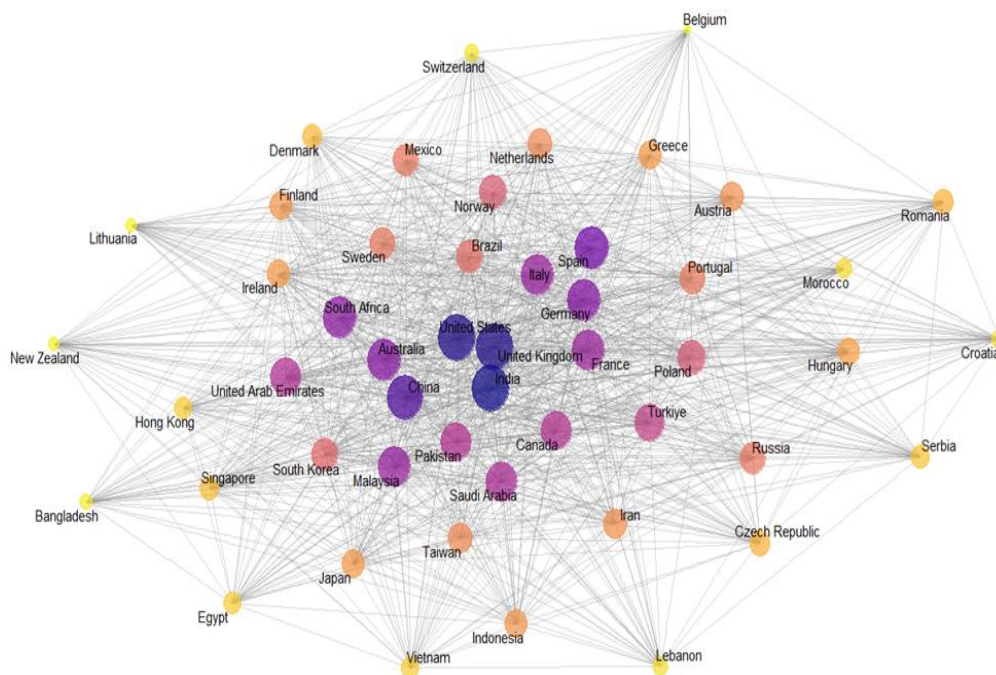


Figure 9. Non-Funded: Country Level Collaboration Network (Top 50 countries with higher connections).

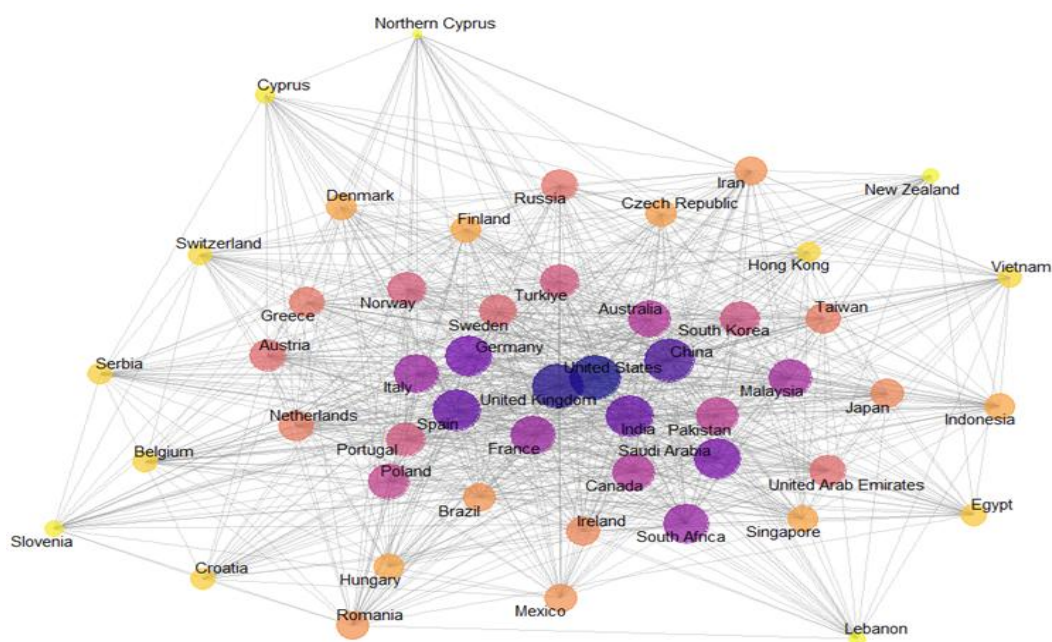


Figure 10. Funded Project: Country-Level Collaboration Network (Top 50 countries with higher connections).

The two most widely discussed components of Industry 4.0 are the Internet of Things (IoT) and Cyber Physical Systems (CPS) (Liao et al., 2017; Manavalan & Jayakrishna, 2019). Integration of these technologies into a system cannot be achieved instantly. They rely on combining several enabling know-how, Cloud Computing, operations technologies, networking processes, protocols, and sensors (Tran et al., 2019). The deployment of Industry 4.0 is a phased process. The first step is to develop a strategy, followed by a roadmap to implement it. The next step is to understand the organizational level of maturity and readiness for digital transformation (Mittal et al., 2018; Santos &

Martinho, 2019). The next section discusses the growth of I4.0 in specific key areas based on the data analysis and findings from the Web of Science databases.

3. Emerging Research Areas from the Literature Review on I4.0

We skimmed the title, keywords, and abstract to identify emerging themes and narrowed down the papers for a full review. The papers were sorted into distinct categories based on themes and relevance to this paper.

I4.0 integrates various manufacturing and communication technologies into business practices (Dalenogare et al., 2018; Wagire et al., 2019) into cyber-physical Technology (Sarvari et al., 2018). Figure 9 represents publications in specific areas, such as Engineering (6,796 papers) and Computer Science (3,645 papers), followed by Business Economics (2,732 papers), which dominate the research on Industry 4.0 and have the highest number of publications. The data in Figure 9 is not the number of publications. It is based on several research areas. Therefore, the total number of research areas exceeds 15,053, as one paper can cover multiple research areas. Other growing areas are Operations Research and Management Science, Chemistry, Telecommunications, Environmental Sciences, and Science and Technology. Figure 11 examines the evolution of focus areas within Industry 4.0. It delineates the evolution of the theme, emphasizing resilience, human-centric approaches, and digital twin notions within Industry 4.0. Appendix C provides further details on keywords and focuses areas.

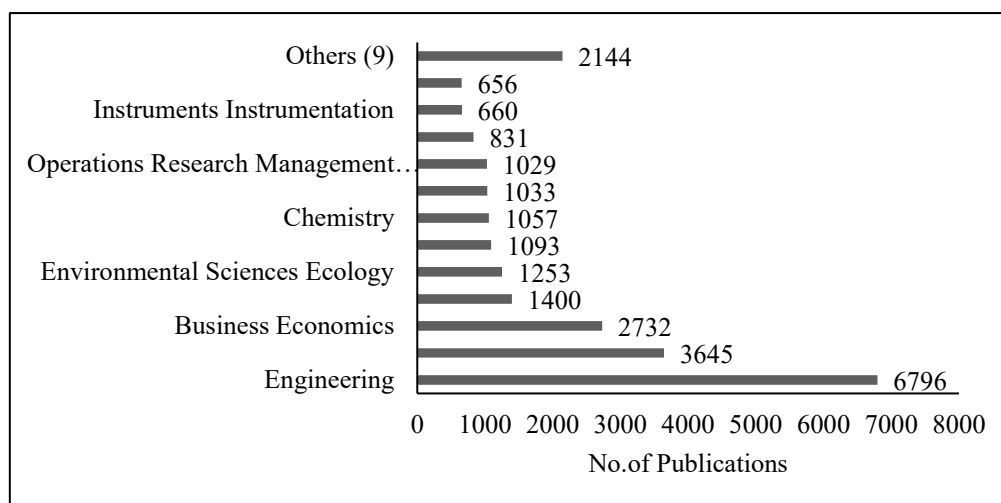


Figure 11. Emerging Research Areas of I4.0.

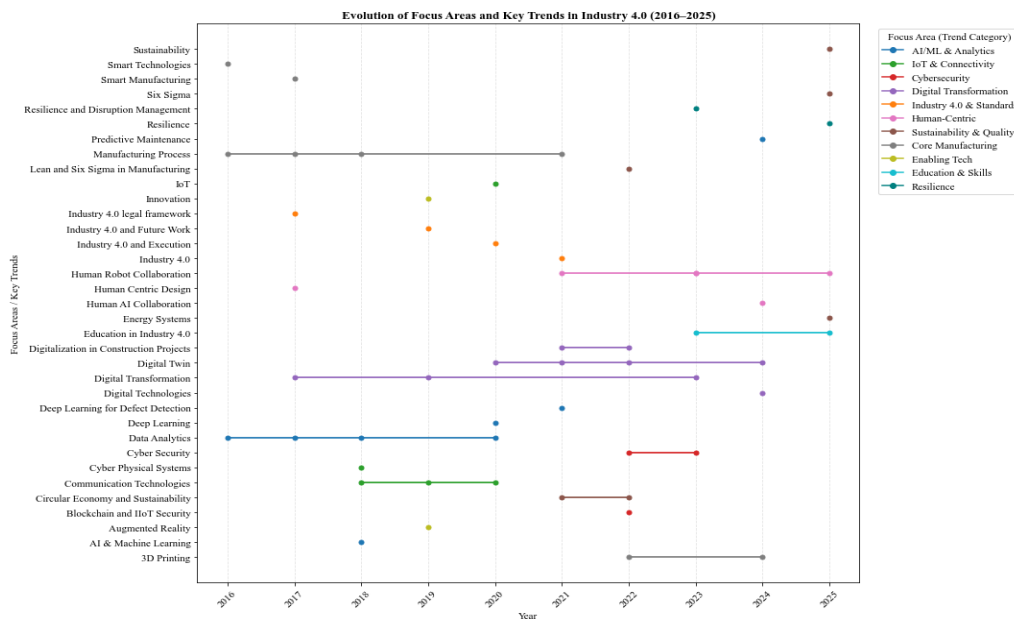


Figure 12. Evolution of Focus Areas and Key Trends in Industry 4.0 (2016 – 2025).

I4.0 and lean manufacturing utilize decentralized control to increase productivity and flexibility (Buer et al., 2018). For instance, Weidmüller Group is a leader in automation and connectivity, producing products for manufacturers and serving various industries. The company aimed to enhance its efficiency with Industry 4.0 by leveraging SAP, utilizing advanced digital and unified equipment, and combining these with solutions. The venture began in 2017 with an integrated shop floor, and the company also looked forward to vertical integration. The project was based on more than 300 data points related to machine health, performance, production, and downtime. The results showed a reduction in manual efforts by up to 50% after eliminating the need for employees to walk to each machine (Hero, 2021).

A theoretical study has been influential in constructing frameworks (Seuring and Müller, 2008), advancing some paradigms (Gunasekaran and Ngai, 2005), and offering insights into Logistics and Supply Chain practices (Power, 2005). However, concerns have been expressed over the ability of reviews to advance our domain knowledge (Carter and Washispack, 2018).

Literature on supply chain modernization or digitalization has been centered on limited themes and technologies such as cloud computing, big data, data analytics, and technological applications in selected industries (Ivanov and Sokolov, 2012; Jede and Teuteberg, 2015; Kache and Seuring, 2017; Papert and Pflaum, 2017; Vendrell-Herrero et al., 2017). Supply chain networks are rapidly digitalizing by adopting Industry 4.0 practices and standards for improved output and customer service.

I4.0 collaborates and integrates procedures at both operational and management levels to enhance productivity, efficiency, and flexibility, enabled by product customization. I4.0, characterized by computing developments, can create a platform for addressing the challenge by facilitating comprehensive connectivity (Fatorachian and Kazemi, 2018). Due to the Complexities in supply chain management, big data is vital in gathering information to improve performance and efficiency in the multi-layered supplier network (Ghobakhloo, 2018; Gilchrist, 2016; Wu et al., 2016). Robotic technology is widely utilized in various industries, including logistics and e-commerce (Demetriou, 2011). Thirdly, the IoT platform will enable real-time traceability and tracking of goods and services, enabling faster decision-making (Gunasekaran et al., 2016).

The technology will enable the real-time traceability of goods and transactions in the global supply chain more quickly (Gurtu & Johny, 2019). Lastly, the role of cybersecurity in I4.0 will be broader due to the increased risk of internet-based systems (Ghadge et al., 2019). New risks and

barriers are emerging due to digital transformation, and supply chains have become increasingly vulnerable to various risks resulting from rapid globalization and digitalization (Pandey et al., 2021).

However, there are challenges while implementing I4.0. Figure 10 shows that connected factories can seamlessly integrate data, applications, and processes. Industry intrusions can be avoided by shielding data and applications. Using the Internet of Things (IoT), a company can connect devices, assets, and sensors to accumulate unexploited data. This enables an organization to deliver scalable, reliable applications more quickly, meeting the ever-changing demands of its customers. The connected factory represents a total restructuring of the methodology for creating, utilizing current tools, and establishing better trust in networks.

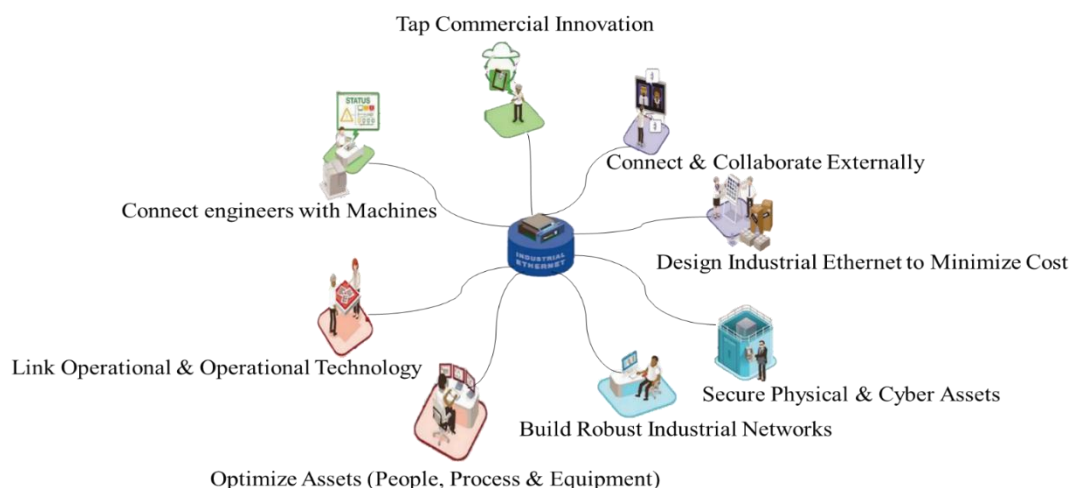


Figure 13. A modified version of The Connected Factory; Source: (Belden, 2022).

4. Attributes Emerging from the Literature Review of I4.0

The speed of transformation reflects 'Moore's Law' on the pace at which information technology-driven change happens. For instance, Ericsson's factory in Tallinn has demonstrated that reducing the average fault detection time, combined with improved ergonomics and faster information sharing, can enhance efficiency by up to 50% through the use of augmented reality troubleshooting. Supply chain problems, such as unexpected changes in the flow of materials due to delays or disruptions, result from supply chain risk. Due to digitalization in supply chain management, risk, agility, and resilience are crucial for I4.0's adaptability and sustainability. Moreover, Sustainability provides a fierce edge over competitors in an environment where business is extremely competitive and challenging (Sonar et al., 2022). Our comprehensive review identified several key attributes related to Industry 4.0, which are explained in the next section. This section discusses various attributes, such as flexibility, risk, agility, and resilience, of a robust I4.0.

4.1. Openness to Change & Agility in I4.0

Openness to Change is a crucial attribute of Industry 4.0 (Heng, 2014; Liao et al., 2017), associated with both the process and enterprise levels. Openness to change refers to the ability to change by replacing or expanding individual models (Vogel-Heuser & Hess, 2016). It enables cyber-physical Production Technology (CPPT) application in value-creating networks (Shrouf et al., 2014). "I4.0 allows a high degree of change both in the development, diagnostics, and maintenance as well as the operation of automated systems" (Jazdi, 2014) and improves the quality of products and services (Sommer, 2015). Prerequisites used for flexibility in businesses are connexons (Heng, 2014), reconfigurable (Wang et al., 2016; Zhong et al., 2017), modular systems (Vogel-Heuser and Hess, 2016; Weyer et al., 2015), and efficient communication between makers and buyers (Li et al., 2017). Nonetheless, openness to

change “enables business processes to be structured more dynamically” and to “react more flexibly to changes in demand or breakdowns in the value chain that occur at short notice” (Heng, 2014).

The term ‘agility’ was initially devised by the US Air Force strategists, which meant the ability to maneuver aircraft (Richards, 1996). Subsequently, it became an accepted strategy for the entire military to be more proactive and responsive than the enemy. Agility is the dynamic capability of an organization to manage changes and ambiguities in the business environment. Agility in supply chains helps achieve a competitive advantage, enabling the exploration of opportunities under pressure and responding quickly to customer needs at an agreeable cost. Goldman (1995) identified four basic dimensions of agility: awareness among customers, improving competitive advantages, adapting to change in times of uncertainty, and leveraging the impact of people and information. Furthermore, enhanced supply chain solutions incorporate data from providers and facility providers, ensuring that stakeholders within the organization make decisions based on the same facts. Real-time visibility will empower companies to respond more quickly to disruptions and mitigate risks.

A supply chain is designed and devised to have better agility and flexibility, enabling faster responsiveness to meet growing demands. For instance, the critical question is how production continuity could be ensured during COVID-19. The pandemic proves the need for flexibility and responsiveness. For example, *Air Liquide* was required to increase the production capacity of its artificial respirators. The company produces 200 units per year; however, due to the ongoing crisis, the need to increase production to 10,000 units in 50 days is challenging (Consultancy.eu, 2020). The ability to respond quickly to competitive challenges is a key element in Industry 4.0. Organizations with responsive supply chains are well-prepared to respond to uncertainties and changes.

4.1.1. Risk in I4.0

Logistics firms strive for operational excellence by delivering exceptional logistics services, thereby fostering sustainable long-term market growth. (Christopher, 1996). Risks in supply chains are one of the hurdles to attaining operational superiority. Many research scholars think that supply chain and logistics risks are problems (Davis, 1993; Lee, 2002; Miller, 1992; Prater, 2005; Wang, 2018). Moreover, supply chain risks play a crucial role in building the resistance and sustainability of organizations (Christopher and Peck, 2004). Many authors have raised concerns about the lack of resolutions to supply chain risks (Jereb et al., 2012; Micheli et al., 2008; Sanchez-Rodrigues et al., 2010; Simangunsong et al., 2012; Wang, 2018).

Supply chain risk is a complex phenomenon that manifests in various forms. These risks can be primary, such as supply chain sources risk, or consequential from other risk drivers (Christopher & Lee, 2004; Jüttner et al., 2010; Manuj & Mentzer, 2008; Sanchez et al., 2008). The pace of change in the business environment raises challenges for enterprises. Hence, innovations become essential for achieving competitive advantage (Lin and Jung, 2011). Creating innovative culture, procedures, and capabilities is vital to managing and alleviating supply chain risks (Dani, 2010).

4.1.2. Resilience in I4.0

Resilience does not mean the ability of an organization or a system to bounce back after a hindering incident. It refers to the capacity to change and renovate. Resilience has been promoted in various fields as a virtue that can help individuals cope with turmoil (Gao et al., 2016). SCM jumped on the resilience movement more than ten years ago. Furthermore, SCM has developed diverse insights into the antecedents and performance efficacy of resilience (Christopher & Peck, 2004; Durach et al., 2020; Pettit et al., 2013; Sheffi & Rice Jr., 2005; Wieland & Wallenburg, 2013). Traditional SCRM and resilience approaches differ slightly. Resilience takes a systemic approach rather than focusing on risk sources. Supply chain resilience refers to the ability to persist, adapt, or transform in response to changes within a supply chain.

Nonetheless, there is a risk associated with losing capabilities and the ability of organizations to remain open to change, agile, and resilient in the face of unexpected disruptions in supply chains

(Ralston and Blackhurst, 2020). I4.0 is still in an evolutionary stage. However, organizations are eager to implement modern technologies to achieve a competitive advantage in the business environment. For example, Albis Plastic GmbH, a leading company in distributing and compounding technical thermoplastics and elastomers, has connected production lines with predictive quality management. The company can now identify quality risks before they arise and understand complex interdependencies in production by connecting and visualizing IoT data (Hero, 2021).

The paper discusses the scope and challenges of I4.0 in an organization and the academic research that has been developed in this field. However, modern digital tools also increase the complexity and risk associated with them, as the same benefits have yet to be fully realized. Hence, risks, agility, and resilience are crucial in I4.0. From the above discussion, it becomes clear that implementing various modern tools into an existing system poses challenges. A few challenges that organizations face, as discussed above, are highlighted in Figure 7.



Figure 14. Emerging Challenges of Organization in I4.0 Implementation.

5. Discussion and Conclusion

This paper presents an overview of Industry 4.0, its challenges, and its future. It presents the benefits, limitations, and vulnerabilities of I4.0. The main contribution of this paper is a holistic view of Industry 4.0 and its future, which provides a competitive advantage through lower costs, shorter delivery periods, greater manufacturing openness, and improved quality.

Nonetheless, I4.0 needs significant investment. It may not be financially viable for low-income countries, particularly with a large pool of skilled workforce (Singh & Gurtu, 2021). For example, India has a highly skilled workforce and low labor costs relative to the European Union (E.U.) or North America. Perhaps this is why Indian organizations limit their investments to automated process control systems, CNC machines, and CAD, rather than adopting the full suite of I4.0 technologies (Singh & Gurtu, 2021).

While speed, openness to change, and quality are desirable in manufacturing organizations, the security of information and the protection of intellectual property (IP) are essential for long-term survival. It encompasses the entire supply chain, including manufacturing, digital, and integrated operations. This saves time, improves transparency, and makes supply chains traceable, making IP vulnerable to theft. Additionally, due to the integrated nature of technology, the systems within the industry 4.0 manufacturing setup work seamlessly until a breakdown occurs. The integrated nature of the technologies presents a significant risk to the system (Gurtu & Johny, 2021). Any breakdown in the entire system, intentional or unintentional, will cause significant disruption to operations and supply chains.

Another technology that might disrupt the current format of Industry 4.0 and change its trajectory is 3D printing. Now, 3D printers are used in various applications, from creating

smartphone covers to producing human organs for replacements (Radenkovic et al., 2016), and are also implemented in smart home design. The size and type of 3D printers, as well as the input materials, determine the possible products. This technology is maturing fast and has tremendous potential. As 3D printing technology matures, the manufacturing industry is expected to undergo a significant transformation, potentially threatening the existence of conventional manufacturing methods. Instead of having many finished products, one may need several 3D printers of varying sizes and basic input materials to produce any item within a category. The reason for using the term “any item within a category” is that input materials for replacing an organ will differ from those for a cell phone or an automobile. This might be similar to producing assorted colors by mixing white paint with three primary colors (Red, Yellow, and Blue). This disruption could be similar to that of the imaging industry (photographic paper, roll, and development industry) after the introduction of digital cameras, or to the print-on-demand technology in the book publishing industry (Gallagher, 2014). The 3D printer may eliminate the need for large manufacturing setups and inventories of raw materials, items, sub-assemblies, and finished goods.

In addition to its research contributions, this work also makes practical applications. This paper can provide practitioners and academics with a framework for future research, given the limited existing research, as evidenced by the number of publications. This paper will be of great value in analyzing the existing gap in the emerging fields of publications. This paper also has some limitations. For example, each tool (e.g., 3D printing) has a wide variety that has not been discussed in detail. Therefore, this research can be expanded by diving deeper into such areas. A possible extension is a survey on the status, motivations, and obstacles to implementing Industry 4.0 in various economies.

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Abbreviations

The following abbreviations are used in this manuscript:

SCM Supply Chain Management
 IoT Internet of Things
 CNC Computer Numerical Control
 CPT Cyber Physical Technology

Appendix A

Top Publishers in I4.0 as per Web of Science

Top Publishers	Publications
MDPI AG	2995
Elsevier	2737
Springer Nature	1407
IEEE	1274
Taylor & Francis	1068
Emerald	1057
Wiley	477
Sage	228
Frontiers Media Sa	130
Aosis	90
Hindawi	89
Walter De Gruyter	86
World Scientific	75

Polska Akad Nauk	73
Inderscience	69
Los Press	63
Wiley - Hindawi	63
IGI Global	56
Routledge	55
Sciendo	54
Tech Science Press	51

Appendix B

Top Journals in Publications I4.0

Journal Name	Publications
Sustainability	711
Applied Sciences Basel	479
IEEE Access	416
Sensors	410
International Journal of Advanced Manufacturing Technology	214
IEEE Transactions on Industrial Informatics	198
Computers Industrial Engineering	190
International Journal of Production Research	184
Technological Forecasting and Social Change	178
Electronics	161
Computers in Industry	160
Energies	151
Processes	151
Journal of Manufacturing Systems	143
Journal of Cleaner Production	132
Journal of Manufacturing Technology Management	111
International Journal of Computer Integrated Manufacturing	108
IEEE Internet of Things Journal	96
Journal of Intelligent Manufacturing	91
Machines	90
Production Planning Control	86
International Journal of Production Economics	84
Journal of Industrial Information Integration	83
IEEE Transactions on Engineering Management	76
TQM Journal	74
International Journal of Interactive Design and Manufacturing	68
Robotics and Computer-Integrated Manufacturing	64
Buildings	59
Annals of Operations Research	56
Benchmarking an International Journal	56
Manufacturing Letters	56
Heliyon	55
Business Strategy and the Environment	54
Engineering Applications of Artificial Intelligence	54
Expert Systems with Applications	51

Appendix C

Evolution of Technological Trends in Industry 4.0

Year	Technologies	Trends
2016	Smart Technologies Data Analysis Manufacturing Process	Smart Technologies in Manufacturing Process
2017	Industry 4.0 legal framework	Industry 4.0 legality

	Manufacturing process Smart Manufacturing Data Analysis Digital Transformation Human Centric Design	Smart Technologies in Manufacturing Human Centric Design
2018	Communication Technologies Cyber Physical Systems AI & Machine Learning Manufacturing Process Data Analytics	Cyber Physical Systems AI & Machine Learning Communication Technologies
2019	Industry 4.0 and Future Work Communication Technologies Augmented Reality Digital Transformation Innovation	Industry 4.0 and Future Work Communication Technologies Digital Transformation
2020	IoT Deep Learning Communication Technologies Digital Twins Industry 4.0 and Execution Data Analysis	IoT Communication Technologies Digital Twins
2021	Digital Twin Digitalization in Construction Projects Industry 4.0 Manufacturing Process Circular Economy and Sustainability Deep Learning for Defect Detection Human Robot Collaboration	Digital Twin Circular Economy and Sustainability Human Robot Collaboration Manufacturing Process in Industry 4.0
2022	Digital Twin 3D Printing Blockchain and IIoT Security Digitalization in Construction Projects Cyber Security Circular Economy and Sustainability Practices in I4.0 Lean and Six Sigma in Manufacturing	Digital Twin IIoT Security & Cyber Security Circular Economy and Sustainability Practices in I4.0
2023	Education in Industry 4.0 Cybersecurity Digital Transformation Human Robot Collaboration Resilience and Disruption Management Human Robot Collaboration	Cybersecurity Digital Transformation Human Robot Collaboration Resilience
2024	Digital Twin Digital Technologies 3D Printing Human AI Collaboration Predictive Maintenance	Digital Twin Digital Technologies Human Robot Collaboration
2025	Education in Industry 4.0 Human Robot Collaboration Resilience Sustainability Energy Systems Six Sigma	Human Robot Collaboration Resilience Sustainability

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