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# AI in Intelligent Manufacturing: A Review

Yisong Chen<sup>1</sup>, Yixin Zhang<sup>2,\*</sup>

## Abstract

Intelligent Manufacturing, through the integration of emerging technologies, holds the potential to link with future wealth. This article aims to examine the development trends and current research of Intelligent Manufacturing. It presents a theoretical framework that facilitates achievements and values. A descriptive analysis of relevant articles was conducted, e.g., the analysis of annual publications and citations, categories distribution analysis, country and institutional analysis, and journal Co-citation analysis. Through the cluster analysis, the research topics were identified and explored. Since 2019, there has been an increase in the annual publications and citations, accompanied by a broad distribution across various categories. The current research focuses on the environmental impact of Industry 4.0, synergies between lean & Industry 4.0, digital twin, digital transformation in manufacturing, sustainability in manufacturing, smart supply chain management, circular economy integration, performance improvements, environmental impact of Industry 4.0 and lean manufacturing practices. This research offers guidance for practitioners, policymakers, and researchers interested in Intelligent Manufacturing to drive innovation and improve operational efficiency.

**Keywords:** Industry 4.0, AI (artificial intelligence), intelligent manufacturing, smart manufacturing, sustainable manufacturing, cyber physical systems, digital transformation, digital twins.

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## I. INTRODUCTION

With the development of AI (artificial intelligence), science and technology are reshaping human society. Manufacturing has become the core stage of this change. AI brings unprecedented opportunities and challenges to this traditional industry. From automated production lines in smart factories to efficient supply chain management systems, AI is transitioning the production model and operational efficiency of the manufacturing industry with its powerful data processing capabilities, deep learning algorithms and intelligent decision-

making mechanisms. For example, PepsiCo's Frito-Lay factory uses an artificial intelligence-driven predictive maintenance system to predict equipment failures in advance and arrange maintenance by analyzing sensor data, reducing unexpected downtime and significantly improving production efficiency. Airbus uses artificial intelligence technology to shorten the aircraft aerodynamic prediction time from 1 hour to 30 milliseconds, allowing engineers to test a large number of design iterations in a short period of time, greatly improving innovation capabilities. In addition, some manufacturing companies use edge analysis technology to monitor the operating status of production equipment in real time, detect potential failure risks in a timely manner, and use wearable devices to track worker health and safety. These innovations include using AI algorithms to analyze data to predict equipment failures in advance, reduce downtime and maintenance costs, check product defects through computer vision and machine learning algorithms to improve product quality, use machine learning algorithms to quickly generate multiple design options to find the optimal design solution, and test and optimize in a virtual environment through digital twin models to reduce the cost and time of physical prototype production. These applications not only improve production efficiency and product quality but promote the development of the manufacturing industry towards intelligence, personalization and sustainability [Wang, et al., 2015; Zhong, et al., 2016; Babiceanu & Seker, 2016; Qin, et al., 2016; Oztemel & Gursev, 2020; Monostori, et al., 2016; Lu, et al., 2020; Qi & Tao, 2018; Ferreira, et al., 2023].

The technical support system behind intelligent manufacturing is rich and diverse, covering cutting-edge technologies in many fields such as artificial intelligence and machine learning, Internet of Things (IoT), big data and cloud computing, digital twins, robotics, 3D printing technology, industrial Internet and 5G technology. These technologies are integrated with each other and jointly promote the intelligent transformation of manufacturing industry. Artificial intelligence and machine learning are the core of intelligent manufacturing, which can achieve predictive maintenance, quality control, production optimization and intelligent decision-making in the production process. The Internet of Things technology realizes the interconnection between equipment, products and people, collects data in real time through sensors and communication modules and transmits it to the industrial Internet platform for analysis and processing. Big data and cloud computing technologies are responsible for extracting valuable information from massive data to support

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corporate decision-making. At the same time, cloud computing provides powerful computing and storage resources for big data processing. Digital twin technology simulates and optimizes the production process by creating virtual models of physical equipment, combining the Internet of Things, big data and artificial intelligence. Robotics technology, as an important execution unit of intelligent manufacturing, is widely used in production links to improve production efficiency and quality. 3D printing technology can quickly manufacture complex-shaped parts based on computer-aided design models. As a key information infrastructure that links the entire industrial system, the entire industrial chain and the entire value chain, the industrial Internet closely connects and integrates all industrial elements through the platform. 5G technology provides possibilities for new areas of wireless technology in industrial applications and lays the foundation for future flexible production. The integration and innovative application of these technologies provide strong technical support for intelligent manufacturing and promote the development of manufacturing industry in an efficient, intelligent and sustainable direction [Wang, et al., 2016; Weyer, et al., 2015; Li, 2018; Oesterreich & Teuteberg, 2016; Qi, et al., 2019; Stock, et al., 2016; Machado, et al., 2020; Jabbour, et al., 2018].

With the rapid development of cutting-edge technologies such as artificial intelligence, the Internet of Things and big data, intelligent manufacturing has become a key force in promoting the transformation and upgrading of the manufacturing industry. For example, the AI-enabled intelligent manufacturing industry-education integration seminar to be held in 2025 will bring together experts from academia, industry and government departments to discuss the application and future development of AI in intelligent manufacturing. In addition, the "Joint Laboratory of Intelligent Manufacturing System Control" jointly established by Shanghai Jiaotong University and Midea Group aims to solve corporate problems and promote the advancement of intelligent manufacturing technology through the integration of industry, academia and research. These studies not only focus on breakthroughs in technology itself, but also involve its impact on the economy, society and labor market. For example, some studies have pointed out that intelligent manufacturing can encourage innovative cooperation among enterprises by accelerating knowledge spillovers and enhancing innovation advantages. At the same time, the impact of intelligent manufacturing on the share of labor income has also become a research hotspot. Relevant studies have shown that although the development of intelligent manufacturing will improve labor productivity, it will also have a complex impact on the share of labor income. In-depth discussions of these studies will provide important theoretical support and practical guidance for the future development of intelligent manufacturing [Brettel, et al., 2017; Javaid & Rana, 2022; Kiel & Rana, 2017; Kumar, et al., 2020; Ching, et al., 2022; Dantas, et al., 2021].

In recent years, with the rapid development of artificial intelligence, the number of studies on Intelligent Manufacturing have gradually increased, and its importance has become increasingly prominent. Especially in the context of

increasingly fierce competition in the global manufacturing industry, Intelligent Manufacturing is regarded as a keyway to enhance industrial competitiveness and achieve high-quality development. Governments, enterprises and research institutions of various countries have increased their investment to promote the deep integration of artificial intelligence and manufacturing, in order to gain a leading edge in the field of intelligent manufacturing. This trend has not only promoted the continuous emergence of new technologies but accelerated the transformation and upgrading of traditional manufacturing, and improved production efficiency and product quality. At the same time, with the increasing demand of consumers for personalized and customized products, Intelligent Manufacturing has also shown great potential in meeting market demand and improving user experience. Therefore, Intelligent Manufacturing has become the focus of common attention of academia and industry at present and in the future [Rajput & Singh, 2019; Esmailian, et al., 2020; Jabbour, et al., 2018; Lu, et al., 2020; Pereira & Ribeiro, 2017; Ivanov, et al., 2016; Hofmann & Rüsçh, 2017].

This article will review the development trends and current research hotspots. Specifically, we tried to make deeper studies on cluster analyses, cited reference comparisons, and citing articles reviews. The paper is structured (Figure 1) as follows. Section II describes the methodology and paper selection. Section III comprises a descriptive analysis. Section IV makes cluster analysis on the selected articles. Section V analyses the highly cited references. Section VI presents insights from the citing articles analysis. Section VII explores potential future research. Section VIII concludes this paper.

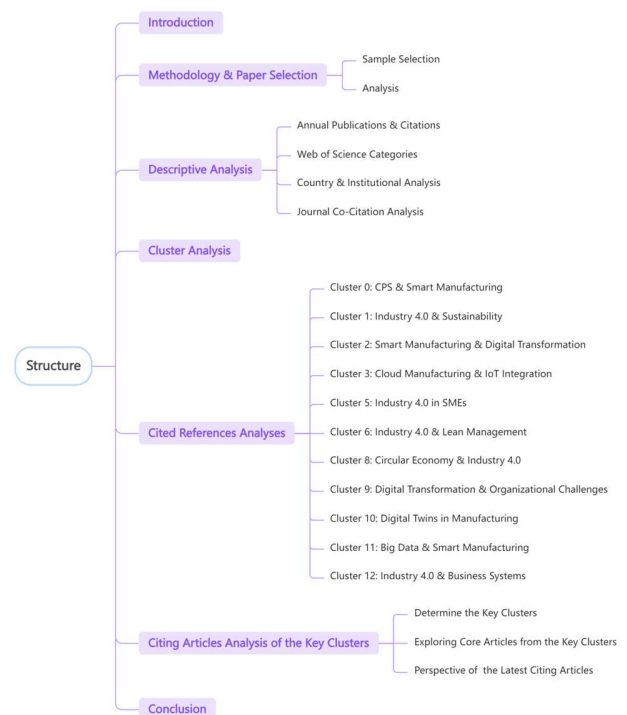


Figure 1. The Structure of the Paper

## II. METHODOLOGY & PAPER SELECTION

### Sample Selection

We searched for articles from WoS and SCOPUS databases. At the first stage, "Intelligent Manufacturing" was chosen as the author keyword to search published papers. The search returned 659 results, which indicates that Intelligent Manufacturing is an emerging research topic. At the second stage, the keywords related to "Intelligent Manufacturing" were collected from the 659 articles. relevant keywords were identified: "Intelligent Manufacturing", "Smart Manufacturing", "Industry 4.0", "Industry 5.0", "Cyber-Physical Production System", "Agile Manufacturing", "Sustainable Manufacturing", "Artificial Intelligence in Manufacturing", "Machine Learning in Manufacturing", "Deep Learning in Manufacturing", "Big Data Analytics in Manufacturing", "Augmented Reality in Manufacturing", "Virtual Reality in Manufacturing", "Wireless Sensor Network in Manufacturing", "Flexible Manufacturing System", "Computer Integrated Manufacturing", "Simulation Optimization in Manufacturing", "Data Mining in Manufacturing", "Data Visualization in Manufacturing", "Manufacturing Cyber-Physical Systems", "Cloud Manufacturing", "Service-Oriented Architecture in Manufacturing", "Human-Robot Collaboration in Manufacturing", "Virtual Manufacturing", "Virtual Prototyping in Manufacturing", "Common Information Model in Manufacturing", "Industrial Internet of Things in Manufacturing", "Human-Cyber-Physical System in Manufacturing", "Supply Chain Management in Smart Manufacturing", "Resource Allocation in Manufacturing", "Energy Consumption in Manufacturing", "Energy Modelling in Manufacturing", "Environmental Performance in Manufacturing", "Green Supplier Selection in Manufacturing", "Blockchain in Manufacturing Supply Chain", "Cybersecurity in Manufacturing", "Finite Element Analysis in Manufacturing", "Radio Frequency Identification (RFID) in Manufacturing", "Human-Machine Cooperation in Manufacturing". At the end, based on the keywords, we searched for articles in the title, author keywords, and Keywords Plus (the deadline for the search was December 31, 2024, and the search date was January 20, 2025).

### Analysis

According to the literature review process, a total of 12,427 documents were obtained with publication years ranging from 1996 to 2024.

By screening the related categories, we limited the types of documents to research articles and reviews, excluding records in categories with less relevance to the focus of this research, and obtained 11,426 documents. Based on the 11,426 articles collected, a descriptive analysis was conducted, covering the annual publications and citations analysis; the categories distribution analysis; the country & institutional analysis, and the journal Co-citation analysis.

Since the main publication period started in 2019, we limited the research to 2019-2024 and obtained 9,127 articles.

The highest cited references of the articles each year were selected to establish a Co-citation network for clustering. 21 clusters were obtained, and we selected the largest 11 clusters for subsequent analysis. An in-depth analysis of the cited references & citing articles was conducted to identify basic literature through high cited references and explore existing research in the field through citing articles in important 6 clusters.

By examining the intersection of 112 cited references and 2205 citing articles, there are 32 high-cited articles revealing the important topics. Based on 654 citing articles from 2022 to 2024, we explored the current research topics as well. The future development was discussed and illustrated. The procedure is depicted in Figure 2.

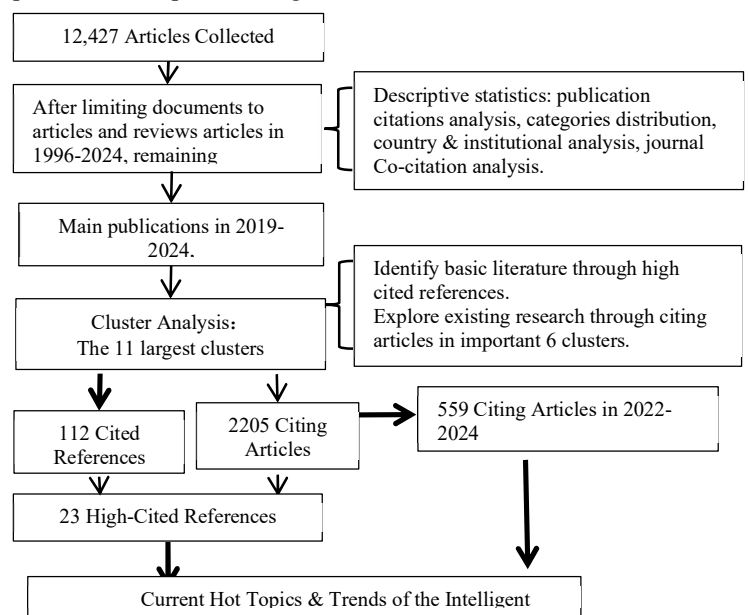


Figure 2. Literature Selecting Procedures

## III. DESCRIPTIVE ANALYSIS

### Annual Publications & Citations

From 1996 to 2024, we selected 11,426 intelligent manufacturing-related articles (10,051 research papers + 1,375 reviews). The publications and citations have increased annually (Figure 3). The annual publication count of articles has risen from 816 in 2019 to 1676 in 2024, while the citation count has increased from 1,819 in 2019 to 91,238 in 2024.

Specifically, the quantity of publications and their citations experienced a moderate increase from 1996 to 2018. A qualitative shift in scholarly engagement has been observed since 2019, with both annual publications and citation rates exhibiting a sustained upward pattern. Our focus is directed towards articles published between 2019 and 2024, categories include: Computer Science Information Systems, Engineering Electrical Electronic, Telecommunications, Business Finance, and Economics.

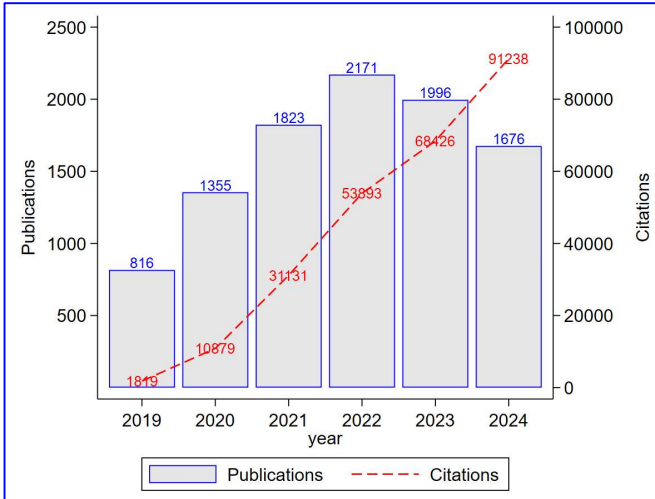


Figure 3. The Distribution of Publication & Citations (2012 - 2024)

**Detailed Categories**

We classified the 11,426 articles published between 1996 and 2024. The results (Figure 4) revealed that the categories with the most articles are Engineering Manufacturing (2,515 articles), Engineering Industrial (1,992 articles), Engineering Electrical Electronic (1,708 articles), Computer Science Interdisciplinary Applications (1,413 articles), Operations Research Management Science (1,361 articles), Environmental Sciences (1,245 articles), Green Sustainable Science Technology (1,244 articles), and Computer Science Information Systems (1,127 articles). The relevant research on Intelligent Manufacturing mainly focused on the 8 categories. However, there were still significant gaps in the depth and breadth of research.

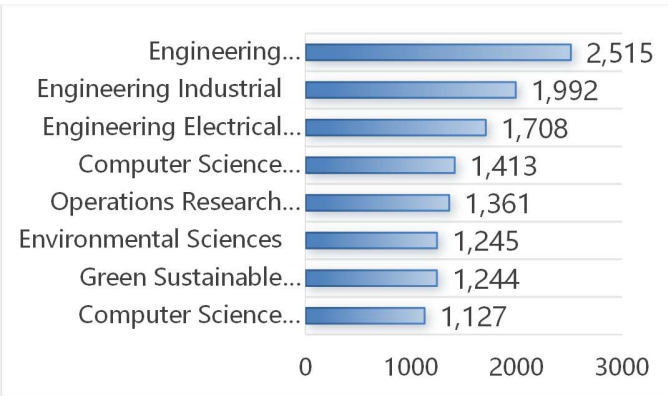


Figure 4. Research Categories

The 8 categories have shown a growth trend since 2012 (Figure 5). Figure 4 shows that from 2012 to 2024, all 8 categories in the Intelligent Manufacturing field showed a growth trend, and the number of literatures has increased rapidly since 2012 to reach the peak in 2022. However, there are significant differences in the development of these categories after 2022. After that, the number of published literature (Engineering Manufacturing, Engineering Industrial, Green Sustainable Science Technology, Operations Research Management Science, Computer Science Interdisciplinary Applications) began to decline, whereas, the number of published literature (Engineering Electrical Electronic and Computer Science Information Systems) has increased since

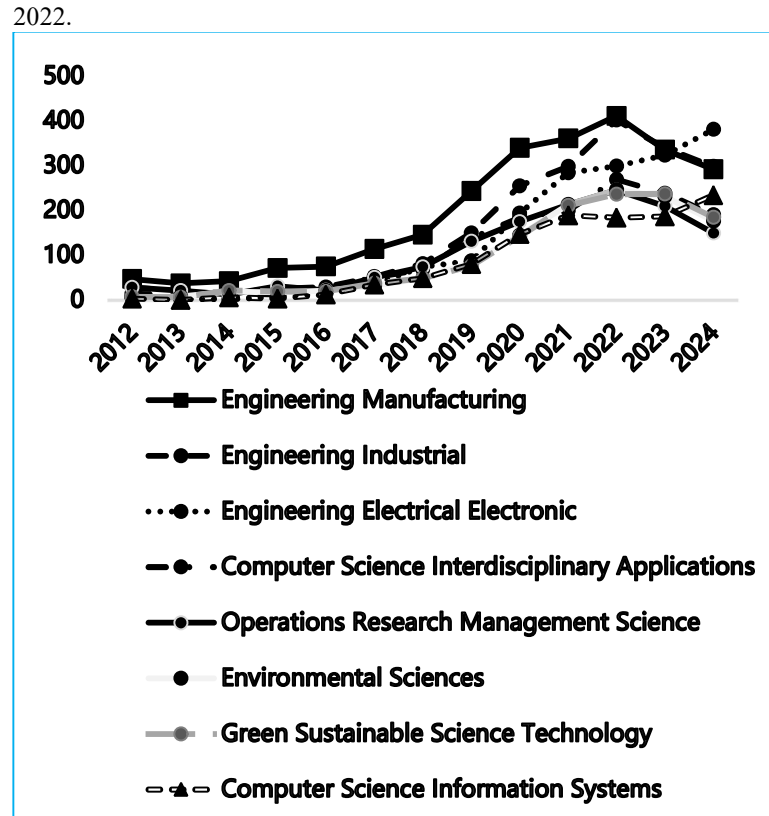


Figure 5. Publication Years in the Largest 8 Categories

**Country & Institutional Analysis**

To reveal the degree of concern in Intelligent Manufacturing, analysis of the publications that institutions engaged from 1996 to 2024 was conducted (Table 1). The top 8 countries are China, Italy, United Kingdom, United States, Brazil, Saudi Arabia, India, Spain, Poland and Sweden. China, Italy, United Kingdom, United States, Saudi Arabia, India, Spain and Sweden started research on Intelligent Manufacturing as early as 2012. China has invested significantly in Intelligent Manufacturing research, with 1,397 institutions and 2,396 papers published. It accounts for over 20% of the world's publications. Italy, United Kingdom, United States, Saudi Arabia, India, Spain and Sweden have also launched research on Intelligent Manufacturing. 469 institutions in Italy published 1,005 articles, 404 institutions in United Kingdom published 1,071 articles, 356 institutions in United States published 1,220 articles, 175 institutions in Saudi Arabia published 34 articles, 140 institutions in India published 971 articles, 136 institutions in Spain published 683 articles and 116 institutions in Sweden published 284 articles. Brazil and Poland started their research on Intelligent Manufacturing later (in the year of 2014). 176 institutions in Brazil published 434 articles and 116 institutions in Poland published 284 articles.

Table 1

Institutions & Publications			
Country		Institutions	Publications
China	2012	1397	2396
Italy	2012	469	1005
United Kingdom	2012	404	1071

United States	2012	356	1220	<i>IEEE Transactions on Industrial Informatics</i>	2,390
Brazil	2014	176	434	<i>Robotics and Computer-Integrated Manufacturing</i>	2,247
Saudi Arabia	2012	175	34	<i>Journal of Intelligent Manufacturing</i>	2,199
India	2012	140	971	<i>Technological Forecasting and Social Change</i>	2,139
Spain	2012	136	683	<i>CIRP Annals - Manufacturing Technology</i>	1,841
Poland	2014	117	361	<i>IFAC-PapersOnLine</i>	1,821
Sweden	2012	116	284	<i>International Journal of Computer Integrated Manufacturing</i>	1,698
				<i>Production Planning &amp; Control</i>	1,696
				<i>Expert Systems with Applications</i>	1,645
				<i>European Journal of Operational Research</i>	1,500
				<i>Journal of Manufacturing Technology Management</i>	1,460
				<i>Lecture Notes in Computer Science</i>	1,410
				<i>International Journal of Operations &amp; Production Management</i>	1,176
				<i>Journal of Industrial Information Integration</i>	1,168
				<i>Procedia Computer Science</i>	1,100
				<i>IEEE Internet of Things Journal</i>	1,098
				<i>Journal of Business Research</i>	1,023
				<i>Future Generation Computer Systems</i>	1,017

Notes: Limited to the top 10 countries by the number of institutions

**Journal Co-Citation Analysis**

In view of the research in Intelligent Manufacturing, we conducted an in-depth analysis of the articles published between 1996 and 2024 (Table 2). The journals were cited more than 1,000 times during this period, including *International Journal of Production Research*, *Journal of Cleaner Production*, *International Journal of Advanced Manufacturing Technology*, *Proceedings of the CIRP*, *International Journal of Production Economics*, *Journal of Manufacturing Systems*, *Computers in Industry*, *Computers & Industrial Engineering*, *Procedia Manufacturing*, *IEEE Transactions on Industrial Informatics*, *Robotics and Computer-Integrated Manufacturing*, *Journal of Intelligent Manufacturing*, *Technological Forecasting and Social Change*, *CIRP Annals - Manufacturing Technology*, *IFAC-PapersOnLine*, *International Journal of Computer Integrated Manufacturing*, *Production Planning & Control*, *Expert Systems with Applications*, *European Journal of Operational Research*, *Journal of Manufacturing Technology Management*, *Lecture Notes in Computer Science*, *International Journal of Operations & Production Management*, *Journal of Industrial Information Integration*, *Procedia Computer Science*, *IEEE Internet of Things Journal*, *Journal of Business Research*, *Future Generation Computer Systems*.

Table 2  
Journal Co-Citation

Cited Journals	Publications
<i>International Journal of Production Research</i>	4,571
<i>Journal of Cleaner Production</i>	3,336
<i>International Journal of Advanced Manufacturing Technology</i>	3,332
<i>Proceedings of the CIRP</i>	3,280
<i>International Journal of Production Economics</i>	3,272
<i>Journal of Manufacturing Systems</i>	3,064
<i>Computers in Industry</i>	2,949
<i>Computers &amp; Industrial Engineering</i>	2,730
<i>Procedia Manufacturing</i>	2,469

<i>International Journal of Computer Integrated Manufacturing</i>	1,698
<i>Production Planning &amp; Control</i>	1,696
<i>Expert Systems with Applications</i>	1,645
<i>European Journal of Operational Research</i>	1,500
<i>Journal of Manufacturing Technology Management</i>	1,460
<i>Lecture Notes in Computer Science</i>	1,410
<i>International Journal of Operations &amp; Production Management</i>	1,176
<i>Journal of Industrial Information Integration</i>	1,168
<i>Procedia Computer Science</i>	1,100
<i>IEEE Internet of Things Journal</i>	1,098
<i>Journal of Business Research</i>	1,023
<i>Future Generation Computer Systems</i>	1,017

Notes: Limited to the journals with citation frequencies above 1000

IV. CLUSTER ANALYSIS

The high-cited references are the basis for conducting research. Relevant academic literature was primarily published between 2019 and 2024, conducting an in-depth analysis of 9,127 citing articles (7,971 articles + 1,156 reviews) and 367,106 cited references published between 2019 and 2024. The cluster analysis is to explore the important research of intelligent manufacturing. Based on 367,106 cited references, we selected the top 50 high cited references each year to construct a Co-citation network and cluster them. 23 clusters were finally identified, of which the largest 11 clusters covered a total of 112 highly cited references (Table 3).

Table 3

Summary of the Largest 11 Clusters

Cluster	size	silh oue tte	period	Mean (year)	Keywords
Cluster 0:	14	0.9	2014-	2016	smart
CPS & Smart		53	2020		manufacturing, digital twin

Cluster	Count	Score	Start Year	End Year	Keywords	Cluster	Count	Score	Start Year	End Year	Keywords
Manufacturing					systematic literature review, digital transformation, cyber-physical system, intelligent manufacturing, case study, artificial intelligence, machine learning, future research direction	Cluster 5: Industry 4.0 in SMEs	10	0.9	2016-2019	2017	case study, research challenge, literature review, manufacturing industry, cloud manufacturing, systematic review, business model lean production, empirical study, future research direction, large manufacturing, operations management, systematic literature review, smart manufacturing, digital transformation, case study, digital technologies
Cluster 1: Industry 4.0 & Sustainability	13	0.9	2017-2022	2019	circular economy, digital technologies, systematic literature review, sustainable manufacturing, sustainable development goal, digital transformation, smart manufacturing, digital twin, case study, smart manufacturing system	Cluster 6: Industry 4.0 & Lean Management	10	0.9	2018-2022	2019	moderating role, operational performance, mediating role, empirical study, firm performance, digital transformation, digital technologies, smart manufacturing, adopting industry, manufacturing companies
Cluster 2: Smart Manufacturing & Digital Transformation	12	0.9	2015-2021	2017	smart manufacturing, systematic literature review, digital transformation, literature review, systematic review, empirical study, case study, cyber-physical system, manufacturing industry, sustainable manufacturing	Cluster 8: Circular Economy & Industry 4.0	9	1	2018-2020	2019	circular economy, systematic literature review, digital technologies, supply chain, circular economy practice, modern manufacturing ecosystem, systematic survey, world region,
Cluster 3: Cloud Manufacturing & IoT Integration	11	1	2014-2020	2016	smart manufacturing, digital twin, systematic literature review,						

Cluster	Count	Silhouette	Start Year	End Year	Keywords	References	Median Year	Keywords
Cluster 9: Digital Transformation & Organizational Challenges	9	0.9	2018-2021	2019	data-driven analysis, sustainable supply chain, management trend, digital transformation, emerging economy, smart manufacturing, critical success factor, circular economy, success factor, manufacturing industry, case study, comparative analysis, resource dependence theory	47	2021	manufacturing industry smart factories, empirical study, systematic review, smart manufacturing, case study, future research direction, bibliometric analysis, sustainable manufacturing, emerging research agenda, sustainable supply chain
Cluster 10: Digital Twins in Manufacturing	9	0.8	2017-2021	2019	digital twin, smart manufacturing, systematic literature review, industrial digital twin, learning ecosystem, intelligent manufacturing, cyber-physical system, industrial internet, case study, digital twin framework	71	2021	
Cluster 11: Big Data & Smart Manufacturing	8	0.8	2015-2018	2017	smart manufacturing, digital twin, intelligent manufacturing, cyber-physical system, smart manufacturing system, systematic review, sustainable manufacturing, production planning, big data,	65	2018	
					Total	112		2014-2022

The 112 cited references contained in these 11 clusters were published between 2014 and 2022 and are highly cited references. Among them, cluster 11 has the smallest silhouette value, but it is also greater than 0.7 (the clustering effect is ideal when the silhouette value of the cluster is greater than 0.7), and the homogeneity of the articles within the cluster is high. Cluster 0 is the largest cluster, containing 14 references from 2014 to 2020, and the median year of the cited references is 2016. Cluster 1 is the second largest cluster, and the clustering effect is slightly better than cluster 0. Cluster 1 contains 13 references from 2017 to 2022, and the median year of the cited references is 2019. Cluster 2 is the 3rd cluster, with 12 references from 2015-2021, and the median year of citations is 2017. The details of other clusters are in table 3.

The degree of integration between clusters is high. These 112 highly cited references are the research basis for 2,205 citing references in Intelligent Manufacturing from 2019 to 2024. The overlap of the literature keywords in the 11 clusters indicates that the highly cited references in each cluster provided the basis for the citing articles among clusters.

This study conducted an analysis of 11 intelligent manufacturing clusters that have close interactions with each other. The research stages of each topic are different. Some topics have not published new articles for many years. On the other hand, some topics continue to have new highly cited references, and the research topics are still hot. From the research period and the median year of the cited references, the articles in cluster 11, cluster 12, cluster 5, cluster 0, cluster 3, and cluster 8 were all published earlier than 2021, these relatively old clusters have no highly cited references in recent years. Cluster 2, cluster 9, cluster 10, cluster 1, cluster 6, are relatively new. Next, we analyze cited references and citing articles around these 11 clusters.

V. CITED REFERENCES ANALYSES

According to the cluster analysis, the largest 11 clusters cover 112 highly cited references published between 2014 and 2022 (Table 4). While the highly cited references of cluster 11, cluster 12, cluster 5, cluster 0, cluster 3, and cluster 8 were all published relatively early, Cluster 2, cluster 9, cluster 10, cluster 1 and cluster 6 have newer highly cited references published. Considering that the contents of the 11 clusters have a high degree of overlap, the articles in some clusters were published relatively early and no highly cited references appeared in recent years, the early articles of these clusters are still constantly cited by the subsequent research of the other clusters.

Table 4  
Cluster Publication Trends (2014-2022)

Cluster	Year										Total
	2	2	2	2	2	2	2	2	2	2	
	0	0	0	0	0	0	0	0	0	0	
	1	1	1	1	1	1	2	2	2	2	
	4	5	6	7	8	9	0	1	2		
Cluster 0: CPS & Smart Manufacturing	2	2	7	2				1			14
Cluster 1: Industry 4.0 & Sustainability				2	3		4	2	2		13
Cluster 2: Smart Manufacturing & Digital Transformation		1	2	5	1	1		2			12
Cluster 3: Cloud Manufacturing & IoT Integration	4	1	1	1	2	1	1				11
Cluster 5: Industry 4.0 in SMEs			2		6	2					10
Cluster 6: Industry 4.0 & Lean Management				1	3	3	2	1			10
Cluster 8: Circular Economy & Industry 4.0				2	4	3					9
Cluster 9: Digital Transformation & Organizational Challenges				1	2	4	2				9
Cluster 10: Digital Twins in Manufacturing				1	2	2	2	2			9
Cluster 11: Big Data & Smart Manufacturing	1			1	6						8

Cluster 12: Industry 4.0 & Business Systems	5	1	1						7	
<b>Total</b>	<b>1</b>	<b>5</b>	<b>1</b>	<b>1</b>	<b>2</b>	<b>1</b>	<b>1</b>	<b>1</b>	<b>3</b>	<b>112</b>
	1	3	2	5	5	8	0			

**Cluster 0: CPS & Smart Manufacturing**

This cluster (Table 5) is the integration of Cyber-Physical Systems (CPS) within the realm of smart manufacturing. It explores how CPS, through real-time monitoring and control, is revolutionizing manufacturing processes and shaping the future of industrial operations. The advancements in CPS have enabled enhanced efficiency, flexibility, and adaptability in manufacturing systems.

Table 5  
Topics of Cluster 0

Topics	Explanations
<b>CPS in Manufacturing</b>	The integration of CPS in manufacturing, highlighting advancements in smart factories and the impact on future manufacturing trends [Wang, et al., 2015; Zhong, et al., 2016; Babiceanu & Seker, 2016; Qin, et al., 2016].
<b>IoT Integration in Manufacturing</b>	The role of IoT in enhancing manufacturing processes through real-time data collection and analysis [Oztemel & Gursev, 2020; Monostori, et al., 2016; Wang, et al., 2016; Weyer, et al., 2015].
<b>Big Data in Manufacturing</b>	The use of big data analytics to improve decision-making and operational efficiency in manufacturing [Li, 2018; Oesterreich & Teuteberg, 2016; Qi, et al., 2019; Stock, et al., 2016].

The integration of CPS into smart manufacturing has significantly elevated production efficiency and system flexibility while offering more sustainable and innovative manufacturing models.

**Cluster 1: Industry 4.0 & Sustainability**

This cluster (Table 6) examines the role of Industry 4.0 technologies in driving sustainability within manufacturing. By leveraging technologies such as the Internet of Things (IoT), Big Data analytics, and cloud computing, Industry 4.0 offers opportunities for optimizing resource utilization and

minimizing waste in manufacturing processes.

Table 6  
Topics of Cluster 1

Topic	Explanations
Sustainability in Manufacturing	Industry 4.0 technologies can drive sustainability in manufacturing through resource efficiency and reduced waste [Oztemel & Gursev, 2020; Machado, et al., 2020; Jabbour, et al., 2018; Brettel, et al., 2017; Javaid & Rana, 2022].
Environmental Impact of Industry 4.0	Environmental benefits and challenges of Industry 4.0. Benefits include reduced energy consumption and waste. Challenges encompass cybersecurity risks and the need for sustainable tech development [Kiel & Rana, 2017; Kumar, et al., 2020; Ching, et al., 2022; Dantas, et al., 2021].
Circular Economy Integration	The integration of circular economy principles with Industry 4.0 for sustainable manufacturing. Industry 4.0 technologies enable the implementation of circular economy practices by providing real-time data and analytics for optimizing resource flows and reducing environmental impact [Qi, et al., 2019; Rajput & Singh, 2019; Esmailian, et al., 2020; Jabbour, et al., 2018; Lu, et al., 2020].

Industry 4.0 presents a transformative potential for sustainable manufacturing, though its implementation is accompanied by environmental and social challenges that require careful navigation. Future research could strive to harmonize technological innovation with sustainable development goals to ensure that Industry 4.0 serves as a catalyst for both economic growth and environmental stewardship.

**Cluster 2: Smart Manufacturing & Digital Transformation**

This cluster (Table 7) investigates the convergence of smart manufacturing practices with digital transformation strategies. It highlights how digital technologies are reshaping manufacturing landscapes, enabling more efficient, responsive, and customer-centric production systems. The integration of digital tools and platforms is fostering a new era of innovation

and competitiveness in the manufacturing sector.

Table 7  
Topics of Cluster 2

Topic	Explanations
Digital Transformation in Manufacturing	The role of digital transformation, which involves the integration of digital technologies such as IoT, CPS, and big data analytics, to create intelligent manufacturing systems that enhance manufacturing efficiency and competitiveness [Weyer, et al., 2015; Pereira & Ribeiro, 2017; Ivanov, et al., 2016].
Smart Supply Chain Management	Smart technologies can optimize supply chain management and logistics. Smart supply chains leverage the IoT, CPS, and big data analytics to enhance visibility, reduce delays, and improve responsiveness [Li, 2018; Oesterreich & Teuteberg, 2016; Hofmann & Rüsçh, 2017; Schumacher, et al., 2016].
Lean Manufacturing Practices	The integration of lean principles with Industry 4.0 technologies to enhance manufacturing efficiency. Lean manufacturing aims to eliminate waste, improve process flow, and maximize value for customers [Dalenogare, et al., 2018; Ciano, et al., 2020; Osterrieder, et al., 2020; Zheng, et al., 2021].

The digital transformation of manufacturing, underscored by smart manufacturing initiatives, is instrumental in enhancing operational efficiencies and driving business growth. Digital innovations will be important to thrive in an increasingly competitive and dynamic global market.

**Cluster 3: Cloud Manufacturing & IoT Integration**

This cluster (Table 8) centers on the transformative potential of cloud manufacturing and its integration with the Internet of Things (IoT). It discusses how cloud-based solutions enable resource sharing, on-demand services, and scalable computing power in manufacturing. The synergy between cloud computing and IoT is creating intelligent manufacturing environments that are both flexible and resilient.

Table 8  
Topics of Cluster 3

Topic	Explanations
Cloud Manufacturing Systems	The integration of cloud computing in manufacturing to enable resource sharing and on-demand services [Tao, et al., 2014; Lu, 2017; Xu & Wang, 2014; Xu & Duan, 2019].
IoT and CPS Integration	The synergy between IoT and CPS in creating intelligent manufacturing environments [Li, 2018; Oesterreich & Teuteberg, 2016; Qi, et al., 2019; Stock, et al., 2016].
Digital Twin Applications	Practical applications of digital twin technology in manufacturing, including product design and predictive maintenance [Kritzinger, et al., 2018; Tao & Cheng, 2019; Qi & Tao, 2018].

The integration of cloud manufacturing with IoT is redefining industrial operations, i.e., enhance system adaptability, enable predictive maintenance, and support the transition to smart factories. As these technologies mature, the combined impact delivers even greater efficiencies and innovations across the manufacturing spectrum.

**Cluster 5: Industry 4.0 in SMEs**

This cluster (Table 9) focuses on the adoption of Industry 4.0 technologies within small and medium-sized enterprises (SMEs). It addresses the unique challenges faced by SMEs in implementing these technologies, including financial constraints and knowledge gaps, as well as the significant opportunities for enhanced flexibility and competitiveness.

Table 9  
Topics of Cluster 5

Topic	Explanations
Challenges for SMEs	Key challenges faced by SMEs in adopting Industry 4.0 technologies, including financial and knowledge constraints [Buer, et al., 2018; Ben-Daya, et al., 2019; Ghobakhloo, 2018].
Opportunities for SMEs	The potential benefits of Industry 4.0 for SMEs. Industry 4.0 technologies offer SMEs

the opportunity to enhance operational efficiency, reduce costs, and develop new business models [Dantas, et al., 2021; Zhang & Wang, 2019; Yadav, et al., 2020].

Strategic Roadmaps for SMEs

Strategic frameworks and detailed roadmaps for Small and Medium-sized Enterprises (SMEs) to effectively implement Industry 4.0 technologies [Javaid & Rana, 2022; Dantas, et al., 2021; Yadav, et al., 2020; Mittal, et al., 2018].

While SMEs face hurdles in embracing Industry 4.0, the potential benefits in terms of operational improvements and market competitiveness are substantial. With the right strategic frameworks and support mechanisms, SMEs can successfully navigate this technological transition and position themselves for sustainable growth.

**Cluster 6: Industry 4.0 & Lean Management**

This cluster (Table 10) explores the synergistic relationship between Industry 4.0 technologies and lean management principles. It examines how lean practices, when combined with the advanced capabilities of Industry 4.0, can lead to optimized production processes, reduced lead times, and enhanced product quality.

Table 10  
Topics of Cluster 6

Topic	Explanations
Lean Manufacturing Practices	Lean principles can be integrated with Industry 4.0 technologies to enhance manufacturing efficiency, enabling lean manufacturing to achieve higher levels of automation, flexibility, and responsiveness [Dalenogare, et al., 2018; Ciano, et al., 2020; Osterrieder, et al., 2020].
Synergies Between Lean & Industry 4.0	The combined impact of lean management and Industry 4.0 technologies. Integration leads to better operational efficiency, shorter lead times, and improved product quality [de Assis, et al., 2022; Tao, et al., 2018; Culot, et al., 2020].

Performance Improvements The integration of lean and Industry 4.0 leads to significant performance improvements in manufacturing [de Assis, et al., 2022; Tao, et al., 2018; Culot, et al., 2020; Manavalan & Jayakrishna, 2019].

The integration of lean management with Industry 4.0 technologies represents a powerful approach to achieving operational excellence in manufacturing. By leveraging the data-driven insights and automation capabilities of Industry 4.0, organizations can amplify the waste-reduction and efficiency-enhancing benefits of lean methodologies.

**Cluster 8: Circular Economy & Industry 4.0**

This cluster (Table 11) investigates the intersection of the circular economy with Industry 4.0, emphasizing strategies for minimizing waste and maximizing resource efficiency. It discusses how Industry 4.0 technologies can facilitate the transition to a circular economy by enabling real-time data analytics, product lifecycle extension, and sustainable supply chain management.

Table 11  
Topics of Cluster 8

Topic	Explanations
Circular Economy Integration	Industry 4.0 technologies can support circular economy practices in manufacturing by providing real-time data and analytics for optimizing resource flows [Rajput & Singh, 2019; Esmacilian, et al., 2020; Jabbour, et al., 2018].
Sustainable Supply Chain Management	The role of Industry 4.0 in creating sustainable supply chains. These technologies such as IoT, CPS, and big data analytics, significantly enhance supply chain visibility, reduce delays, and improve overall responsiveness [Yadav, et al., 2020; Manavalan & Jayakrishna, 2019; Luthra & Mangla, 2018].
Blockchain for Sustainability	Blockchain technology can enhance transparency and sustainability in supply chains. Its integration with Industry 4.0 technologies can lead to more sustainable and resilient supply chain systems [Masood & Sonntag, 2020; Büchi, et al., 2020].

The alignment of Industry 4.0 with circular economic principles offers a pathway to sustainable industrial development. By harnessing the power of these technologies, industries can create closed-loop systems that reduce environmental impact while driving economic value for a sustainable future.

**Cluster 9: Digital Transformation & Organizational Challenges**

This cluster (Table 12) addresses the organizational challenges associated with digital transformation in the context of Industry 4.0. It explores the resistance to change often encountered within organizations, the perspectives of management, and the barriers that can impede the successful adoption of new digital technologies.

Table 12  
Topics of Cluster 9

Topic	Explanations
Organizational Resistance to Change	The resistance from employees and middle management to the adoption of Industry 4.0 technologies [Vial, 2019; Verhoef, et al., 2021; Horváth & Szabó, 2019].
Managerial Perspectives on Industry 4.0	Insights into how top executives interpret Industry 4.0 and the drivers for its adoption [Masood & Sonntag, 2020; Büchi, et al., 2020; Stentoft, et al., 2021].
Barriers to Digital Transformation	Key barriers to digital transformation, including lack of digital strategy, resource scarcity, and cybersecurity concerns [Kumar, et al., 2020; Büchi, et al., 2020].

Navigating the challenges of digital transformation requires a holistic approach that considers both technological and human factors. Organizations that can effectively manage change, invest in employee training, and foster a culture of innovation will be better positioned to reap the benefits of Industry 4.0 and sustain competitive advantage in the digital age.

**Cluster 10: Digital Twins in Manufacturing**

This cluster (Table 13) examines the applications and implications of digital twin technology in manufacturing. Digital twins, which create virtual replicas of physical manufacturing systems, are explored for their roles in enhancing product design, enabling predictive maintenance, and optimizing production processes through real-time simulation and analysis.

Table 13  
Topics of Cluster 10

Topic	Explanations
Digital Twin Applications	Practical applications of digital twin technology in manufacturing, including product design and predictive maintenance [Kritzinger, et al., 2018; Tao & Cheng, 2019; Qi & Tao, 2018].
Digital Twin & IoT Integration	The integration of digital twin technology with IoT for enhanced manufacturing intelligence [Qi, et al., 2019; Stock, et al., 2016; Lu, et al., 2020].
Digital Twin & AI Integration	The role of AI in digital twin technology for advanced analytics and decision-making. This integration enables intelligent manufacturing systems that can adapt to changing conditions and continuously improve [Weyer, et al., 2015; Lee, et al., 2014].

Digital twin technology is revolutionized by deep insights and decision-making. As technology evolves, its capacity to enhance system resilience, reduce downtime, and drive innovation will be increasingly critical to manufacturers seeking to excel in an era defined by complexity and rapid change.

**Cluster 11: Big Data & Smart Manufacturing**

This cluster (Table 14) highlights the role of Big Data analytics in advancing smart manufacturing initiatives. It discusses how the analysis of vast datasets generated by manufacturing operations can uncover patterns, predict trends, and inform strategic decisions that enhance production efficiency and product quality.

Table 14  
Topics of Cluster 11

Topic	Explanations
Big Data Analytics in Manufacturing	Highlights the use of big data analytics in improving manufacturing processes and decision-making [Zheng, et al., 2018; Yin, et al., 2018; Tao, et al., 2018; Kusiak, 2017].

Deep Learning for Smart Manufacturing  
Focused on the application of deep learning algorithms to manufacturing data for achieving smarter operations [Stock, et al., 2016; Lee, et al., 2014; Rosen, et al., 2015; Wollschlaeger & Gholami, 2017].

Big Data analytics stands as a cornerstone of smart manufacturing and the tools necessary to transform raw data into actionable intelligence. As manufacturing systems grow in complexity, the ability to leverage Big Data will be essential for maintaining competitiveness and driving continuous improvement in an industry where precision and innovation are important.

**Cluster 12: Industry 4.0 & Business Systems**

This cluster (Table 15) analyzes the impact of Industry 4.0 on business systems, with a focus on the emergence of smart factories and the challenges of system integration. It discusses how Industry 4.0 is reshaping business models and operational strategies, with new approaches to manage the complexity and connectivity of modern manufacturing environments.

Table 15  
Topics of Cluster 12

Topic	Explanations
Smart Factories & Industry 4.0	The concept of smart factories and their role in the fourth industrial revolution. Smart factories leverage IoT, CPS, and big data analytics to enable real-time monitoring, adaptive control, and optimized production. These factories represent a shift towards more flexible, efficient, and customer-centric manufacturing systems [Li & Wang, 2014; Drath & Gholami, 2014; Vaidya & Rana, 2018].
System Integration Challenges	The challenges of integrating various systems in Industry 4.0 environments. Key challenges include interoperability issues, data security concerns, and the need for standardized communication protocols [Weyer, et al., 2015; Stock, et al., 2016; Lee, et al., 2014].

The evolution of business systems in response to Industry 4.0 is marked by both promise and complexity. Organizations that can effectively integrate these technologies while addressing integration challenges will be best equipped to leverage Industry 4.0 as a driver of innovation and growth in an increasingly connected industrial landscape.

VI. CITING ARTICLES ANALYSIS OF THE KEY CLUSTERS

Determine the Key Clusters

In order to explore the foundation of intelligent manufacturing, this study analyzed 112 highly cited references. However, the research scope of these articles goes far beyond the field of Intelligent Manufacturing. We turned to examine the 2205 citing articles that cited these 112 articles to reveal the current research status. In Table 16, this article identified 5 clusters with a large number of highly cited references in recent years, which are: cluster 1, cluster 2, cluster 6, cluster 9, and cluster 10.

Cluster	Year						Total
	2019	2020	2021	2022	2023	2024	
Cluster 0: CPS & Smart Manufacturing	87	94	83	25	9	1	299
Cluster 1: Industry 4.0 & Sustainability		29	48	63	46	55	241
Cluster 2: Smart Manufacturing & Digital Transformation	41	71	64	38	20	18	252
Cluster 3: Cloud Manufacturing & IoT Integration	54	71	30	39	13	2	209
Cluster 5: Industry 4.0 in SMEs	8	42	83	55	29	6	223
Cluster 6: Industry 4.0 & Lean Management		21	30	61	72	66	250
Cluster 8: Circular Economy & Industry 4.0		6	27	60	35	16	144
Cluster 9: Digital Transformation & Organizational Challenges			17	39	51	47	154
Cluster 10: Digital Twins in Manufacturing			19	50	38	30	137
Cluster 11: Big Data & Smart Manufacturing	34	49	29	35	32	8	187
Cluster 12: Industry 4.0 & Business Systems	53	21	25	3	7		109

<b>Total</b>	<b>27</b>	<b>40</b>	<b>45</b>	<b>46</b>	<b>35</b>	<b>24</b>	<b>2205</b>
	<b>7</b>	<b>4</b>	<b>5</b>	<b>8</b>	<b>2</b>	<b>9</b>	

Exploring Core Articles from the Key Clusters

The highly cited references are the research foundation of intelligent manufacturing-related fields. However, highly cited references are not only from the field of Intelligent Manufacturing, and its research field has expanded and diversified. If we explore the topics of Intelligent Manufacturing through highly cited references, two problems are: first, the topics explored through highly cited references deviate from the field of Intelligent Manufacturing; Second, highly cited references were published earlier, articles published in recent years would be missing. The first problem was solved by selecting core articles according to the following criteria:

First, taking the intersection of 112 highly cited references and 2205 citing articles to obtain 84 important selected literature.

Second, deleting the clusters that have no recent highly cited references, and the 30 articles remain.

Since some articles appear repeatedly in different clusters, the 23 articles were selected after removing duplicates. The 23 articles are both high cited references and citing articles. We treat them as Core Articles. (Figure 6).

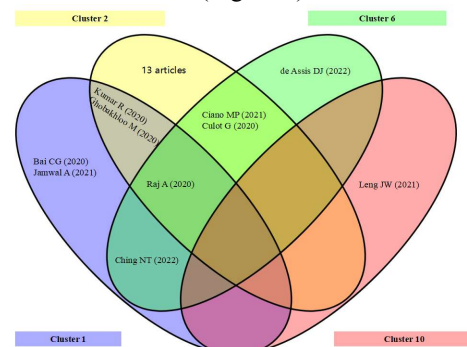


Figure 6. 23 Distribution of Core Articles

The core articles consolidate key findings into 9 main topics: Sustainability in Manufacturing, Digital Transformation in Manufacturing, Smart Supply Chain Management, Environmental Impact of Industry 4.0, Lean Manufacturing Practices, Circular Economy Integration, Digital Twin, Performance Improvements and Synergies Between Lean & Industry 4.0 (Table 17). The core articles from the key clusters encompassed all the topics of these clusters.

Table 17  
Topics of 23 Core Articles (2019-2022)

Topics	Explanations
Sustainability in Manufacturing	Sustainability. It encompasses research on how Industry 4.0 technology aids in achieving sustainability in manufacturing processes, such as enhancing productivity, decreasing resource consumption, and minimizing environmental impact [Qi & Tao, 2018; Ching, et al., 2022;

	Culot, et al., 2020; Jamwal, et al., 2021; Raj, et al., 2020; Leng, et al., 2021].
Digital Transformation in Manufacturing	Industry 4.0 drives the digital transformation of manufacturing, involving changes in business models, production systems, and supply chains [de Assis, et al., 2022; Manavalan & Jayakrishna, 2019; Büchi, et al., 2020; Alcácer & Cruz-Machado, 2019].
Smart Supply Chain Management	Industry 4.0 technologies, such as the Internet of Things (IoT) and big data analytics, which can enhance supply chain visibility, risk control, and sustainability [Ben-Daya, et al., 2019; Stentoft, et al., 2021; Ivanov, et al., 2019; Ivanov & Dolgui, 2021].
Environmental Impact of Industry 4.0	Industry 4.0 technologies positively impact environmental sustainability, including improvements in energy efficiency, reductions in harmful emissions, and optimization of resource use [Kumar, et al., 2020; Ghobakhloo, 2020; Bai, et al., 2020; Frank, et al., 2019].
Lean Manufacturing Practices	The combination of Industry 4.0 and lean production, which can improve operational performance. However, it requires an in-depth analysis of their interaction at the practical level [Ciano, et al., 2020; Zheng, et al., 2021; Tortorella, et al., 2019; Sony & Naik, 2019].
Circular Economy Integration	The integration of Industry 4.0 technology with the circular economy, which can facilitate the reuse and recycling of waste. For instance, network technology, reverse logistics, and additive manufacturing can support circular economic practices [Kumar, et al., 2020; Manavalan & Jayakrishna, 2019; Nascimento, et al., 2019].
Digital Twin	Digital twin technology, which has the potential to be applied in supply chain risk management and intelligent manufacturing system design. It can enhance the ability for predictive and reactive decision-making [Leng, et al., 2021; Ivanov & Dolgui, 2021].
Performance Improvements	The application of Industry 4.0 technology can lead to improved operational performance. However, it is essential to consider the breadth and depth of the technology, as well as the impact of enterprise size [Vial, 2019; Verhoef, et al., 2021; Horváth & Szabó, 2019; Büchi, et al., 2020; Zheng, et al., 2018; Yin, et al., 2018; Tao, et al., 2018; Kusiak, 2017].
Synergies Between Lean & Industry 4.0	Industry 4.0 technology can enhance a variety of worker capabilities, such as super strength, enhanced perception, and virtual abilities, to support the execution of manufacturing activities [de Assis, et al., 2022].

Transformation & Organizational Challenges, and Digital Twins in Manufacturing.

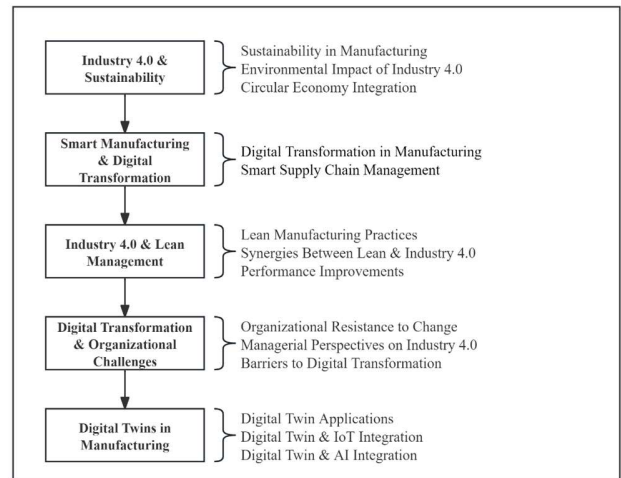


Figure 7. Future Trends of Intelligent Manufacturing

**Industry 4.0 & Sustainability**

The integration of Industry 4.0 with sustainability principles emphasizes the role of advanced technologies in reducing environmental impacts in manufacturing processes. Industry 4.0 technologies, such as smart sensors, automation, and cyber-physical systems, enable real-time monitoring and data collection, which can be leveraged to optimize resource usage, reduce waste, and minimize energy consumption. This alignment is essential for achieving a balance between industrial growth and environmental preservation, for the transition toward greener manufacturing models [Zhong, et al., 2016; Qin, et al., 2016; Li, 2018; Stentoft, et al., 2021; Asad, et al., 2023].

In addition, the circular economy concept, supported by Industry 4.0, fosters the creation of closed-loop systems where products are designed for reuse, refurbishment, and recycling. By using digital technologies, businesses can trace the lifecycle of products and materials with supply chain transparency and sustainable decision-making. These innovations could meet global sustainability goals and reduce carbon footprints while maintaining competitive advantages in an increasingly eco-conscious market [Machado, et al., 2020; Ching, et al., 2022; Tao, et al., 2014; Rosen, et al., 2015].

**Smart Manufacturing & Digital Transformation**

Smart manufacturing, enabled by Industry 4.0 technologies, focuses on the digitalization of production systems to enhance efficiency, flexibility, and customization. The use of connected devices, machine learning algorithms, and predictive analytics within manufacturing processes allows for improved decision-making and operational agility. Digital transformation in manufacturing also involves shifting from traditional manufacturing models to data-driven, automated, and interconnected systems that can adapt to changing market demands with minimal human intervention [Verhoef, et al., 2021; Jamwal, et al., 2021; Cimino, et al., 2024].

This transformation optimizes operational performance and enables manufacturers to embrace innovations like artificial

VII. FUTURE DIRECTIONS

In this section, we highlight five potential future research directions of intelligent manufacturing (Figure 7), such as Industry 4.0 and sustainability, Smart Manufacturing & Digital Transformation, Industry 4.0 & Lean Management, Digital

intelligence (AI) and the Internet of Things (IoT). These technologies contribute to a deeper integration of information systems for the seamless exchange of data across the production chain. The combination of smart devices and AI enhances predictive maintenance, reduces downtime, and fosters the creation of more sustainable and cost-effective manufacturing practices [Ivanov, et al., 2016; Nascimento, et al., 2019; Alkaraan, et al., 2023; Saniuk, 2022].

#### **Industry 4.0 & Lean Management**

Lean management focuses on maximizing value while minimizing waste, a principle that dovetails well with the objectives of Industry 4.0. The integration of smart technologies like sensors, AI, and robotics into lean practices allows organizations to streamline their operations and enhance process efficiency. Real-time data collection and analytics provide insights that help in continuous process improvement and reduce operational waste to optimize production flows and resources [Xu & Wang, 2014; Alcácer & Cruz-Machado, 2019; Yu, et al., 2022; Dwivedi, et al., 2022].

Furthermore, Industry 4.0 enables the implementation of more advanced lean strategies through the use of digital twins, which provide virtual models of production processes. This enables manufacturers to simulate and analyze different process flows, identify inefficiencies, and make data-driven decisions. By integrating these technologies, organizations can ensure that lean practices are more accurately executed to a higher level of productivity and quality [Osterrieder, et al., 2020; Yin, et al., 2018; Chi, et al., 2023; Garcia, et al., 2022].

#### **Digital Transformation & Organizational Challenges**

Digital transformation in manufacturing often encounters organizational resistance due to the complexities of integrating new technologies into existing processes. Organizational challenges, such as employee skill gaps, resistance to change, and insufficient managerial support, can hinder the adoption of Industry 4.0 technologies. To successfully implement digital transformation, organizations could foster a culture of innovation, ensure proper training, and align leadership strategies with technological advancements [Brettel, et al., 2017; Stentoft, et al., 2021; Frank, et al., 2019; Costa, et al., 2024].

Furthermore, digital transformation requires addressing barriers like legacy systems and cybersecurity concerns. Companies could prioritize integrating new technologies with existing infrastructure, build robust cybersecurity frameworks to protect sensitive data, and align organizational goals with digitalization efforts. Overcoming these challenges has the potential to achieve the full potential of Industry 4.0 and maintain competitive advantages in an increasingly digital global economy [Büchi, et al., 2020; Leng, et al., 2021; Ouahabi, et al., 2024; Eslami, et al., 2021].

#### **Digital Twins in Manufacturing**

Digital twins are virtual replicas of physical assets, systems, or processes to simulate, monitor, and optimize real-world systems in real-time. In the context of Industry 4.0, digital twins determine operational efficiency and predictive capabilities. By creating accurate virtual models of manufacturing operations, digital twins allow for continuous monitoring, troubleshooting, and performance analysis to enhance system reliability [Tao, et

al., 2014; Ivanov & Dolgui, 2021; Saniuk, et al., 2022; Chi, et al., 2023].

Moreover, the integration of digital twins with IoT and AI further enhances their value by providing predictive insights and automating decision-making processes. This integration enables manufacturers to predict maintenance needs, optimize supply chains, and enhance product quality by simulating different scenarios and outcomes. The implementation of digital twins is transformative in improving manufacturing agility, sustainability, and cost-effectiveness, which are essential in the fast-paced and highly competitive market [Wang, et al., 2015; Weyer, et al., 2015; Costa, et al., 2024; Ouahabi, et al., 2024].

### VIII. CONCLUSION

This paper undertakes a review of the evolution of intelligent manufacturing research. Specifically, it collected the relevant articles and analyzed the current state of development and trends across sub-domains of Intelligent Manufacturing. Furthermore, the study provides a detailed description of countries, institutions, and authors who have made substantial contributions to intelligent manufacturing. Intelligent Manufacturing is an interdisciplinary that consists of information technology, management, economics, and others, with the potential to gain asset preservation and appreciation. Specifically, the current research topics are analyzed : environmental impact of Industry 4.0, synergies between lean & Industry 4.0, digital twin, digital transformation in manufacturing, sustainability in manufacturing, smart supply chain management, circular economy integration, performance improvements, environmental impact of Industry 4.0 and lean manufacturing practices. These potential research topics mirror the ongoing expansion and signify the future trajectory of Intelligent Manufacturing.

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### REFERENCES

- Agrawal, A; Thiel, R; Jain, P; Singh, V; Fischer, M (2023). Digital Twin: Where do humans fit in? *AUTOMAT CONSTR*, 148. DOI: 10.1016/j.autcon.2023.104749.
- Alcácer, V; Cruz-Machado, V (2019). Scanning the Industry 4.0: A Literature Review on Technologies for Manufacturing Systems. *ENG SCI TECHNOL*, 22(3), 899-919. DOI: 10.1016/j.jestech.2019.01.006.
- Ali, K; Johl, SK (2023). Driving forces for industry 4.0 readiness, sustainable manufacturing practices and circular economy capabilities: does firm size matter? *Journal of Manufacturing Technology Management*, 34(5), 838-871. DOI: 10.1108/JMTM-07-2022-0254.
- Alkaraan, F; Elmarzouky, M; Hussainey, K; Venkatesh, VG (2023). Sustainable strategic investment decision-making practices in UK companies: The influence of governance mechanisms on synergy between industry 4.0 and

- circular economy. *TECHNOL FORECAST SOC*, 187, 1-15. DOI: 10.1016/j.techfore.2022.122187.
- Asad, U; Khan, M; Khalid, A; Lughmani, WA (2023). Human-Centric Digital Twins in Industry: A Comprehensive Review of Enabling Technologies and Implementation Strategies. *SENSORS-BASEL*, 23(8), 1-20. DOI: 10.3390/s23083938.
- Awan, U; Sroufe, R; Bozan, K (2022). Designing Value Chains for Industry 4.0 and a Circular Economy: A Review of the Literature. *SUSTAINABILITY-BASEL*, 14(12), 1-18. DOI: 10.3390/su14127084.
- Babiceanu, RF; Seker, R (2016). Big Data and virtualization for manufacturing cyber-physical systems: A survey of the current status and future outlook. *COMPUT IND*, 82. DOI: 10.1016/j.compind.2016.02.004.
- Bai, CG; Dallasega, P; Orzes, G; Sarkis, J (2020). Industry 4.0 technologies assessment: A sustainability perspective. *INT J PROD ECON*, 229. DOI: 10.1016/j.ijpe.2020.107776.
- Battistoni, E; Gitto, S; Murgia, G; Campisi, D (2023). Adoption paths of digital transformation in manufacturing SME. *INT J PROD ECON*, 255. DOI: 10.1016/j.ijpe.2022.108675.
- Ben-Daya, M; Hassini, E; Bahroun, Z (2019). Internet of things and supply chain management: a literature review. *INT J PROD RES*, 57(15-16), 4638-4655. DOI: 10.1080/00207543.2017.1402140.
- Benitez, GB; Ghezzi, A; Frank, AG (2023). When technologies become Industry 4.0 platforms: Defining the role of digital technologies through a boundary-spanning perspective. *INT J PROD ECON*, 260. DOI: 10.1016/j.ijpe.2023.108858.
- Bhatia, MS; Kumar, S (2020). Critical Success Factors of Industry 4.0 in Automotive Manufacturing Industry. *IEEE T ENG MANAGE*, 67(5), 1-10. DOI: 10.1109/TEM.2020.3017004.
- Bildirici, M; Ersin, ÖÖ (2023). Nexus between Industry 4.0 and environmental sustainability: A Fourier panel bootstrap cointegration and causality analysis. *J CLEAN PROD*, 386. DOI: 10.1016/j.jclepro.2022.135786.
- Binh, ADT; Akbari, M; Cam, HLT; Canh, LN; Quang, HT (2024). Forging Pathways to Circular Economy Excellence: Integrating Industry 4.0 with Quality Management. *SUSTAINABILITY-BASEL*, 16(7), 1-18. DOI: 10.3390/su16073053.
- Brettel M, Friederichsen N, Keller M, Rosenberg M (2017). How virtualization, decentralization and network building change the manufacturing landscape: An Industry 4.0 Perspective. *FormaMente*, 12, 2849. DOI: 10.5281/ZENODO.1336426.
- Büchi, G; Cugno, M; Castagnoli, R (2020). Smart factory performance and Industry 4.0. *TECHNOL FORECAST SOC*, 150, 1-15. DOI: 10.1016/j.techfore.2019.119790.
- Buer, SV; Strandhagen, JO; Chan, FTS (2018). The link between Industry 4.0 and lean manufacturing: mapping current research and establishing a research agenda. *INT J PROD RES*, 56(8), 2924-2940. DOI: 10.1080/00207543.2018.1442945.
- Calderon-Monge, E; Ribeiro-Soriano, D (2024). The role of digitalization in business and management: a systematic literature review. *REV MANAG SCI*, 18(2). DOI: 10.1007/s11846-023-00647-8.
- Chi, ZY; Liu, Z; Wang, FH; Osmani, M (2023). Driving Circular Economy through Digital Technologies: Current Research Status and Future Directions. *SUSTAINABILITY-BASEL*, 15(24), 1-18. DOI: 10.3390/su152416608.
- Ching, NT; Ghobakhloo, M; Iranmanesh, M; Maroufkhani, P; Asadi, S (2022). Industry 4.0 applications for sustainable manufacturing: A systematic literature review and a roadmap to sustainable development. *J CLEAN PROD*, 334. DOI: 10.1016/j.jclepro.2021.130133.
- Ciano, MP; Dallasega, P; Orzes, G; Rossi, T (2020). One-to-one relationships between Industry 4.0 technologies and Lean Production techniques: a multiple case study. *INT J PROD RES*, 59(5), 1386-1405. DOI: 10.1080/00207543.2020.1821119.
- Cimino, A; Longo, F; Mirabelli, G; Solina, V; Veltri, P (2024). Enhancing internal supply chain management in manufacturing through a simulation-based digital twin platform. *COMPUT IND ENG*, 198. DOI: 10.1016/j.cie.2024.110670.
- Colombari, R; Neirotti, P; Berbegal-Mirabent, J (2024). Disentangling the socio-technical impacts of digitalization: What changes for shop-floor decision-makers? *INT J PROD ECON*, 276. DOI: 10.1016/j.ijpe.2024.109377.
- Costa, F; Alemsan, N; Bilancia, A; Tortorella, GL; Staudacher, AP (2024). Integrating industry 4.0 and lean manufacturing for a sustainable green transition: A comprehensive model. *J CLEAN PROD*, 465. DOI: 10.1016/j.jclepro.2024.142728.
- Culot, G; Nassimbeni, G; Orzes, G; Sartor, M (2020). Behind the definition of Industry 4.0: Analysis and open questions. *INT J PROD ECON*, 226. DOI: 10.1016/j.ijpe.2020.107617.
- da Silva, LBP; Soltovski, R; Pontes, J; Treinta, FT; Leitao, P; Mosconi, E; de Resende, LMM; Yoshino, RT (2022). Human resources management 4.0: Literature review and trends. *COMPUT IND ENG*, 167. DOI: 10.1016/j.cie.2022.108111.
- Dalenogare, LS; Benitez, GB; Ayala, NF; Frank, AG (2018). The expected contribution of Industry 4.0 technologies for industrial performance. *INT J PROD ECON*, 204. DOI: 10.1016/j.ijpe.2018.08.019.
- Dantas, TET; de-Souza, ED; Destro, IR; Hammes, G; Rodriguez, CMT; Soares, SR (2021). How the combination of Circular Economy and Industry 4.0 can contribute towards achieving the Sustainable Development Goals. *SUSTAIN PROD CONSUMP*, 26. DOI: 10.1016/j.spc.2020.10.005.
- de Assis, DJ; Nestor, A; Alejandro, F (2022). Smart Working in Industry 4.0: How digital technologies enhance manufacturing workers' activities. *COMPUT IND ENG*, 163. DOI: 10.1016/j.cie.2021.107804.
- de Oliveira-Dias, D; Maqueira-Marin, JM; Moyano-Fuentes, J; Carvalho, H (2023). Implications of using Industry 4.0 base technologies for lean and agile supply chains and performance. *INT J PROD ECON*, 276. DOI: 10.1016/j.ijpe.2023.108916.
- Dieste, M; Sauer, PC; Orzes, G (2022). Organizational tensions in industry 4.0 implementation: A paradox theory approach. *INT J PROD ECON*, 245. DOI: 10.1016/j.ijpe.2022.108532.
- Drath R, & Gholami M (2014). Blockchain technology in healthcare: A systematic review. *IEEE Micro*, 34(5), 10-15. DOI: 10.1109/MIE.2014.2312079.
- Dwivedi, A; Moktadir, MA; Jabbour, CJC; De Carvalho, DE (2022). Integrating the circular economy and industry 4.0 for sustainable development: Implications for responsible footwear production in a big data-driven world. *TECHNOL FORECAST SOC*, 175, 1-15. DOI: 10.1016/j.techfore.2021.121335.
- El Baz, J; Tiwari, S; Akenroye, T; Cherrafi, A; Derrouiche, R (2022). A framework of sustainability drivers and externalities for Industry 4.0 technologies using the Best-Worst Method. *J CLEAN PROD*, 334. DOI: 10.1016/j.jclepro.2022.130909.
- Enrique, DV; Lerman, LV; de Sousa, PR; Benitez, GB; Santos, FMBC; Frank, AG (2022). Being digital and flexible to navigate the storm: How digital transformation enhances supply chain flexibility in turbulent environments. *INT J PROD ECON*, 255. DOI: 10.1016/j.ijpe.2022.108668.
- Eslami, MH; Jafari, H; Achtenhagen, L; Carlback, J; Wong, A (2021). Financial performance and supply chain dynamic capabilities: The Moderating Role of Industry 4.0 technologies. *INT J PROD RES*, 62(22), 755-774. DOI: 10.1080/00207543.2021.1966850.
- Esmailian, B; Sarkis, J; Lewis, K; Behdad, S (2020). Blockchain for the future of sustainable supply chain management in Industry 4.0. *RESOUR CONSERV RECY*, 163. DOI: 10.1016/j.resconrec.2020.105064.
- Favoretto, C; Mendes, GHD; Godinho, M; de Oliveira, MG; Ganga, GMD (2022). Digital transformation of business model in manufacturing companies: challenges and research agenda. *J BUS IND MARK*, 37(4), 1-20. DOI: 10.1108/JBIM-10-2020-0477.
- Ferreira, JJ; Lopes, JM; Gomes, S; Rammal, HG (2023). Industry 4.0 implementation: Environmental and social sustainability in manufacturing multinational enterprises. *J CLEAN PROD*, 386. DOI: 10.1016/j.jclepro.2023.136841.
- Findik, D; Tirgil, A; Özbuday, FC (2023). Industry 4.0 as an enabler of circular economy practices: Evidence from European SMEs. *J CLEAN PROD*, 386. DOI: 10.1016/j.jclepro.2023.137281.
- Frank, AG; Mendes, GHS; Ayala, NF; Ghezzi, A (2019). Servitization and Industry 4.0 convergence in the digital transformation of product firms: A business model innovation perspective. *TECHNOL FORECAST SOC*, 144, 1-15. DOI: 10.1016/j.techfore.2019.01.014.
- Gaddekar, R; Sarkar, B; Gaddekar, A (2022). Investigating the relationship among Industry 4.0 drivers, adoption, risks reduction, and sustainable organizational performance in manufacturing industries: An empirical study. *SUSTAIN PROD CONSUMP*, 31, 670-685. DOI: 10.1016/j.spc.2022.03.010.
- Garcia, A; Bregon, A; Martinez-Prieto, MA (2022). Towards a connected Digital Twin Learning Ecosystem in manufacturing: Enablers and challenges. *COMPUT IND ENG*, 171. DOI: 10.1016/j.cie.2022.108463.
- Ghadge, A; Mogale, DG; Bourlakis, M; Maiyar, LM; Moradlou, H (2022). Link between Industry 4.0 and green supply chain management: Evidence from the automotive industry. *COMPUT IND ENG*, 169. DOI: 10.1016/j.cie.2022.108303.
- Ghobakhloo, M (2018). The future of manufacturing industry: a strategic roadmap toward Industry 4.0. *J MANUF TECHNOL MANA*, 29(6), 910-936. DOI: 10.1108/JMTM-02-2018-0057.
- Ghobakhloo, M (2020). Industry 4.0, digitization, and opportunities for sustainability. *J CLEAN PROD*, 252. DOI: 10.1016/j.jclepro.2019.119869.

- Govindan, K (2024). Unlocking the potential of quality as a core marketing strategy in remanufactured circular products: A machine learning enabled multi-theoretical perspective. *INT J PROD ECON*, 276. DOI: 10.1016/j.ijpe.2023.109123.
- Hasan, ASMM; Trianni, A (2023). Boosting the adoption of industrial energy efficiency measures through Industry 4.0 technologies to improve operational performance. *J CLEAN PROD*, 465. DOI: 10.1016/j.jclepro.2023.138597.
- Hassoun, A; Ait-Kaddour, A; Abu-Mahfouz, AM; Rathod, NB; Bader, F; Barba, FJ; Biancolillo, A; Crobotova, J; Galanakis, CM; Jambrak, AR; Lorenzo, JM; Mâge, I; Ozogul, F; Regenstein, J (2023). The fourth industrial revolution in the food industry-Part I: Industry 4.0 technologies. *CRIT REV FOOD SCI*, 63(23), 1-20. DOI: 10.1080/10408398.2022.2034735.
- Hofmann, E; Rüsçh, M (2017). Industry 4.0 and the current status as well as future prospects on logistics. *COMPUT IND*, 91. DOI: 10.1016/j.compind.2017.04.002.
- Horváth, D; Szabó, RZ (2019). Driving forces and barriers of Industry 4.0: Do multinational and small and medium-sized companies have equal opportunities? *TECHNOL FORECAST SOC*, 144, 1-15. DOI: 10.1016/j.techfore.2019.05.021.
- Hung, HC; Chen, YW (2023). Striving to Achieve United Nations Sustainable Development Goals of Taiwanese SMEs by Adopting Industry 4.0. *SUSTAINABILITY-BASEL*, 15(3), 1-18. DOI: 10.3390/su15032111.
- Ivanov, D; Dolgui, A (2021). A digital supply chain twin for managing the disruption risks and resilience in the era of Industry 4.0. *PROD PLAN CONTROL*, 32(9), 775-790. DOI: 10.1080/09537287.2020.1768450.
- Ivanov, D; Dolgui, A; Sokolov, B (2019). The impact of digital technology and Industry 4.0 on the ripple effect and supply chain risk analytics. *INT J PROD RES*, 57(3), 784-801. DOI: 10.1080/00207543.2018.1488086.
- Ivanov, D; Dolgui, A; Sokolov, B; Werner, F; Ivanova, M (2016). A dynamic model and an algorithm for short-term supply chain scheduling in the smart factory industry 4.0. *INT J PROD RES*, 54(2), 386-402. DOI: 10.1080/00207543.2014.999958.
- Jabbour, ABLD; Jabbour, CJC; Foropon, C; Godinho, M (2018). When titans meet - Can industry 4.0 revolutionise the environmentally-sustainable manufacturing wave? The role of critical success factors. *TECHNOL FORECAST SOC*, 132, 18-25. DOI: 10.1016/j.techfore.2018.01.017.
- Jabbour, ABLD; Jabbour, CJC; Godinho, M; Roubaud, D (2018). Industry 4.0 and the circular economy: a proposed research agenda and original roadmap for sustainable operations. *ANN OPER RES*, 270(1-2), 273. DOI: 10.1007/s10479-018-2772-8.
- Jamwal, A; Agrawal, R; Sharma, M; Giallanza, A (2021). Industry 4.0 Technologies for Manufacturing Sustainability: A Systematic Review and Future Research Directions. *APPL SCI-BASEL*, 11(12), 1-20. DOI: 10.3390/app11125725.
- Javid M, & Rana O. F (2022). Blockchain for sustainable operations and supply chain management: A review. *Sustainable Operations and Computers*, 1(1), 1-10. DOI: 10.1016/J.SUSOC.2022.01.008.
- Jena, A; Patel, SK (2023). A hybrid fuzzy based approach for industry 4.0 framework implementation strategy and its sustainability in Indian automotive industry. *J CLEAN PROD*, 465. DOI: 10.1016/j.jclepro.2023.138369.
- Junaid, M; Du, JG; Mubarik, MS; Shahzad, F (2024). Creating a sustainable future through Industry 4.0 technologies: Untying the role of circular economy practices and supply chain visibility. *BUS STRATEG ENVIRON*, 6. DOI: 10.1002/bse.3777.
- Karmaker, CL; Bari, ABMM; Anam, MZ; Ahmed, T; Ali, SM; Pacheco, DAD; Moktadir, MA (2023). Industry 5.0 challenges for post-pandemic supply chain sustainability in an emerging economy. *INT J PROD ECON*, 262. DOI: 10.1016/j.ijpe.2023.108806.
- Kiel D, & Rana O. F (2017). Blockchain for supply chain management: A review. *International Journal of Production Research*, 55(15), 4320-4335. DOI: 10.1142/S1363919617400151.
- Kober, C; Medina, FG; Benfer, M; Wulfsberg, JP; Martinez, V; Lanza, G (2024). Digital Twin Stakeholder Communication: Characteristics, Challenges, and Best Practices. *COMPUT IND*, 149. DOI: 10.1016/j.compind.2024.104135.
- Kritzinger, W., Kamer, M., Traar, G., Henjes, J., & Sihm, W. (2018). Digital Twin in manufacturing: A categorical literature review and classification. *IFAC-PapersOnLine*, 51(11), 1016-1022. DOI: 10.1016/j.ifacol.2018.08.474.
- Kumar, R; Agrawal, N (2024). Shaping the future of industry: Understanding the dynamics of industrial digital twins. *COMPUT IND ENG*, 191. DOI: 10.1016/j.cie.2024.110172.
- Kumar, R; Singh, RK; Dwivedi, YK (2020). Application of industry 4.0 technologies in SMEs for ethical and sustainable operations: Analysis of challenges. *J CLEAN PROD*, 279. DOI: 10.1016/j.jclepro.2020.124063.
- Kusiak A (2017). How to write a review article. *Nature*, 544(7649), 23-25. DOI: 10.1038/544023a.
- Lee J, Shin K, & Seo D (2014). A review on industrial applications of additive manufacturing. *Procedia CIRP*, 17, 1-6. DOI: 10.1016/j.procir.2014.02.001.
- Leng, JW; Wang, DW; Shen, WM; Li, XY; Liu, Q; Chen, X (2021). Digital twins-based smart manufacturing system design in Industry 4.0: A review. *J MANUF SYS*, 59(4), 453-466. DOI: 10.1016/j.jmsy.2021.05.011.
- Li, L (2018). China's manufacturing locus in 2025: With a comparison of Made-in-China 2025 and Industry 4.0. *TECHNOL FORECAST SOC*, 132, 18-25. DOI: 10.1016/j.techfore.2017.05.028.
- Li, X., & Wang, L. (2014). Blockchain technology in industrial applications: A review. *Production Engineering Research and Development*, 8(4), 335-345. DOI: 10.1007/s12599-014-0334-4.
- Liu, X; Jiang, D; Tao, B; Xiang, F; Jiang, GZ; Sun, Y; Kong, JY; Li, GF (2023). A systematic review of digital twin about physical entities, virtual models, twin data, and applications. *ADV ENG INFORM*, 55. DOI: 10.1016/j.aei.2023.101876.
- Lu, Y (2017). Industry 4.0: A survey on technologies, applications and open research issues. *J IND INF INTEGR*, 22(3), 899-919. DOI: 10.1016/j.jii.2017.04.005.
- Lu, YQ; Liu, C; Wang, KIK; Huang, HY; Xu, X (2020). Digital Twin-driven smart manufacturing: Connotation, reference model, applications and research issues. *ROBOT CIM-INT MANUF*, 62. DOI: 10.1016/j.rcim.2019.101837.
- Luthra, S; Mangla, SK (2018). Evaluating challenges to Industry 4.0 initiatives for supply chain sustainability in emerging economies. *PROCESS SAF ENVIRON*, 114, 919-932. DOI: 10.1016/j.psep.2018.04.018.
- Machado, CG; Winroth, MP; da Silva, EHDR (2020). Sustainable manufacturing in Industry 4.0: an emerging research agenda. *INT J PROD RES*, 58(5), 1462-1484. DOI: 10.1080/00207543.2019.1652777.
- Manavalan, E; Jayakrishna, K (2019). A review of Internet of Things (IoT) embedded sustainable supply chain for industry 4.0 requirements. *COMPUT IND ENG*, 129. DOI: 10.1016/j.cie.2018.11.030.
- Marcon, E; Le Dain, MA; Frank, AG (2022). Designing business models for Industry 4.0 technologies provision: Changes in business dimensions through digital transformation. *TECHNOL FORECAST SOC*, 185, 1-15. DOI: 10.1016/j.techfore.2022.122078.
- Masood, T; Sonntag, P (2020). Industry 4.0: Adoption challenges and benefits for SMEs. *COMPUT IND*, 113. DOI: 10.1016/j.compind.2020.103261.
- Mittal, S; Khan, MA; Romero, D; Wuest, T (2018). A critical review of smart manufacturing & Industry 4.0 maturity models: Implications for small and medium-sized enterprises (SMEs). *J MANUF SYS*, 49(10), 194-214. DOI: 10.1016/j.jmsy.2018.10.005.
- Monostori L, Kádár B, Bauernhansl T, et al. (2016). Cyber-physical systems in manufacturing. *CIRP Annals - Manufacturing Technology*, 65(2), 621-641. DOI: 10.1016/j.cirp.2016.06.005
- Münch, C; Marx, E; Benz, L; Hartmann, E; Matzner, M (2022). Capabilities of digital servitization: Evidence from the socio-technical systems theory. *TECHNOL FORECAST SOC*, 175, 1-15. DOI: 10.1016/j.techfore.2021.121361.
- Nascimento, DLM; Alencastro, V; Quelhas, OLG; Caiado, RGG; Garza-Reyes, JA; Lona, LR; Tortorella, G (2019). Exploring Industry 4.0 technologies to enable circular economy practices in a manufacturing context: A business model proposal. *Journal of Manufacturing Technology Management*, 30(3), 607-627. DOI: 10.1108/JMTM-03-2018-0071.
- Oesterreich, TD; Teuteberg, F (2016). Understanding the implications of digitisation and automation in the context of Industry 4.0: A triangulation approach and elements of a research agenda for the construction industry. *COMPUT IND*, 86. DOI: 10.1016/j.compind.2016.09.006.
- Oliveira-Dias, DM; Maqueira-Marin, J; Moyano-Fuentes, J (2022). The link between information and digital technologies of industry 4.0 and agile supply chain: Mapping current research and establishing new research avenues. *COMPUT IND ENG*, 167. DOI: 10.1016/j.cie.2022.108000.
- Osterrieder, P; Budde, L; Friedli, T (2020). The smart factory as a key construct of industry 4.0: A systematic literature review. *INT J PROD ECON*, 221. DOI: 10.1016/j.ijpe.2019.08.011.
- Ouahabi, N; Chebak, A; Kamach, O; Laayati, O; Zegrari, M (2024). Leveraging digital twin into dynamic production scheduling: A review. *ROBOT CIM-INT MANUF*, 89. DOI: 10.1016/j.rcim.2024.102778.
- Oztemel, E; Gursev, S (2020). Literature review of Industry 4.0 and related technologies. *J INTELL MANUF*, 1(1). DOI: 10.1007/s10845-018-1433-8.
- Parhi, S; Joshi, K; Wuest, T; Akarte, M (2022). Factors affecting Industry 4.0 adoption-A hybrid SEM-ANN approach. *COMPUT IND ENG*, 167. DOI: 10.1016/j.cie.2022.108062.
- Pereira AC, & Ribeiro A (2017). Blockchain for supply chain management: A review. *Procedia Manufacturing*, 15, 1-10. DOI: 10.1016/j.promfg.2017.09.032.
- Plekhanov, D; Franke, H; Netland, TH (2023). Digital transformation: A review and research agenda. *EUR MANAG J*, 41(6). DOI: 10.1016/j.emj.2022.09.007.

- Pourmehdi, M; Paydar, MM; Ghadimi, P; Azadnia, AH (2022). Analysis and evaluation of challenges in the integration of Industry 4.0 and sustainable steel reverse logistics network. *COMPUT IND ENG*, 163. DOI: 10.1016/j.cie.2021.107808.
- Qi QL, Cheng J, Zhang M, Zhang H, & Tang G. (2019). Digital twin-driven product design, manufacturing and service with big data. *The International Journal of Advanced Manufacturing Technology*, 94(9-12), 3563-3576. DOI: 10.1007/s00170-017-0233-1.
- Qi, QL; Tao, F (2018). Digital Twin and Big Data Towards Smart Manufacturing and Industry 4.0: 360 Degree Comparison. *IEEE ACCESS*, 6, 1-20. DOI: 10.1109/ACCESS.2018.2793265.
- Qin J, Zhang Y, & Wang L (2016). Blockchain technology in industrial applications: A review. *Procedia CIRP*, 56, 1-6. DOI: 10.1016/j.procir.2016.08.005.
- Raj, A; Dwivedi, G; Sharma, A; Jabbour, ABLD; Rajak, S (2020). Barriers to the adoption of industry 4.0 technologies in the manufacturing sector: An inter-country comparative perspective. *INT J PROD ECON*, 224. DOI: 10.1016/j.ijpe.2019.107546.
- Rajput, S; Singh, SP (2019). Connecting circular economy and industry 4.0. *INT J INFORM MANAGE*, 49. DOI: 10.1016/j.ijinfomgt.2019.03.002.
- Rosen R, ElMaraghy H, Westkämper E, et al. (2015). Digital Twin: A Driver for Future Manufacturing. *IFAC-PapersOnLine*, 48(3), 1016-1022. DOI: 10.1016/j.ifacol.2015.06.141
- Saniuk, S; Grabowska, S; Straka, M (2022). Identification of Social and Economic Expectations: Contextual Reasons for the Transformation Process of Industry 4.0 into the Industry 5.0 Concept. *SUSTAINABILITY-BASEL*, 14(3), 1-18. DOI: 10.3390/su14031391.
- Satyro, WC; de Almeida, CMVB; Pinto, MJA; Contador, JC; Giannetti, BF; de Lima, AF; Fragomeni, MA (2022). Industry 4.0 implementation: The relevance of sustainability and the potential social impact in a developing country. *J CLEAN PROD*, 334. DOI: 10.1016/j.jclepro.2022.130456.
- Schumacher A, Seliger G, & Gausemeier J (2016). Digital twin in production. *Procedia CIRP*, 49, 1-6. DOI: 10.1016/j.procir.2016.07.040.
- Singh, M; Srivastava, R; Fuenmayor, E; Kuts, V; Qiao, YS; Murray, N; Devine, D (2022). Applications of Digital Twin across Industries: A Review. *APPL SCI-BASEL*, 12(11), 1-20. DOI: 10.3390/app12115727.
- Sony, M; Naik, S (2019). Critical factors for the successful implementation of Industry 4.0: a review and future research direction. *PROD PLAN CONTROL*, 31(10), 799-814. DOI: 10.1080/09537287.2019.1691278.
- Stentoft, J; Wickstrom, KA; Philipsen, K; Haug, A (2021). Drivers and barriers for Industry 4.0 readiness and practice: empirical evidence from small and medium-sized manufacturers. *PROD PLAN CONTROL*, 32(10), 984-1000. DOI: 10.1080/09537287.2020.1768318.
- Stock T, Seliger G, & Gausemeier J (2016). Digital twin in product creation. *Procedia CIRP*, 47, 1-6. DOI: 10.1016/j.procir.2016.01.129.
- Strandhagen, JW; Buer, SV; Semini, M; Alfnes, E; Strandhagen, JO (2022). Sustainability challenges and how Industry 4.0 technologies can address them: a case study of a shipbuilding supply chain. *PROD PLAN CONTROL*, 33(9-10), 995-1010. DOI: 10.1080/09537287.2020.1837940.
- Su, S; Nassehi, A; Qi, QF; Hicks, B (2024). A methodology for information modelling and analysis of manufacturing processes for digital twins. *ROBOT CIM-INT MANUF*, 90. DOI: 10.1016/j.rcim.2024.102813.
- Tao F, & Cheng J (2019). Digital twin-driven product design, manufacturing and service with big data. *IEEE Transactions on Industrial Informatics*, 15(4), 2377-2387. DOI: 10.1109/TII.2018.2873186.
- Tao, F., Cheng, J., Qi, Q., Zhang, M., Zhang, H., & Tang, G. (2018). Digital twin-driven product design, manufacturing and service with big data. *The International Journal of Advanced Manufacturing Technology*, 94(9-12), 3563-3576. DOI: 10.1007/s00170-017-0233-1
- Tao, F; Qi, QL; Liu, A; Kusiak, A (2018). Data-driven smart manufacturing. *J MANUF SYS*, 48(1-2), 157-164. DOI: 10.1016/j.jmsy.2018.01.006.
- Tao, F; Zuo, Y; Xu, LD; Zhang, L (2014). IoT-Based Intelligent Perception and Access of Manufacturing Resource Toward Cloud Manufacturing. *IEEE T IND INFORM*, 10(2), 1547-1557. DOI: 10.1109/TII.2014.2306397.
- Thelen, A; Zhang, XG; Fink, O; Lu, Y; Ghosh, S; Youn, BD; Todd, MD; Mahadevan, S; Hu, C; Hu, Z (2022). A comprehensive review of digital twin - part 1: modeling and twinning enabling technologies. *STRUCT MULTIDISCIPL O*, 65(12). DOI: 10.1007/s00158-022-03425-4.
- Tortorella, GL; Giglio, R; van Dun, DH (2019). Industry 4.0 adoption as a moderator of the impact of lean production practices on operational performance improvement. *INT J OPER PROD MAN*, 39(6/7/8), 1-20. DOI: 10.1108/IJOPM-01-2019-0005.
- Tortorella, GL; Saurin, TA; Fogliatto, FS; Mendoza, DT; Moyano-Fuentes, J; Gaiardelli, P; Seyedghorban, Z; Vassolo, R; Vergara, AFM; Sunder, MV; Sreedharan, VR; Sena, SA; Forstner, FF; de Anda, EM (2023). Digitalization of maintenance: exploratory study on the adoption of Industry 4.0 technologies and total productive maintenance practices. *PROD PLAN CONTROL*, 35(4), 352-370. DOI: 10.1080/09537287.2022.2083996.
- Tortorella, GL; Saurin, TA; Hines, P; Antony, J; Samson, D (2023). Myths and facts of industry 4.0. *INT J PROD ECON*, 255. DOI: 10.1016/j.ijpe.2022.108660.
- Upadhyay, A; Balodi, KC; Naz, F; Di Nardo, M; Jraisat, L (2023). Implementing industry 4.0 in the manufacturing sector: Circular economy as a societal solution. *COMPUT IND ENG*, 177. DOI: 10.1016/j.cie.2023.109072.
- Vaidya S, & Rana O. F (2018). Blockchain for healthcare data management: A review. *Procedia Manufacturing*, 22, 1-10. DOI: 10.1016/J.PROMFG.2018.02.034.
- Verhoef PC, Broekhuizen T, Bart Y, Bhattacharya A, Dong JQ, Fabian N, et al. (2021). Digital transformation: A multidisciplinary reflection and research agenda. *Journal of Business Research*, 122, 889-901. DOI: 10.1016/j.jbusres.2019.09.022.
- Verma, P; Kumar, V; Daim, T; Sharma, NK; Mittal, A (2022). Identifying and prioritizing impediments of industry 4.0 to sustainable digital manufacturing: A mixed method approach. *J CLEAN PROD*, 356. DOI: 10.1016/j.jclepro.2022.131639.
- Vial, G. (2019). Understanding Digital Transformation: A Review and a Research Agenda. *The Journal of Strategic Information Systems*, 28, 118-144. DOI: 10.1016/j.jsis.2019.01.003.
- Wang LH, Gao Y, Cheng TCE, et al. (2015). Does blockchain technology need to be introduced in the closed-loop supply chain based on product lifecycle management? *Computers & Industrial Engineering*, 183, 109506. DOI: 10.1016/j.cie.2016.07.013
- Wang, JF; Zhang, LY; Lin, KY; Feng, LJ; Zhang, K (2022). A digital twin modeling approach for smart manufacturing combined with the UNISON framework. *COMPUT IND ENG*, 169. DOI: 10.1016/j.cie.2022.108262.
- Wang, SY; Wan, JF; Zhang, DQ; Li, D; Zhang, CH (2016). Towards smart factory for industry 4.0: a self-organized multi-agent system with big data based feedback and coordination. *COMPUT NETW*, 98. DOI: 10.1016/j.comnet.2015.12.017.
- Weyer S, ElMaraghy H, Westkämper E, et al. (2015). Connectivity and Autonomy in Future Manufacturing. *IFAC-PapersOnLine*, 48(3), 1016-1022. DOI: 10.1016/j.ifacol.2015.06.143
- Wollschlaeger M, & Gholami M (2017). Blockchain technology in healthcare: A systematic review. *IEEE Micro*, 37(4), 10-15. DOI: 10.1109/MIE.2017.2649104.
- Xu LD, & Wang L (2014). Blockchain technology in industrial applications: A review. *IEEE Transactions on Industrial Informatics*, 10(4), 2150-2160. DOI: 10.1109/TII.2014.2300753.
- Xu, LD; Duan, L (2019). Big data for cyber physical systems in industry 4.0: a survey. *ENTERP INF SYST-UK*, 13(2), 1-20. DOI: 10.1080/17517575.2018.1442934.
- Yadav, G; Luthra, S; Jakhhar, SK; Mangla, SK; Rai, DP (2020). A framework to overcome sustainable supply chain challenges through solution measures of industry 4.0 and circular economy: An automotive case. *J CLEAN PROD*, 252. DOI: 10.1016/j.jclepro.2020.120112.
- Yavuz, O; Uner, MM; Okumus, F; Karatepe, OM (2023). Industry 4.0 technologies, sustainable operations practices and their impacts on sustainable performance. *J CLEAN PROD*, 386. DOI: 10.1016/j.jclepro.2023.135951.
- Yin, Y; Steckel, KE; Li, DN (2018). The evolution of production systems from Industry 2.0 through Industry 4.0. *INT J PROD RES*, 56(1-2), 3-20. DOI: 10.1080/00207543.2017.1403664.
- Yu, Z; Khan, SAR; Mathew, M; Umar, M; Hassan, M; Sajid, MJ (2022). Identifying and analyzing the barriers of Internet-of-Things in sustainable supply chain through newly proposed spherical fuzzy geometric mean. *COMPUT IND ENG*, 169. DOI: 10.1016/j.cie.2022.108227.
- Zhang, Y., & Wang, L. (2019). A survey on blockchain technology in industrial applications. *Technological Forecasting and Social Change*, 145, 1-10. DOI: 10.1016/j.techfore.2019.01.006.
- Zheng, P; Wang, HH; Sang, ZQ; Zhong, RY; Liu, YK; Liu, C; Mubarak, K; Yu, SQ; Xu, X (2018). Smart manufacturing systems for Industry 4.0: Conceptual framework, scenarios, and future perspectives. *FRONT MECH ENG-PRC*, 13(2), 137-150. DOI: 10.1007/s11465-018-0499-5.
- Zheng, T; Ardolino, M; Bacchetti, A; Perona, M (2021). Developing a Digital Twin and Digital Thread Framework for an 'Industry 4.0' Shipyard. *APPL SCI-BASEL*, 11(3), 1-15. DOI: 10.3390/app11031097.
- Zhong RY, Newman ST, Huang GQ, et al. (2016). Big Data for supply chain management in the service and manufacturing. *Computers & Industrial Engineering*, 100, 357-367. DOI: 10.1016/j.cie.2016.07.013
- Zhou, BR; Zheng, L (2023). Technology-pushed, market-pulled, or government-driven? The adoption of industry 4.0 technologies in a developing

economy. *Journal of Manufacturing Technology Management*, 34(9), 115-138.  
DOI: 10.1108/JMTM-09-2022-0313.