"Comprehensive Bibliometric Analysis of Robotics in Manufacturing (2015-2024): Trends, Impact, and Innovation Hotspots from Industry 3.0 to Industry 5.0"

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Abstract: This article presents a comprehensive bibliographic analysis of 1,000 papers on robotics in manufacturing. They were published in the Web of Science database from year 2015 to 2024 using a systematic approach. The span of data collection had all experiences of various trends from Industry 3.0 to Industry 4.0/5.0. The research data was analyzed using R 4.3.2 and RStudio software. Authors, sources, articles, countries and institutions were ranked based on factors such as total citations, number of documents, average citations per document, total link strength, annual scientific performance, and relevance. Author's keyword analysis Indexed keywords and original content identify important research trends in robot creation. This analysis highlights key research issues and emerging hotspots within manufacturing robotics. Analyzed 1,000 robotics papers in manufacturing (2015-2024) to assess key research trends, scientific impact, and relevance. Identified leading authors, institutions, and countries, along with emerging trends from Industry 3.0 to Industry 5.0. Highlighted key research issues and innovation hotspots in manufacturing robotics through citation metrics and link strength analysis.

Keywords: Manufacturing robots; Bibliographic analysis Network analysis Citation analysis, clustering; research trends knowledge mapping

Introduction: The increasing use of robots in industrial production has changed the manufacturing landscape by improving efficiency, accuracy, and safety. Although robots are used to perform repetitive tasks, Automatically and reduce human labor in hazardous environments recent developments have extended their use to more complex dynamic settings, benefits, challenges, and focus on development trends. In today's social setting, consumers inadvertently transfer human-like standards onto robots[1]. This study aims to perform a comprehensive bibliographic analysis, of industrial trends and hotspot areas in manufacturing robotics using 1,000 papers published in the Web of Science database from 2015 to 2024, Previous studies have used bibliometric techniques to explore different areas of robotics. including soft robotics in nursing and construction. surgical robot and robotics but systematic reviews focusing on manufacturing robotics are lacking. This article addresses this gap by answering a key question on the research landscape: What are the key issues and trends in robot building? Which authors and institutions are leaders in this field? Using advanced bibliographic tools this work aims to map the knowledge base and highlight emerging research hotspots in robotics applied to manufacturing processes. While many firms are eager to implement these technologies to boost productivity[2]. Intelligent robotics in manufacturing is enabling programmable, sensory-interactive, computer-controlled robots that can operate independently or under human supervision.[3]. Manufacturing robots have transformed the industrial landscape by improving production efficiency, accuracy, and scalability across several industries. These modern machines are intended to automate repetitive processes, reduce human error, and increase overall production, making them vital in sectors such as automotive, electronics, and heavy machinery. Manufacturing robots have developed from their humble beginnings in Industry 3.0, when they were mostly utilized for simple, repetitive assembly-line jobs, to highly sophisticated systems capable of completing complicated, multi-step operations. Today, with the influence of Industry 4.0 and Industry 5.0, robots in manufacturing is rapidly linked with cutting-edge technologies such as artificial intelligence (AI), machine learning (ML), the Internet of Things (IoT), and big data analytics. These advancements allow robots to adapt to new settings and interact with human workers and do very precise tasks independently. Robots are increasingly critical in improving flexible manufacturing lines, allowing them to move between different goods with little downtime. Furthermore, the usage of collaborative robots, which are meant to operate alongside people, has improved manufacturing operations' safety and efficiency. The move to Industry 5.0 anticipates even more individualized manufacturing systems that blend human creativity and robotic accuracy, achieving a balance between mass production and customization. As a result, factory robots are creating the future of industrial automation while also boosting global competitiveness, sustainability, and innovation. With sufficient research done, the bibliometric technique may now be analyzed using its own methodology[4]. Bibliometric approaches have already been employed in the realm of robotics. An overview of the field was undertaken to determine the bibliometric analysis of soft robotics[5], surgery robotics[6], robotics in nursing[7], and robotics in construction[8]. Using similar approaches, we investigate robotics in manufacturing.

Objectives of the study: The purpose of this project is to undertake a detailed bibliographic analysis of 1,000 publications on manufacturing robots published in the Web of Science database between 2015 and 2024. It aims to identify major research trends, emerging hotspots, and development patterns in the area, with an emphasis on the transition from Industry 3.0 to Industry 5.0. The research will evaluate and rank authors, institutions, nations, and sources using a variety of measures, such as total citations, number of documents, average citations per document, overall link strength, and yearly scientific performance. Using modern bibliometric methods, the study will map the manufacturing robotics knowledge base, delving into crucial topics in robot design and application to dynamic and complex industrial environments. This study addresses a gap in systematic reviews relating to manufacturing robots, showcasing important figures and recent developments in the industry.

Purpose and Significance in the Context of Sustainable Manufacturing Robotics:

Purpose: The purpose of this study is to conduct a complete bibliographic analysis of 1,000 papers on factory robots from 2015 to 2024. This report highlights research trends, key authors, institutions, and developing hotspots in robots in manufacturing, with a focus on the transition from Industry 3.0 to Industry 5.0. The research intends to map the knowledge base, appraise important breakthroughs in robotics technology, and investigate their use in sustainable manufacturing processes.

Significance in Context of Sustainable Manufacturing Robotics**:**

I. Transition to Sustainable Practices: Advancements in robotics, such as additive manufacturing, soft robotics, and swarm robots, integrate AI, IoT, and big data to improve resource efficiency and reduce waste.
II. Innovative Industry Contributions: Robots contribute to Industry 4.0 and 5.0 advancements by allowing mass customization, collaborative workspaces, and human-robot collaboration resulting in improved workplace safety and sustainability.

III. Global Collaboration: International collaboration (26.5%) demonstrates a worldwide focus on sustainable robotics, including aerospace & swarm robots, which optimize resource consumption and enable recycling.

IV. Driving Innovation: Robotics for additive and soft manufacturing have the potential to change production processes and address sustainability gaps.

V. Enabling Sustainability: The study highlights robots' impact on energy efficiency, waste reduction, and environmental responsibility in manufacturing. It offers insights for researchers, legislators, and industry leaders to promote sustainable practices.

Gaps in Existing Studies: Existing research on factory robotics shows significant gaps. Comprehensive systematic studies are few, with most research concentrating on specialized fields such as collaborative robotics or additive manufacturing. The move from Industry 3.0 to Industry 5.0, which emphasizes human-robot collaboration and sustainability, is yet underexplored. Global collaborative patterns in robotics research are not thoroughly examined, and sustainability—critical for contemporary manufacturing—is inadequately addressed, notably robots' role in waste reduction and energy optimization. Furthermore, while advances such as soft and swarm robots are being researched, there has been little attempt to synthesize emergent ideas into a unified framework for sustainable production.

Necessity of Current Research: This study fills critical gaps in manufacturing robots by examining 1,000 publications (2015-2024) using powerful bibliometric methods. It offers a comprehensive overview of trends, significant contributors, and innovation hotspots, with an emphasis on sustainability under Industry 5.0 and a bridge between technical progress and environmental goals. It emphasizes developing fields such as soft robotics and swarm robotics by mapping key authors, institutions, and worldwide partnerships, demonstrating their potential to alter industries and improve sustainable, adaptable manufacturing systems.

Advancing the Field of Sustainable Manufacturing Robotics: This study improves sustainable manufacturing robots by mapping significant research trends, allowing stakeholders to discover areas for innovation and cooperation. It highlights how robotics may improve sustainability by implementing energy-efficient procedures, reducing waste, and creating circular production systems. Studying worldwide cooperation trends, it demonstrates how international collaborations generate innovation in sustainable robotics. The findings provide governments and industry leaders with direction on how to match robotic technology with sustainability goals, as well as a path for integrating these technologies while maintaining efficiency and environmental responsibility. The study also provides the framework for future research, notably on customized manufacturing and the socioeconomic implications of robots

Methodology:

I. Materials and Methods:

The methodology follows four main steps: (a) data extraction, (b) creation of a citation network, (c) identification of highly related elements, and (d) clustering analysis. R 4.3.2 and RStudio were used to perform bibliographic analysis. Bibliographic analysis of 1,000 documents related to robots in manufacturing. Data is extracted from the Web of Science database which covers quality papers. The dataset includes articles from the Science Citation Index Expanded, Social Science Citation Index, Arts and Humanities Citation Index, symposiums. and other academic publications. To collect relevant documents a search based on the keywords “robotics” and “manufacturing” was conducted and the initial search returned more than 600 articles, which were refined using citation network analysis. A dataset contains documents that have at least one citation to another article. This guarantees the relevance of the focus of the study on robots in manufacturing. Direct citation analysis is used to establish relationships between documents and to map knowledge structures. Direct citation networks outperform other connection approaches such as co-citation[9] and bibliographic coupling in accurately representing knowledge taxonomies and identifying research fronts[10],[11]. Important criteria have been extracted. Including the number of publications. All references Average citations per document and trends in co-authoring citation networks are used to identify groups of related documents. The results of the analysis are shown in Figure 1 and summarized in Table 1.

II. Transparency in Analysis:

Software and Version:

The bibliographic analysis in this study was carried out using R 4.3.2 and RStudio. These tools were used to perform a variety of data analytic tasks, including citation network analysis, bibliometric mapping, and clustering. These two software programs serve as the foundation for complex data extraction and analysis procedures. R 4.3.2 is the version of the R programming language (R version 4.3.1 (2023-06-16 curt) -- "Beagle Scouts". Copyright (C) 2023 The R Foundation for Statistical Computing. Platform: x86_64-w64-mingw32/x64 (64-bit) that is used for statistical computation and data visualization. RStudio is an integrated development environment (IDE) that supports the R programming language, making the analytical workflow more efficient and user-friendly. R is free software.

III. Key Libraries and Packages:

The bibliometric and citation network studies were carried out using multiple R programs. Some of the important ones are:

Bibliometrics: This is the primary software for doing bibliometric analyses. It has features for extracting and analyzing bibliometric data, doing citation network analysis, and creating bibliometric maps. This tool is particularly useful for working with huge datasets and undertaking comprehensive citation-based analysis. Key functions used: biblioshiny(), networkPlot(), authorKeywords(), citationNetwork().

Generic Findings and Lack of Interpretation:

The bibliographic study of robotics in manufacturing, which runs from 2015 to 2024, highlights major research clusters and trends that highlight notable breakthroughs in different robotic technologies. These clusters include robotics in additive manufacturing, soft robotics, mobile robots, smart manufacturing, robotic manipulators, aerospace manufacturing, and swarm robotics. However, while the study gives useful insights on scientific production and robotics trends, these findings require a more in-depth analysis within the framework of sustainable manufacturing.

Data Summary:

The dataset extends from 2015 to 2024 with 1,000 documents from 400 sources (Fig. 1a,b,c,d). Despite the negative annual growth rate of -19.12%, the dataset contains a wide variety of documents. With an average citation rate of 15.46 per document, a total of 3,925 authors contributed to the dataset. This includes 17 single-authored papers. Co-authoring is common. It has an average of 4.71 authors per document and 26.5% of collaborations involve international co-authoring. Table no. 1 Extracted data with the help of R 4.3.2 and Rstudio Using 1,000 papers on factory robots from 2015 to 2024, a bibliographic analysis sheds light on significant publishing patterns. This information was compiled from 400 sources and shows a notable yearly growth rate of -19.12%, which suggests a decrease in publishing frequency in the last few years. The documents have an average age of 2.87 years and an average of 15.46 citations per document. Total 1,307 "Keywords Plus" and 3,176 "Author's Keywords," the study also exhibits substantial reference usage, highlighting the research's diversity in themes. Only 17 of the 3,925 writers that contributed to these publications were single authors, indicating a high level of researcher cooperation. The average number of co-authors per paper was 4.71, and 26.5% of those partnerships were international, highlighting the fact that manufacturing robotics research is a worldwide field. There are several different kinds of documents in total: there are 617 articles, 92 proceedings papers, 254 editorial materials, and 1 review. There were also 11 early-access papers and a few additional formats, including book chapters and results, showing that there are many different types of formats in this discipline.

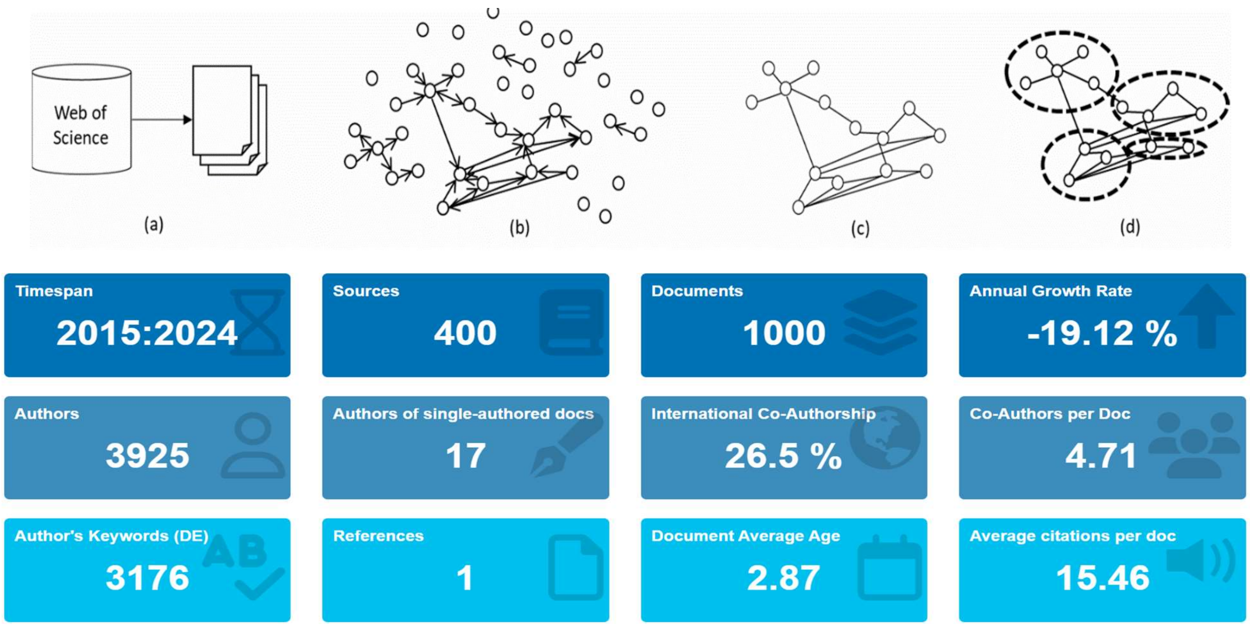

Fig1 (a,b,c,d) Main Information Plot

Table no. 1 Extracted data with the help of R 4.3.2 and Rstudio.

Description	**Results**
Timespan	2015:2024
Sources	400
Documents	1000

Annual Growth Rate %	-19.12
Document Average Age	2.87
Average Citations per Doc	15.46
References	1
Document Contents	
Keywords Plus (ID)	1307
Author's Keywords (DE)	3176
Authors	3925
Authors of Single-Authored Docs	17
Authors Collaboration	
Single-Authored Docs	17
Co-Authors per Doc	4.71
International Co-authorships %	26.5
Document Types	
Article	617
Article Book Chapter	3
Results	14
Article Early Access	11
Article Proceedings Paper	7
Editorial Material	1
Editorial Material Book Chapter	254
Proceedings Paper	92
Review	2

Results

I. Robotics and Manufacturing Research

Research into robotics in manufacturing has continued to grow since 2015, with a significant increase in publications since 2014. After 2014 we can see a bigger number of publications[12] in the field of manufacturing and in this field robotics becoming an important part of the new social technology [13]. Figure 2 shows the annual results of scientific research on robotics in manufacturing. It highlights important trends over time. It has been found that robotics research is part of a broader set of manufacturing technologies. There has been significant growth in participation from fields such as aerospace, intelligent manufacturing, and mobile robots. Table 2 summarizes the groups identified in robotics research. with additive manufacturing soft robotics and robot operators are the main focus of the study.

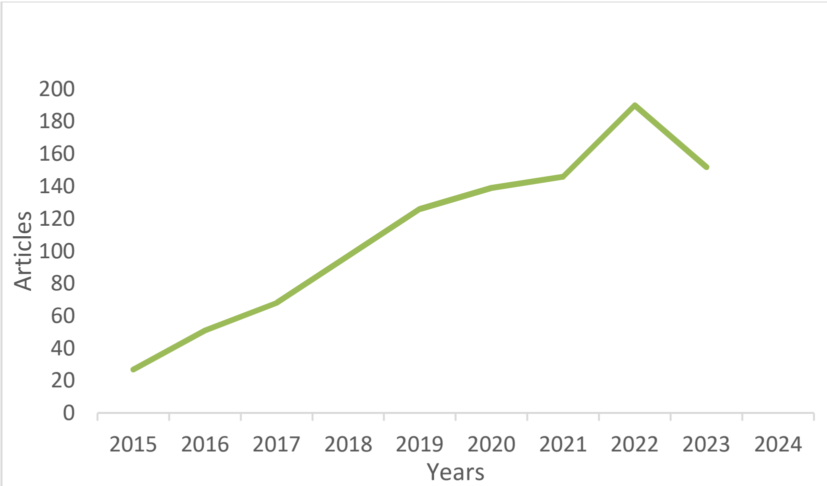

Figure 2 Annual Scientific Production

Table.2 The clusters of robotics in the manufacturing network.

#	Clusters	%
1	Robotics in additive manufacturing	7%
2	Soft robotics	6.4%
3	Robotics manipulators	5.3%
4	Robotics in smart manufacturing	2.5%
5	Mobile robotics	1.6%
6	Robotics in aerospace	0.7%
7	Swarm robotics	0.5%

II. Research Trends in Robotics in Manufacturing

Analysis of data identified seven main clusters within the testimonial network. The most prominent institutions and journals associated with each group are summarized in Table 3. The findings highlight the important contributions of Istituto Italiano Di Tecnologia (IIT) and Vrije Universiteit Brussel in the field of soft robotics. and additive manufacturing, respectively. Journals such as IEEE, CIRP, and IFAC Papers online have become the main publication sites in the field of robotics. Table 3: Bibliometric classification of robot messages in construction. The most common organizations, publications, and authors are highlighted.

Table. 3 Robotics in Manufacturing taxonomy based on bibliography. The most common nations, organizations, publications, and writers are displayed.

Table 3 Prominent institutions and journals associated with each group

#	Cluster Label	Institution	Journals/Conferences	Authors
1	Robotics In Additive manufacturing 2020, 2020 [14][15]	Vrije Universiteit Brussel, Istituto Italiano Di Tecnologia- IIT,	Soft Robotics, IFAC Papers online, Sensors, CIRP, IEEE	Roels E, Terryn S, Sadeghi A, Del Dottore E, Mondini A,
2	Soft Robotics 2017, 2021 [16][17]	Istituto Italiano Di Tecnologia – IIT, Swiss Federal Institutes Of Technology Domain, Swiss Federal Laboratories For Materials Science & Technology (EMPA),	Soft Robotics, IEEE, International Conference System Integrated Intelligence Frontiers In Robotics And AI	Sadeghi A, Mazzolai B, Georgopoulou A, Vanderborght B, Clemens F
3	Mobile Robotics 2016, 2022 [18][19]	University Of Kwazulu Natal, University Of Strathclyde, University Of Palermo,	IFAC Papersonline, Sensors, International Journal of Advanced Manufacturing Techmology, CIRP IEEE	Naidoo N, Bright G, Stopforth R, Yang Mm, Yu Lj, Wong Cb
4	Robotics In Smart Manufacturing 2021, 2019 [20][21]	RWTH Aachen University, University Of California Los Angeles,	Sensors, CIRP, IFAC Papersonline, IEEE,	Huang Zq, Shen Y, Li Jy, Garcia Mar, Rojas R
5	Robotics Manipulators 2018, 2023 [22][23]	University Of Malta, Politecnico Di Bari, University Of Texas System, University Of Texas Dallas	CIRP, International Journal Of Advanced Manufacturing Technology, Applied Sciences Basel, IEEE	Francalanza E, Fenech A, Cutajar P, Percoco G, Tadesse Y
6	Robotics In Aerospace Manufacturing 2018, 2021 [24][25]	CNRS-Institute For Engineering & Systems Sciences (INSIS), University Of Nottingham, University Of Greenwich	IFAC Papersonline, CIRP, Frontiers In Robotics And AI	Zhao R, Irving L, Sanderson D, Wilson A, Martin L
7	Swarm Robotics 2016, 2022 [26][27]	Arizona State University, University Of California Los Angeles, University Of Pavia,	IEEE, Computational Mechanics, IFAC Papersonline,	Wilson S, Gameros R, Sheely M, Auricchio, Ferdinando

Average publication year; article with most citations. SOFT ROBOTICS, IFAC PAPERSONLINE, SENSORS, Frontiers in Robotics and AI, IEEE: International Conference on Soft Robotics, Robotics and Automation Letters, International conference on Automation science and Engineering, IEEE Access, Proceeding of the IEEE, Journal of

Automation Science, CIRP: Conference on Intelligent Computation in Manufacturing, Conference on Digital Enterprise Technologies, Design Conference, Conference on Manufacturing System, Conference on Intelligent Computation in Manufacturing Engineering, Conference on manufacturing System.

At the institutional level, there is no supremacy. Table 3 shows that Istituto Italiano Di Tecnologia (IIT) appeared in clusters 1 and 2, whereas the University of California, Los Angeles (UCLA) appeared in clusters 4 and 5.
In terms of journals and conferences, IEEE occurs in six and IFAC Papers online and CIRP occur in five clusters, and Sensors, and Soft Robotics appear in three, and two, respectively. Table 3 displays the general distribution of the biggest publishing venues.

Table.4: The most popular publications and conferences of robotics in manufacturing.

Journal/Conference	**% of Articles**
IFAC Papers Online	3.6
CIRP	3.4
IEEE	9.9
Sensors	2.5
Soft Robotics	0.4

III. Contextualizing Findings:

Research clusters in robotics and manufacturing (Table 3) highlight significant findings and trends within each domain. The analysis covers seven primary clusters, examining their advancements and publication patterns over time. The study's findings have significant implications for sustainable manufacturing. As robotic systems progress, their role in promoting sustainability in the industrial sector will become increasingly important. Here's how the findings apply to specific difficulties and possibilities in sustainable manufacturing:

a) Robotics in additive manufacturing

Recent studies in robotics for additive manufacturing (AM) have explored the integration of robot technology to increase the efficiency and versatility of AM processes. One notable example is self-healing robots. It can recover from visible gross damage such as scratches, cuts, or broken bones. Previous research has used techniques such as "shaping through folding and self-healing," but recent advances highlight the functional benefits of using robots over traditional AM processes. Key improvements include. Assembled in multiple directions Compliant structure Unsupported production and additive manufacturing These developments highlight the increasing importance of robotics in expanding AM capabilities [14][28].

b) Soft Robotics

Soft robotics represents a transformative field within this field. It is characterized by robots that can grow and build their own structures automatically. This unique class of robots holds important promise for creating more human-friendly and adaptive robotic systems. Industrial applications often involve robust body systems, but soft robots aim to surpass traditional systems by making their movements more biologically inspired and flexible. This group emphasizes the potential of soft robots to revolutionize industrial automation and human-robot interaction [16][29].

c) Mobile Robot

Mobile robots meet the need for flexible material handling. large management and rapid reconfiguration in production environments. Mobile robots are important in reducing production bottlenecks and reducing downtime. This can lead to significant cost savings in industrial environments. Improving the efficiency of mobile robots by making material transport more agile and efficient material transport, mobile robotics enhances the overall responsiveness and efficiency of manufacturing processes [18][30].

d) Robotics in intelligent manufacturing

Robotics in smart manufacturing is a key factor in increasing flexibility and agility in manufacturing. The group focuses on integrating advanced robots with traditional manufacturing systems to promote collaboration between human workers and automation. The combination of robots and smart manufacturing technology supports high levels of production and quality control. Its collaborative production environment plays an important role in maximizing human and robot capabilities [20][31].

e) Robotic management

The use of robot operators in production allows for high efficiency, precision, and adaptability. Robotics have become an essential part of a wide range of industrial processes. This gives it the ability to complete complex tasks with minimal human intervention. This group emphasizes the direct impact of robotic systems on production. especially in improving operational flexibility. while maintaining high levels of accuracy and productivity [22][32].

f) Robotics in aircraft manufacturing

Robotics in aircraft manufacturing has revolutionized processes such as drilling and riveting aircraft components. The case studies in this group demonstrate the modular design of a robot system that integrates multiple subsystems for tasks such as tracking, inspection, and evaluation. These systems integrate collaborative robots with peripherals. Advancing manufacturing and remanufacturing within the aerospace domain [24][33].

g) Swarm of robots

Swarm robotics is an emerging field that models collective behavior and self-organization inspired by swarm intelligence. The group has successfully applied optimization algorithms in areas such as telecommunications, simulation, and manufacturing. Swarm Robotics represents a paradigm shift. It offers a highly flexible approach. which can overcome the limitations of traditional technology. When this branch is developed It has the potential to transform production processes by leveraging decentralized collaborative robot systems[34][27].

Finally, we investigate publication patterns for each cluster: robotics in additive manufacturing, soft robotics, mobile robotics, robotics in smart manufacturing, robotics manipulators, robotics in aerospace manufacturing, and swarm robotics and each cluster represent the progression of several clusters across time. Each cluster may have made significant progress by specified years from 2015 to 2024 as shown in figure 3.

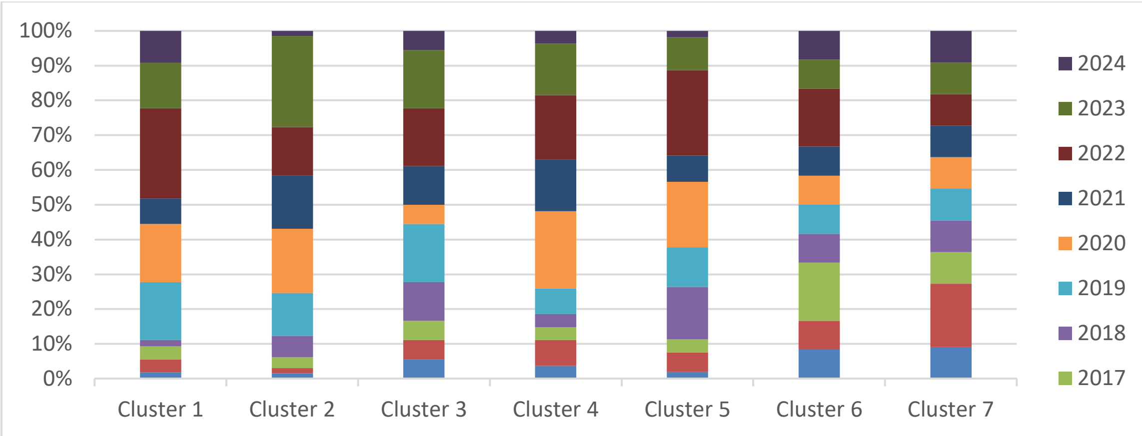

Figure 3. Yearly trends in publication by cluster.

IV. Why do the Results Matter?

The findings emphasize the increasing importance of robots in minimizing the environmental effect of manufacturing operations. With growing pressure to fulfill sustainability targets, manufacturing businesses are increasingly turning to automation and robots to boost efficiency, decrease waste, and limit energy use.

- The demand for more effective resource management, less waste, and lower energy usage is driving the transition toward sustainability in production today.
- Robotics immediately contribute to sustainability by automating processes, enhancing accuracy, and lowering the need for raw materials and human labor.
- The use of AI and IoT in production robots allows for improved optimization, which helps to achieve sustainability goals by increasing flexibility, reducing downtime, and boosting overall resource utilization.

V. How These Findings Align with Sustainability Goals:

These findings directly support major sustainability goals, notably those related to resource efficiency, decreased environmental impact, and human well-being:

- Sustainable Resource Use: Robots in manufacturing decrease material waste by performing more accurate tasks, such as additive manufacturing and soft robotics. They also help to improve material recycling and provide longer-lasting products, which promotes a circular economy model.
- Energy Efficiency: The employment of robotics in smart manufacturing, as well as mobile robots for improved material delivery, contributes to reduced energy usage throughout production processes.
- Workforce Safety and Well-Being: The employment of robots, particularly collaborative robots enhances workplace safety by completing risky or repetitive activities, lowering the risk to human workers and fostering a safer working environment. This also contributes to social sustainability goals by increasing job satisfaction and lowering physical strain on employees.

The robotics trends outlined in this study offer considerable prospects for advancing sustainable manufacturing by fostering energy-efficient, waste-reducing, and adaptable production systems. As the sector progresses, the integration of robots and future technology will continue to transform production methods, aligning them with global sustainability objectives.

VI. Practical Implications of Robotics in Manufacturing:

The conclusions of this bibliographic research have important practical consequences for real-world manufacturing processes, industry standards, and government. These implications concern how research trends and breakthroughs in robotics might be used to improve industrial systems in a variety of sectors.

Enhanced Manufacturing Efficiency: Integrating robotics, particularly mobile robots, into industrial processes increases efficiency by improving material handling and allowing for fast modifications to production lines. This decreases bottlenecks, saves downtime, and lowers expenses. Manufacturers may profit from versatile robotic systems that adapt to changing product lines, reducing resource consumption and simplifying processes. **Improvement in Safety and Precision**: Collaborative robots, which are meant to operate alongside people, improve production safety by completing precise jobs with less human error. In sectors like as electronics and automotive, robots increase worker safety and accuracy. Manufacturers may use robots to speed operations, reduce injuries, and improve operational accuracy.

Customization and Flexibility in Production: Robots can now respond to dynamic production demands thanks to advances in soft robotics and additive manufacturing, allowing for more flexible and customizable production lines. Industries such as aerospace, automotive, and electronics benefit from the ability to swiftly swap between products with minimum downtime, as well as reduce waste and promote efficient, sustainable manufacturing.

Sustainability and Environmental Impact: Robotics, such as self-healing robots and automation, contribute to sustainable production by minimizing waste, optimizing energy consumption, and enhancing recycling operations. Industries such as automotive and aerospace may use these technologies to improve sustainability and reduce environmental impact.

Policy and Industry Standards: Policymakers may develop legislation to promote robotics adoption by addressing labor displacement through upskilling programs and promoting safe, efficient robot use. Setting industry standards for robot safety and interoperability can also help to ensure their seamless incorporation into manufacturing.

Fostering Innovation in Emerging Technologies: Investing in developing technologies such as swarm robotics, soft robotics, and robots in additive manufacturing will help businesses remain competitive. These breakthroughs improve automation, customisation, and technology capabilities, laying the groundwork for future industrial advancements.

Global Collaboration and Knowledge Exchange: Global collaboration is critical for promoting factory robots, with 27% of research including multinational partnerships. Supporting cooperative research and knowledge-sharing activities promotes creativity, improves technology transfer, and keeps up with robotics breakthroughs.

Discussion

The number of publications related to robots has been steadily increasing over the years. This coincides with increased media interest and positive market attitudes towards robots. The integration of robots into production has significantly increased production capacity in various industries[35]. According to the International Robotics Association (International Robotics Association), There were 5.4 million robots sold for personal or home use in 2015, a 16% increase from the previous year. and estimates for 2019[36] expect sales to reach 42 million units. In this context, the impact of robots in production is becoming more important. While many businesses are eager to adopt robotics to increase productivity, there are concerns about the cost of these changes and the potential impact on the workforce. However, research on the economic and social impacts of robotics adoption is mixed. In this scenario, the influence of robotics adoption in manufacturing is becoming increasingly significant in the context of digital transformation. Although many businesses are eager to adopt new technologies to boost productivity, some have expressed worries about the cost of the change and its influence on the workforce[37]. However, research in this area is ambiguous and dependent on other information sources. The results are highly dependent on external factors. This section explores the contrasts and links between robotics research and manufacturing are explained below.

I. Structural Difference between Robotics and Manufacturing Research:

Analysis of the clusters listed in Table 3 reveals structural differences between robotics and manufacturing research. Robotics research has a gradation from basic research to applied research. Meanwhile, production research is more diverse. Some groups are specifically related to robots (e.g., groups 1, 4, 6), while others include robots and design (such as groups 2, 3, 5, and 7).

II. Current Context of Robotics and Manufacturing Research:

Manufacturing systems are evolving rapidly as digital transformation[38] takes place and robotics has played a key role in this transformation since its emergence in the mid-20th century[39]. . Robotics and related technologies are key drivers of the continuous digitization and automation of manufacturing processes[40][41], The capabilities of robot systems and related control methods are continuously improved[42]. This has contributed to important advances in manufacturing. Robotics is an important area of manufacturing studies, replacing humans in repetitive or dangerous tasks and becoming an essential component of industrial production[43][44]. Robotics is expected to be a key factor in future renewable factories. They will be able to interact with humans in uncertain environments, manage diverse tasks, and be quickly reprogrammed by non-experts to adapt to new manufacturing requirements.

III. Relation and Broader Implication for Sustainability in Manufacturing:

This study emphasizes that the incorporation of robots into production has important consequences for sustainability. The bibliometric study of 1,000 publications identified many paths via which robotics advances sustainable practices in manufacturing. The findings highlight that robots in manufacturing not only improve operational efficiency but also help sustainability by:

Waste Reduction: Waste Reduction: Robotics, particularly in additive manufacturing, reduces material waste by exact utilization. Self-healing and obedient robots help to increase system life and reduce the need for replacements.

Energy Optimization: AI and IoT provide energy-efficient procedures. Mobile robots improve material handling and reduce production energy usage.

Circular Economy: Aerospace manufacturing with robotics promotes remanufacturing and recycling, aligning with the circular economy. Collaborative robots enable component reuse, decreasing environmental effects.

Flexibility for Sustainability: Collaborative and swarm robots offer flexibility for sustainability by quickly adapting to product changes, reducing waste, and aligning with on-demand manufacturing.

Sustainable Production Lines: Soft robotics and manipulators enhance human-robot collaboration, leading to safer workplaces, better resource allocation, and cleaner manufacturing.

Broader Implications: Broader implications: Robotics improves sustainability through:

- Reducing emissions and energy use.
- Increasing product life through predictive maintenance.
- Data-driven optimization helps to conserve resources.

IV. Incorporating Trends in Sustainability and Future Research Directions:

This study reflects and influences sustainability trends in the manufacturing robotics sector by demonstrating the combination of sophisticated robotics technology with sustainable manufacturing practices. The findings are consistent with the wider industry aims of decreasing waste, maximizing resource consumption, and increasing energy efficiency. Below, we highlight major sustainability trends and propose future study directions:

Current Trends in Sustainability and Manufacturing Robotics:

Manufacturing robots is rapidly harmonizing with environmental objectives through a variety of developments. Robots today use energy-efficient technology, lightweight materials, and optimal designs to reduce energy usage. Additive manufacturing (AM) driven by robotics decreases waste by utilizing exact material amounts and self-healing robots that increase equipment lifespans. Robotics also supports circular economy models by facilitating remanufacturing, recycling, and material recovery in industries such as aerospace, with collaborative robots automating sorting at recycling facilities. Human-robot collaboration improves workplace safety and encourages socially responsible behaviors, as demonstrated by Industry 5.0, which combines robotic accuracy with human inventiveness. Furthermore, mobile and swarm robots offer decentralized, localized production, resulting in large reductions in transportation-related carbon emissions.

V. Future Research Directions:

Green Manufacturing Integration: Green Manufacturing Integration: Evaluate robotics technologies for integrating green manufacturing practices, such as using renewable energy and lowering greenhouse gas emissions.

Lifecycle Assessment of Robotics: Conduct a complete lifetime study of robotics to understand the environmental effect of manufacture, deployment, and disposal. Explore sustainable decommissioning solutions.

AI-Driven Sustainability Optimization: AI and machine learning can help improve robot operations for sustainability, including real-time energy usage monitoring and adaptive work scheduling to prevent energy peaks.

Advancing Circular Economy with Robotics: Develop robotic systems for recycling and remanufacturing, with a focus on automating disassembly and improving material recovery efficiency.

Sustainable Materials for Robotics: Consider using biodegradable or recyclable materials in robot building to minimize environmental effect at the end of their lives.

Sustainability Metrics in Robotics Research: Standardized standards for analyzing the sustainability effect of robots in production can facilitate industry-wide benchmarking.

Cross-Disciplinary Research: Foster collaboration among robotics engineers, environmental scientists, and legislators to establish sustainable manufacturing environments that balance technology innovation and environmental preservation.

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