

Review

Moving from Industry 4.0 to Industry 5.0: What Are the Implications for Smart Logistics?

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Abstract: Given the importance of human centricity, resilience, and sustainability, the emerging concept of Industry 5.0 has pushed forward the research frontier of the technology-focused Industry 4.0 to a smart and harmonious socio-economic transition driven by both humans and technologies, where the role of the human in the technological transformation is predominantly focused on. Several studies discuss the impacts of disruptive technologies on smart logistics operations in Industry 4.0. However, since Industry 5.0 is a new concept and still in its infancy, its implications for smart logistics have not been discussed. To fill this gap, this paper presents a comparative bibliometric analysis to show the connection and differences between Industry 4.0 and Industry 5.0 and their implications for smart logistics. A thorough content analysis is then given to illustrate the features of smart logistics in Industry 5.0 concerning four areas, namely intelligent automation, intelligent devices, intelligent systems, and intelligent materials. The results show that, compared with Industry 4.0, the research of smart logistics in Industry 5.0 puts more focus on the interaction between humans and technology in the digital transition, with the increasing adoption of collaborative technologies, e.g., human-machine systems, collaborative robots, and human-robot collaboration. Finally, a research agenda is proposed for identifying future research directions of smart logistics in Industry 5.0.

Keywords: Industry 5.0; Industry 4.0; smart logistics; sustainable logistics; bibliometric analysis; literature review



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1. Introduction

Industrial revolutions, throughout history, are primarily driven by disruptive technological breakthroughs that change the manufacturing paradigms and the way of customer demand satisfaction. With the increasing adoption of advanced manufacturing technologies, digitalization, and information and communication technology (ICT), Industry 4.0, also known as the fourth industrial revolution, aims at achieving a higher level of automation and intelligence [1]. Through leveraging the effectiveness and efficiency of manufacturing processes, Industry 4.0 predominantly emphasizes the paradigm shift led by new technologies, but less attention has been paid to the human aspects [2–4]. This is, however, argued as a threat to the sustainable development of humans and society [5], which requires more attention and effort from both industrial practitioners and academia [6]. Although this concern can be partially addressed by incorporating Industry 4.0 within the context of sustainability [7], circular economy [8], green supply chain [9], and so forth, it is still important to have a systematic conceptual development to fill the missing points of Industry 4.0. Thus, given the importance of human centricity, resilience, and sustainability [10], the concept of Industry 5.0 is proposed to complement the existing Industry 4.0 [11] in order to better meet the industrial and technological goals without compromising the socio-economic and environmental performance [2,3]. Among others, personalization, human-machine collaboration, bioeconomy, and sustainability are the

most important pillars in Industry 5.0 [12]. As argued by Di Nardo and Yu [13], the increasing adoption of Industry 5.0 technologies will not hinder human value, but rather promote a dual integration between human intelligence and machine intelligence in a collaborative environment [14].

Logistics, as a key function of a company or a supply chain, has been significantly affected by recent technological advancements and innovation [15]. Smart logistics operations are enabled by the increasing use of new technological solutions, which lead to the emergence of intelligent warehouse management [16], smart transportation [17], digital twin [18], and so forth. By comparing the development of logistics operations with the four industrial revolutions in history, Wang [19] proposed the concept of Logistics 4.0, which integrates Industry 4.0 technologies into various logistics operations to improve smartness and automation. This concept is further developed to adapt to the characteristics of specific industries, e.g., food logistics [20] and forest supply chain [21].

Even though significant research effort has been given to understand the impacts of new technologies on smart logistics operations and management, no effort has been directed to the human and environmental aspects brought by Industry 5.0. A recent literature review has put forward the concept of supply chain 4.0 to supply chain 5.0 [4], but no research has been done to provide a comprehensive understanding of the implications of Industry 5.0 for smart logistics. To fill this gap, this paper presents a comparative bibliometric analysis to show the connection and differences between Industry 4.0 and Industry 5.0 and smart logistics. A thorough content analysis is then given to illustrate the features of smart logistics in Industry 5.0 concerning four areas, namely intelligent automation, intelligent devices, intelligent systems, and intelligent materials. Finally, a research agenda is proposed for identifying future research directions of smart logistics in the era of Industry 5.0.

The rest of the paper is organized as follows. Section 2 presents the theoretical backgrounds of Industry 4.0 and Industry 5.0, and it also identifies the gaps related to smart logistics and the contributions of this paper. Section 3 introduces the research method. Section 4 formulates the research questions and illustrates the procedures of the literature search. A comparative bibliometric analysis is given in Section 5. Section 6 presents the content analysis and discussions. Finally, the conclusions are given in Section 7.

2. Literature Review

2.1. Industry 4.0

Industry 4.0 is undeniably one of the most important industrial phenomena to have occurred in the last decade, which has drawn significant attention from both industry and academia. The advent of this industrial paradigm has shaped the ground for extensive research topics since its introduction in 2011 at the Hannover fair by highlighting two major concepts: internet of things (IoT) and cyber–physical systems (CPS) [22,23]. The high-speed internet connectivity within manufacturing and logistics systems, i.e., industrial internet of things (IIoT) [24], potentially favors these industries by improving their intelligence and integration levels [25–27]. In this regard, combining automation and intelligence in a highly integrated CPS shows the maturity level of an Industry 4.0 system [1,28]. Through a combination of disruptive technologies and intelligent analytics, e.g., IoT, CPS, big data, artificial intelligence (AI), etc., Industry 4.0 will not only change the manufacturing industry but also impact all sectors of economic cycles. Figure 1 illustrates the nine most important enabling technologies of Industry 4.0, which are considered the pillars of the fourth industrial revolution.

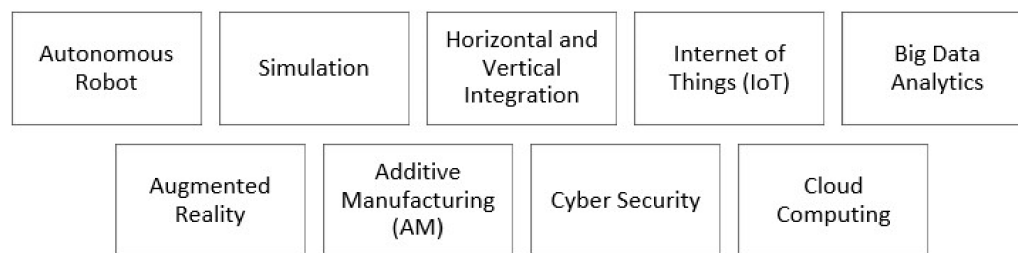


Figure 1. Nine pillars of Industry 4.0.

By integrating these technological pillars into an organized framework, Industry 4.0 is considered a technology-driven paradigm shift that aims at higher productivity through the better utilization of resources [2]. This technological framework incorporates all operational layers and streams of a factory and possesses a high level of intelligence similar to a human's brain. From a holistic point of view, this evokes a fully automated production system that is operated by internet-connected smart machines and robots with minimum human intervention. However, realizing such an objective needs the adoption of several enabling technologies through both vertical and horizontal integrations [1]. For instance, additive manufacturing (AM), e.g., 3D printing, has not only been used for the rapid prototyping of complex designs but has also been widely adopted in the manufacturing processes in several industries, e.g., aviation [29]. It may change the manufacturing paradigm through direct digital manufacturing (DDM), which can better satisfy highly personalized demands. However, on the other hand, it may proportionally increase the sophistication of production management. To this aim, virtual technologies and simulation can be used to evaluate the operational aspects and performance of incorporating AM into a manufacturing plant [30], which can provide comprehensive insights into the technological updates. Thus, the technological integration in a CPS has been categorized into five levels to measure the maturity of an Industry 4.0 system, namely connection level, conversation level, cyber level, cognition level, and configuration level. At the highest level, the system can achieve bi-directional communication and control, intelligent decision-making, and autonomous operations [28].

2.2. Industry 5.0

The primary focus of Industry 4.0 is a technology-driven industrial paradigm transition, but less attention has been given to the human aspects and society. One concern related to this industrial revolution is the possible layoff and job security with the increased adoption of autonomous systems [31]. Thus, it is of great importance that the technological transition must be done in a sustainable way and comply with the socio-economic development goals [3]. The concerns of humans and society in the industrial transition led to the emergence of Industry 5.0, which was raised by Michael Rada [32] in 2015 to put forward the concept of "Industrial Upcycling". This idea emphasizes the cooperation between humans and new technologies, i.e., industrial robots, 3D printers, etc., in production with the purpose that *"we use these tools as tools, do not give them the function and brain to WORK FOR US, but WORK WITH US"* [15]. This concept is closely linked to the technological pillars that have already been employed, and thus studies are carried out to distinguish the scopes, goals, and approaches of Industry 5.0 as a new stage of the industrial revolution. Following the footprints of this paradigm shift, the Japanese government (Keidanren, the most important business federation of Japan) proposed "Society 5.0" based on the high digital transformations in society. This concept aims at protecting societal and environmental benefits along with the direction of economic growth by taking advantage of technological improvements [33,34]. It attempts to turn the novel solutions around for the benefit of society and human life.

With a predominant focus on the role of the human in the technological transition, substantial attention has been paid to human–robot collaboration in Industry 5.0 during the last couple of years [2,3,35–37]. In addition, several studies investigate the human's

role from various perspectives, i.e., technical, ethical, operational, societal, safety, etc., which has become one of the mainstream research directions to shape this new industrial revolution [6,34,38]. Hence, Industry 5.0 aims at establishing a comprehensive framework by adopting disruptive technologies and innovative solutions to tackle the emerging human- and societal-related challenges and achieve sustainable development. In this regard, the European Commission (EC) officially defined the concept of Industry 5.0 in January 2021 [33], which presented a systematic approach in the context of technological and methodological improvements. It establishes a synergy between the main technological drivers and societal development in Industry 5.0, and six major categories are identified, including human–machine interaction, bio-inspired technologies and smart materials, digital twins and simulation, big data analytics, artificial intelligence, and energy efficiency and renewable energies.

2.3. Literature Gaps and Contributions of This Research

The technological breakthroughs in the recent industrial revaluation have provided opportunities for smart logistics management and operations. A recent survey has clearly presented the technological implications of Industry 4.0 for smart logistics operations, including production and purchasing, transportation, warehousing, and digitalization and system integration [15]. In addition, research shows that blockchain, AI, and unmanned aerial vehicles (UAV) are the three widely focused enabling technologies for smart logistics [39–41]. Even though significant efforts have been devoted to research to understand the implications of disruptive technologies in smart logistics [15] and supply chains [9,42,43], warehouse management [44], goods transportation [39], as well as other relevant topics, the primary focus has been given to the technological sides and not to the main characteristics of Industry 5.0. A recent study has presented a comprehensive discussion by connecting Industry 5.0 and supply chain management [4]. However, to our knowledge, no research effort has been made to link Industry 5.0 in the context of smart logistics. Thus, this paper aims at filling this gap by providing an overview to understanding the implications for smart logistics moving from Industry 4.0 to Industry 5.0.

3. Research Method

Considering the rapid advancement of industrial paradigms stemming from technological leaps and the significant socio-economic impacts, it is of significance to analyze the status quo of the literature and project the future landscape of smart logistics in Industry 5.0. This paper presents a systematic literature review (SLR) to thoroughly understand the main characteristics of smart logistics in Industry 5.0. Literature review studies could be distinguished by two taxonomies according to their domain of contribution [45,46], namely conventional and stand-alone literature reviews. The former is broadly known and used by scholars serving as a background study that highlights a literature gap as the basis of a research project. The latter, however, is a solid study that assesses the entire “body of existing knowledge” in a particular field to shed light on the current research status and frame the potential directions. This concrete method was reshaped by Fink in 2005 by outlining the main features of the stand-alone review study [47]: systematic, explicit, comprehensive, and reproducible. To be more precise, such a study ought to accommodate a solid methodology with clear notations on the procedures encompassing deep insights into the corresponding research materials, which can be reproduced by other scholars. Based on this framework, the SLR was defined as [45]: “a systematic, explicit, comprehensive, and reproducible method for identifying, evaluating, and synthesizing the existing body of completed and recorded work produced by researchers, scholars, and practitioners”. An SLR can benefit from both qualitative and quantitative methods by exploiting the meta-analysis, which takes place prior to the qualitative evaluation of the selected articles, and thus neutralizes the impact of selection bias pertaining to a narrative literature review [45,48].

The procedures of an SLR were initially developed by eight steps [45,49]: formulating the problem, validated review protocol (eliminate the conflicts of interest for studies

including more than one reviewer), literature search, screening, quality assurance, data extraction, synthesizing the findings, and reporting. These steps were further aggregated into four logical categories to represent a more transparent overview of the stages involved in this research method [45,50,51]:

1. **Problem Formulation:** Entails the identification of the research goals and scopes by defining relevant research questions. It is worthy to note that, for studies including more than one reviewer, there should be a consensus over the questions to avoid evaluation bias.
2. **Literature Search and Screening:** This stage commences with a precise search within the selected databases according to the identified keywords for each research question. The resulted papers are to be filtered out through the inclusion and exclusion of relevant criteria, which are further narrowed down by the screening procedure.
3. **Bibliometric Analysis:** According to the meta-data associated with the extracted papers, a quantitative analysis is conducted to reveal the relations between various characteristics of the research articles, i.e., publication trend, keywords focus, involved journals, etc.
4. **Content Analysis:** Qualitative analysis that aims at a thorough evaluation of the selected papers to explore the current status of the research area and to highlight the future research agenda.

4. Problem Formulation and Literature Search

The initial step of this research is to formulate the research questions. According to the main objective of this study, we aim at providing a thorough understanding of the transition of smart logistics operations in the fifth industrial revolution. To this aim, three research questions are defined to shape the ground of this stage:

- Research Question 1 (RQ1): What are the connection and differences in smart logistics between Industry 4.0 and Industry 5.0?
- Research Question 2 (RQ2): What are the main characteristics and enabling technologies of smart logistics in Industry 5.0?
- Research Question 3 (RQ3): What is the research agenda of smart logistics in Industry 5.0?

The second stage is the literature search, which aims at finding and extracting the most relevant research articles for further quantitative (Comparative Bibliometric Analysis) and qualitative (Content Analysis) analyses. This stage consists of four steps, namely keyword search, inclusion/exclusion of criteria, first screening (investigation of titles, abstracts, and keywords), and second screening (full-text investigation). In this paper, we used the following steps to identify and select the most relevant articles for answering the research questions:

1. **Keyword Search.** This step employs two search techniques: (1) using a double quotation for an exact match with regard to phrase search; and (2) taking advantage of Boolean operators (OR/AND) to combine various taxonomies of keywords. To thoroughly reveal the connection and differences in smart logistics between Industry 4.0 and Industry 5.0, we searched the respective literature in two groups. The first group emphasized the connection between Industry 4.0 and smart logistics, which primarily yielded two contextual categories connected with "OR", as shown in Table 1. The second group was to explore the literature that discussed the characteristics, implications, driving factors, and definitions of Industry 5.0-enabled smart logistics. The primary database for the literature search was Web of Science (WoS), which is the most extensively used platform [52]. However, due to the limited number of papers related to smart logistics and Industry 5.0 in WoS, Scopus was also used to yield a reasonable sample for analysis. The literature search was conducted in late December 2021, and the initial search for the first group yielded 288 papers, while it resulted in 247 for the second group (91 and 156 in WoS and Scopus, respectively).

Table 1. Identified keywords for smart logistics in Industry 4.0.

Main Category ('AND' Boolean Operator)	Sub-Keywords ('OR' Boolean Operator)
Smart Logistics	smart logistics; logistics 4.0; smart supply chain; supply chain 4.0; operator 4.0
Industry 4.0	industry 4.0; i4.0; fourth industrial revolution; cyber-physical system; internet of things; cloud computing; augmented reality; big data analytics; artificial intelligence; virtual technology; simulation; additive manufacturing; autonomous robots; cyber security; digital twin

2. **Inclusion/Exclusion of Search Criteria.** This procedure attempts to narrow down the collected papers from the previous step by either including or excluding particular criteria. Primarily, the language of the research items was selected as 'English' to emphasize the international contributions. To ensure the quality of analysis, the papers were restricted to journal articles and conference proceedings. As also outlined, the introduction of Industry 4.0 was traced back to 2011 [22,23], while the literature had recorded 2017 for Industry 5.0 despite its initial introduction being in 2015 [2,53]. Thus, the next criterion was to set the publication years of the two groups of papers to be after 2011 and 2017, respectively. Another key filter that remarkably impacts the search results is the publication categories, which seeks to eliminate articles with the least correspondence in terms of their scientific fields. Based on the applied filters, there were 114 and 146 in the two groups. Ultimately, a duplicate check for the second group was essential due to the use of two databases, which, in turn, decreased the results to 110.
3. **First Screening (investigation of titles, abstracts, and keywords).** The initial consideration in this stage was to exclude review articles, which were respectively recorded as 6 and 9 papers for the two groups. This was followed by a thematic investigation that aimed at filtering out the papers with weak conceptual relevance associated with the research questions. Throughout this process, the titles, abstracts, and keywords of the articles were investigated. This process led to the exclusion of 49 and 59 papers in the two groups.
4. **Second Screening (full-text investigation).** During this process, the selected papers from the previous step were entirely read to filter out the ones that were incapable of addressing the research questions directly. After the full-text investigation, 12 papers were eliminated from the first group, and 10 papers were eliminated from the second group.

As shown in Figure 2, the first group was addressed by two categories of keywords, by which the initial search within WoS resulted in 288 articles. This figure, however, was reduced to 53 research items after setting the essential filters and completing the screening procedures. Combining both WoS and Scopus, the second group yielded 247 papers in the initial search. After considering the inclusion/exclusion criteria, the duplicate check, and screening, the final set of research articles was narrowed down to 41 papers. It is noteworthy that, during the second screening, 20 papers were identified to be relevant to understand the implications of Industry 5.0 for smart logistics.

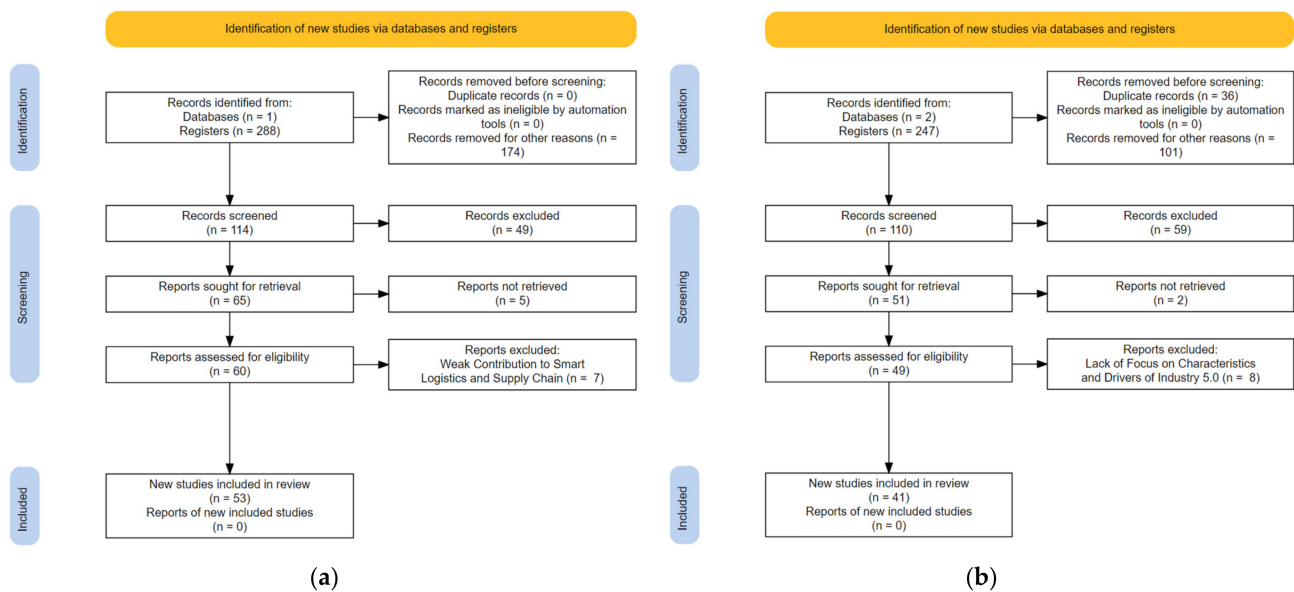


Figure 2. Flow diagrams of literature search: (a) smart logistics in Industry 4.0; (b) smart logistics in Industry 5.0.

5. Comparative Bibliometric Analysis

A bibliometric analysis is a quantitative evaluation of the collected research articles [45], which enables scholars to statistically study the available bibliometric data from different perspectives. In this paper, we focus on the connection and differences of smart logistics in Industry 4.0 and Industry 5.0, so a comparative bibliometric analysis was performed based on the two groups of articles. Following the procedures and recommendations by Donthu and Kumar [54], we present both performance analysis and science mapping of the sample of articles, including the publication trend, co-citation analysis, and keyword co-occurrence analysis.

5.1. Publication Trend

The publication trends are represented in Figure 3. For smart logistics in Industry 4.0, the numbers recorded affirm that increasing attention from academia has been drawn from 2015, and peaked in 2019, with 19 research items accounting for 36% of the accumulated articles. This trend reflects that the incorporation of emerging Industry 4.0 technologies into logistics operations and decisions has become more attractive, which may largely affect this industry by adopting automated guided vehicles (AGVs), UAVs, AM, autonomous robots, etc. Although this rising trend is retrieved after a sharp decrease in 2020, the number of research items in 2021 is not comparable to 2019, which shows a shift in research attention to this area within the last couple of years. Contradictorily, the trend of research activities within the area of Industry 5.0-enabled smart logistics has drastically increased in this period, which boomed in 2021 with 22 articles.

The most significant inference in this regard is the incorporation of sustainability, which has recently emerged among the main objectives of Industry 4.0 and the application of its technologies. Based on previous review studies [15], there is an increasing trend in sustainable logistics beginning from 2019. This trend is aligned with the general goals of Industry 5.0, which puts forward the significance of socio-economic and human-centric activities.

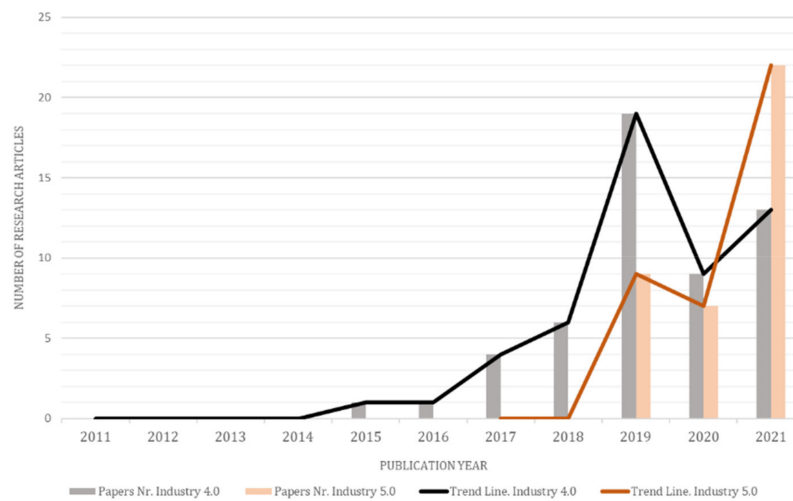


Figure 3. Publication trends.

5.2. Sources Contributions, Interactions, and Co-Citation Analysis

5.2.1. Source Contributions

International journals and conferences are the primary platforms that pave the way towards fostering innovative solutions and ideas. Therefore, it is of significance to evaluate the contributions and interactions of the sources within the sample set, which, from a general scale, gives insights into the active and leading sources of a research topic. Table 2 shows the sources and the number of papers contributing to smart logistics in Industry 4.0 and Industry 5.0, respectively.

Table 2. Distribution of top contributing sources.

Technological Enabler of Smart Logistics	Source Title	No. Items
Industry 4.0	IFIP Advances in Information and Communication Technology	7
	Computers & Industrial Engineering	5
	IFAC-PapersOnline	5
	Procedia Manufacturing	3
Industry 5.0	Lecture Notes in Mechanical Engineering	4
	Applied Sciences Switzerland	3
	Sensors	3
	Journal of The Knowledge Economy	2

Table 2 highlights the four most important sources related to smart logistics in Industry 4.0 and Industry 5.0. With seven articles published, ‘IFIP Advances in Information and Communication Technology’ is the most contributing source within the context of Industry 4.0 and Logistics 4.0 by signifying the technological topics, e.g., computer applications in technology, systems modeling and optimization, artificial intelligence, etc. ‘Computers & Industrial Engineering’ is the following journal, which has contributed to five publications in this field and focuses on computerized approaches in response to industrial problems. In parallel, five research items are published in ‘IFAC-PapersOnline’, which tightly focuses on, but is not limited to, automation and control. Given the importance of manufacturing processes, automation, robotics, and so forth, ‘Procedia Manufacturing’ is another important source that has contributed to three research items. The main focus of these sources is technological advances, e.g., robotics, automation control, etc., and advanced computerized approaches, which not only are the inevitable components of Industry 4.0 but also play an important role in developing smart logistics systems. On the other hand, Industry 5.0 is listed four times in ‘Lecture Notes in Mechanical Engineering’, which covers broad scientific topics including control, robotics, engineering design, automotive engineering, and engineering management. ‘Applied Sciences Switzerland’ and ‘Sensors’ are the

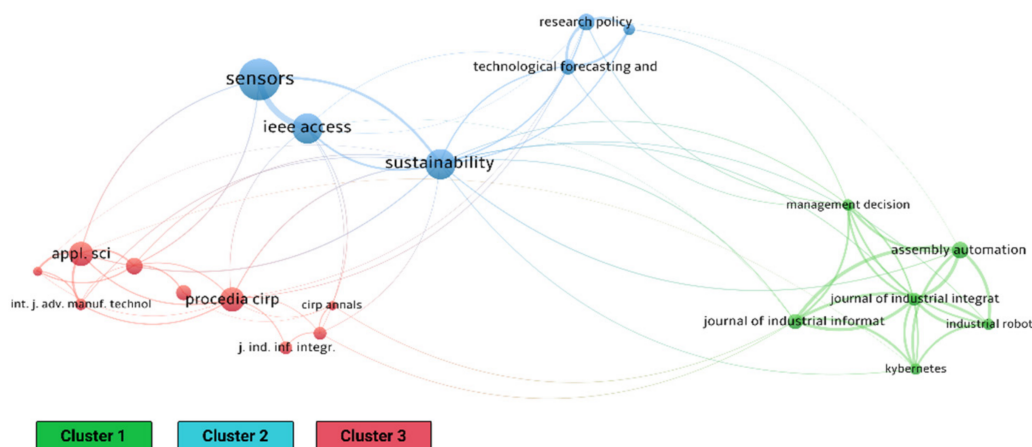


Figure 5. Co-citation analysis network of smart logistics in Industry 5.0.

Figure 4 reveals that the most influential source for smart logistics in Industry 4.0 is the ‘International Journal of Production Research’, which yields 65 co-citations and its TLS weight equals 1176. Given TLS as the comparison criterion, the impact of six more sources is determined to be significant, including ‘Procedia Manufacturing’ (780), ‘Procedia CIRP’ (671), ‘Computers in Industry’ (641), ‘International Journal of Production Economics’ (625), ‘IFAC-PapersOnline’ (544), and ‘Computers & Industrial Engineering’ (541). Table 3 shows the clusters of these highly influential journals related to smart logistics in Industry 4.0 and their primary focus areas. Based on the features of the sources in each cluster, there is an interweaving connection between sources, which emphasizes the role of technological methods and drivers to advance the smart logistics paradigm in Industry 4.0.

Table 3. Co-citation clusters of smart logistics in Industry 4.0.

Cluster	Source Title	TLS	Features
Cluster 1	International Journal of Production Research	1176	The application of computerized technologies in manufacturing and operation research
	Computers in Industry	641	
	International Journal of Production Economics	625	
Cluster 2	Computers & Industrial Engineering	541	Role of technology in manufacturing and logistics
	International Journal of Advanced Manufacturing Technology	390	
Cluster 3	Procedia Manufacturing	780	Manufacturing engineering, processes, and automation
	Procedia CIRP	671	
	IFAC-PapersOnline	544	

The newly emerged topic of Industry 5.0-enabled smart logistics, however, yields different attributes through the quantitative analysis of the sources. Based on the co-citation analysis, ‘Assembly Automation’ entails the highest TLS value, which is equal to 241. This is followed by eight sources, which generate considerable influence according to their TLS weight, including ‘Journal of Industrial Information Integration’ (224), ‘Journal of Industrial Integration and Management’ (217), ‘Sensors’ (195), ‘Industrial Robot’ (192), ‘IEEE Access’ (184), ‘Sustainability (Switzerland)’ (171), ‘Kybernetes’ (166), and ‘Management Decision’ (156).

In the outlined list, ‘Sensors’ is the source that is also involved in Table 2 amongst the most contributing journals. Additionally, it is the most referred source in the literature. This applies also to ‘Sustainability (Switzerland)’ and ‘IEEE Access’, both of which are the second most cited sources, with a record of 16. This reveals the inter-disciplinary nature of the research and the importance of socio-economic factors and sustainability in the direction of Industry 5.0. Another finding from this list is that six sources (out of nine in total), as shown in Table 4, are cross-functional, with a primary focus on manufacturing technologies and information systems and management. Similar to that of Industry 4.0, these sources

have shown that technological advancements and innovation also play a significant role in smart logistics in Industry 5.0 through the adoption of big data analytics, AI, simulation, etc. Figure 5 shows the interaction and influence of these clusters. As demonstrated, there is a weak connection between cluster 1 and cluster 2, while they have intensive cooperation with cluster 3. This indicates that there is an interest in improving manufacturing technologies and information systems with a major focus on social, economic, environmental, and sustainable issues. Through the comparison of the co-citation analysis of articles between the two groups, we find that the paradigm change of smart logistics, from Industry 4.0 to Industry 5.0, must meet the socio-economic and sustainable requirements. In this regard, journals with this feature seem to play an increasingly important role.

Table 4. Co-citation clusters of smart logistics in Industry 5.0.

Cluster	Source Title	TLS	Features
Cluster 1	Assembly Automation	241	An inter-disciplinary combination of manufacturing technologies and information management
	Journal of Industrial Information Integration	224	
	Journal of Industrial Integration and Management	217	
	Industrial Robot	192	
Cluster 2	Sensors	195	An inter-disciplinary readership with a focus on engineering, social, human, economic, and environmental aspects
	IEEE Access	184	
	Sustainability (Switzerland)	171	
Cluster 3	Applied Sciences Switzerland	102	Manufacturing engineering and technology management
	Procedia CIRP	69	
	Computers & Industrial Engineering	66	

5.3. Keyword Co-Occurrence Analysis

The co-occurrence analysis of keywords calculates the number of times each keyword is used along with the interaction between pairs of keywords. This examination is visualized in Figures 6 and 7, where the keywords are represented by nodes and their size is dependent on the number of occurrences of the respective keyword. The links correspond to the interaction between keywords and their thickness indicates the usage frequency of each pair of keywords together. Thus, TLS in this context is the accumulation of links' magnitude associated with each keyword. To yield sufficient and reliable results, 'all keywords' is considered for network generation, which includes indexed keywords as well. Last but not least, the minimum number of occurrences to generate the visualization is set to 2, which leads to 46 and 42 results for the two groups.

Table 5 shows the top 15 keywords related to smart logistics enabled by both Industry 4.0 and Industry 5.0. Concerning Industry 4.0 and smart logistics, the most referred keywords are Industry 4.0, Internet, Operator 4.0, and Logistics 4.0, which identify the general framework of conceptual development. The other keywords, however, show the bond between new concepts and new technological drivers, i.e., big data, augmented reality, internet of things, etc. On the other hand, the keywords from the second group of literature highlight the significant role of Industry 4.0 as well as its enabling technologies within the roadmap of Industry 5.0. The primary finding is that, from a technological perspective, smart logistics in Industry 5.0 is concretely based on that from Industry 4.0. It is worth noting that, apart from a single technological perspective, socio-economic and sustainable issues are better considered and embedded in the smart logistics enabled by Industry 5.0 through the inclusion of human–robot collaboration, collaborative robots, and man–machine systems.

Table 5. Top 15 keywords.

No.	Industry 4.0			Industry 5.0		
	Keyword	Occur.	TLS	Keyword	Occur.	TLS
1	Industry 4.0	32	123	Industry 5.0	33	116
2	Internet	13	58	Industry 4.0	20	84
3	Operator 4.0	13	42	Industrial Revolutions	6	30
4	Big Data	5	31	Robotics	5	29
5	Future	4	30	Artificial Intelligence	6	25
6	Design	5	27	Manufacturing	4	25
7	Industry	4	27	Smart Manufacturing	4	23
8	Logistics 4.0	10	26	Internet of Things	5	22
9	Internet of things	6	24	Human–Robot Collaboration	4	21
10	Things	6	24	Industrial Research	4	18
11	Logistics	6	23	Collaborative Robots	3	16
12	Framework	3	21	Design and Development	3	16
13	Performance	4	21	Man–Machine Systems	3	16
14	Smart Logistics	6	19	Manufacture	2	16
15	Augmented Reality	3	17	Technology	3	16

Figure 6 illustrates the six clusters of keywords related to smart logistics in Industry 4.0. The most influential one is cluster 6, which shows a strong connection between the internet of things (IoT) and Industry 4.0. Cluster 2 addresses the main focus of Logistics 4.0 and smart logistics, as well as some main enabling technologies, i.e., AR, etc. Cluster 3 indicates the importance of internet-based AI and machine learning in smart logistics and smart supply chains. Cluster 5 has a remarkable interaction with cluster 6 and signifies the role of the smart logistics transition, which yields the concept of operator 4.0. Cluster 1 emphasizes digital tools, i.e., simulation, in manufacturing operations and sustainability. Cluster 4 depicts the importance of Industry 4.0 technologies in smart manufacturing and logistics, i.e., cyber–physical systems (CPS), big data, digital twin, etc. In general, the keyword co-occurrence network of these clusters shows that the research focus has been predominantly given to the technological drivers for smart logistics solutions in Industry 4.0. However, cluster 5 shows that increasing effort has been given to the connection between technology and humans, which shows the motivation for a transition from Industry 4.0 to Industry 5.0. Finally, it is obvious that several advanced technologies, i.e., digital twin, simulation, AI, etc., have major contributions to this concept.

Figure 7 illustrates the four clusters related to smart logistics in Industry 5.0. Cluster 3 is by far the most influential category, showing that the root of Industry 5.0 is from Industry 4.0. As discussed earlier, these two concepts have an interweaving connection in which the technological drivers play an undeniably important role. However, the elaboration of the links associated with smart logistics in Industry 5.0 reveals the footprints of social and environmental issues in this context. Cluster 1 comprises topics that immensely study CPS and smart manufacturing based on industrial robots according to the social impacts. Cluster 2 shows the links between the concept of society 5.0 and intelligence systems, human–robot collaboration, and collaborative robots. Cluster 4 evokes the existence of operator 4.0 and elaborates the significance of human factors, human engineering, personnel training, and so forth, in Industry 5.0-enabled smart logistics. On the one hand, Industry 5.0 is tightly linked to the technological drivers of Industry 4.0 in the current digital era, while, on the other hand, Industry 5.0 places predominant attention on socio-economic development, sustainability, and human issues. To this aim, the result of the keyword co-occurrence analysis shows the potential for smart logistics in Industry 5.0 by adopting new technologies while considering the human side in the transition, e.g., enhancing human–robot collaboration.

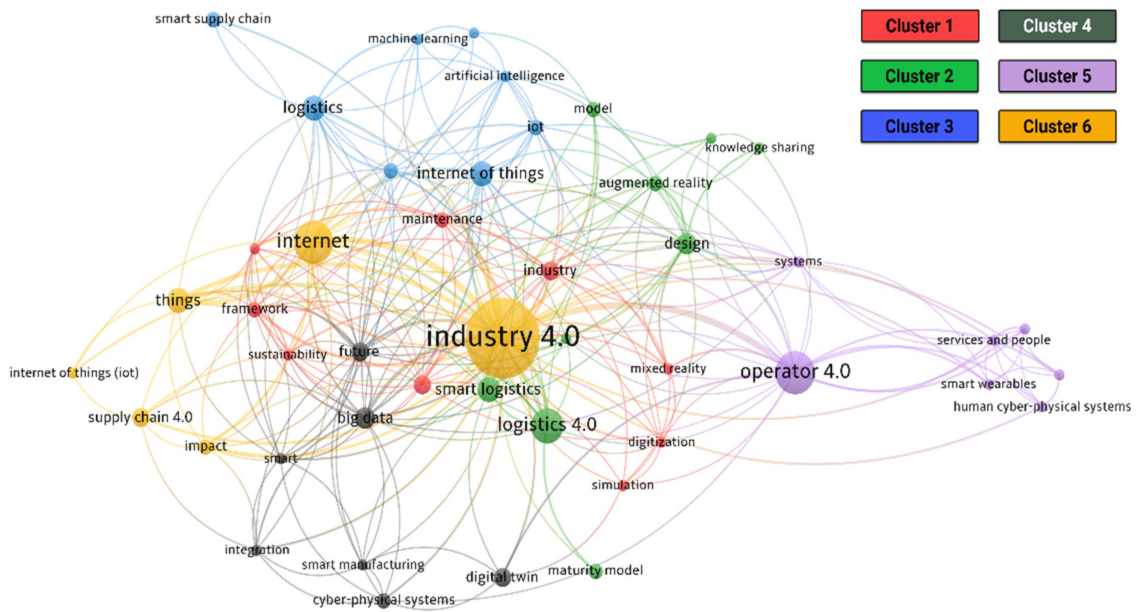


Figure 6. Keyword co-occurrence analysis of smart logistics in Industry 4.0.

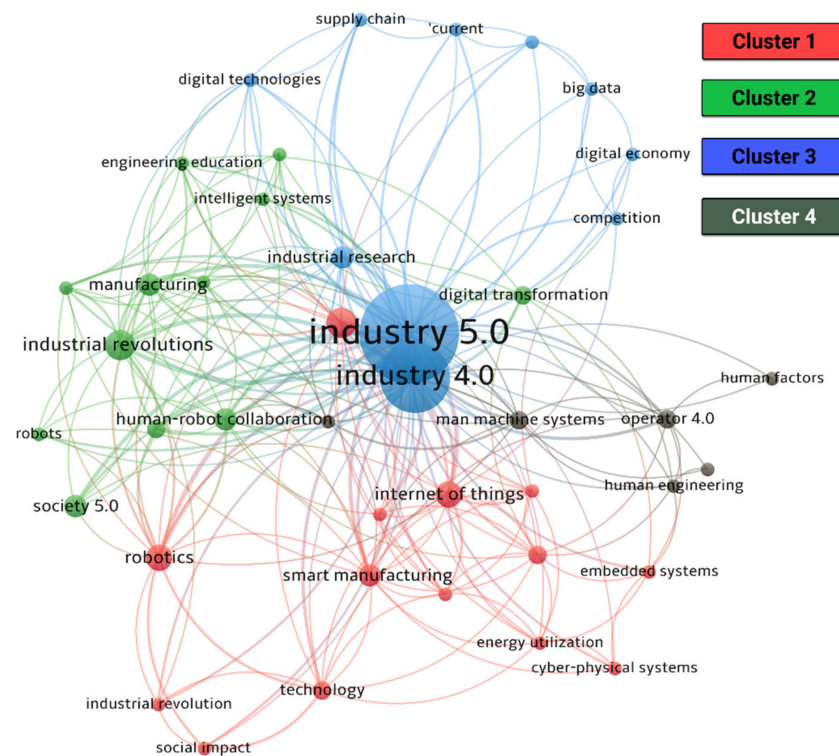


Figure 7. Keyword co-occurrence analysis of smart logistics in Industry 5.0.

6. Content Analysis and Discussion

The results of the comparative bibliometric analysis of the two groups of literature demonstrate that there is an increasing trend in addressing the societal, human, and sustainability aspects, which are the key elements of smart logistics in Industry 5.0 [6], to highlight the harmony between technological development and human-centric socio-economic transition. The evaluation of the most extensively used keywords reveals that smart logistics in Industry 4.0 focuses purely on the technological pillars. However, on the other hand, Industry 5.0 not only emphasizes the adoption of new technologies in smart logistics operations but also substantially stimulates the interaction among humans,

technology, and the environment through human–robot collaboration, collaborative robots, man–machine systems, etc.

6.1. The Three Key Elements of Industry 5.0

As rooted from Industry 4.0, Industry 5.0 embraces similar technologies and a clear distinction between these two industrial revolutions is thus of significance. The official introduction of Industry 5.0 underpins the evolution of this novel paradigm with respect to a trinary concept to pinpoint its corresponding core values [33]: human-centricity, resilience, sustainability.

1. **Human-Centricity.** Conveys the fact the production and logistics system must be improved with solid attention to human benefits and needs, by which the human is transformed from ‘cost’ to ‘investment’ [2]. From the operational aspect, this urges the promotion of hybrid alternatives in response to the industrial challenges, where the human power and human brain are involved not only in maintaining the surveillance but also in incorporating more intelligence and innovation and, to some extent, making decisions [3,35]. Industry 5.0 emphasizes research and development (R&D) activities to translate information into knowledge and meet sustainable social goals by upskilling humans through formal education or training schemes [2,6,36,56,57]. From the social and economic point of view, Industry 5.0 shapes the ground to not only prevent the elimination of human labor engaged in the manufacturing industry but also create more job opportunities in the supportive industries, which provide technological solutions, i.e., robot manufacturing, sensor manufacturing, etc. [3,34,36]. Hence, based on these objectives, Industry 5.0 is a human-centric paradigm that transfers the human back to the center of production cycles.
2. **Resilience.** Represents the flexibility and agility that a production plant needs to maintain in response to market change [36,58]. Today, customers are strikingly bombarded with high-tech innovations and products, and according to the constant changing in the market, personalized demands are one of the most significant challenges to the manufacturing industry [35]. To a larger extent, manufacturing systems are expected to transform from mass customization to mass personalization [36]. From a tactical perspective, this is realized by incorporating the customers into the design phase to build up the personalized product from scratch [34,59]. To improve the operational flexibility in this regard, human–robot collaboration has significant potential, which conducts versatility of fabrication in a more efficient time [36,37]. It is worthwhile to highlight that while the main task is accomplished by the robot, human collaboration facilitates the problem solving of the work and process flows, and improves intelligence and innovation [35,37].
3. **Sustainability.** The concept of sustainable development was initially introduced by Brundtland in 1987 and defined as the “*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*” [60]. While the social- and human-related issues are an integral part of this concept, they are merely discussed within human-centricity in the context of Industry 5.0. This approach emphasizes reverse logistics [61,62], circular economy [2], value chains, and so forth [63]. Sustainable development seeks the protection of the environment through sustainable products and logistics systems to approach the zero waste objective [34]. In addition to waste prevention, the manufacturing processes must be environmentally friendly—for example, by using renewable resources and green computing [37].

6.2. Smart Logistics in Industry 5.0

The core elements of Industry 5.0 show that following the technology-centric transition of Industry 4.0, the societal, environmental, and human perspectives require more attention, which will yield significant impacts on logistics operations and management. For instance, the personalization of demands implies a personalized delivery system [56]. Incorporating customers into the design requires highly intelligent CPS and system integration [37].

Human–machine interaction triggers the interaction of various topics such as safety, human behavior, etc. [35]. Thus, there exist various challenges and approaches to addressing smart logistics issues in Industry 5.0. With a focus on the interaction between technology and humans in smart logistics, we present discussions through a quadripartite intelligence framework [3,36], namely intelligent automation, intelligent devices, intelligent systems, and intelligent material.

6.2.1. Intelligent Automation

The major focus of Industry 5.0 is human-centricity, which, from a pragmatic aspect, puts forward the presence and high importance of the human in a system. However, there is a trade-off between human integration and automation to satisfy the goals of Industry 5.0, and this concern resides in the context of intelligent automation [35,36], e.g., human–robot collaboration. It impacts the resilience of a logistics system and thus requires special attention and intelligence to achieve a lean collaboration [64–66]. The human’s role in a logistics system was initially investigated in 2016 under the concept of ‘Operator 4.0’, which aims, by taking advantage of technological advancements, at maximizing the human’s contribution from three functional aspects [67,68], namely assisted work, collaborative work, and augmented work. The first function highlights the tasks that are mainly completed by human operators with the help of assisting technologies. The second requires collaboration between machine/robot and human. The last relies on technologies that could extend the human’s physical and visual capabilities. Considering logistics operations at different stages, e.g., production, warehousing, etc., material handling and information flow are two operational categories that significantly benefit from these applications [69].

Industry 5.0 paves the way to extending this framework by considering both resilience and human-centricity. Romero and Stahre [70] introduce the concept of ‘Operator 5.0’ as *“a smart and skilled operator that uses human creativity, ingenuity, and innovation empowered by information and technology as a way of overcoming obstacles in the path to create new, frugal solutions for guaranteeing manufacturing operations sustainable continuity and workforce well-being in light of difficult and/or unexpected conditions”*. In the context of Industry 5.0, this paradigm encourages technological development in two main directions: self-resilience and system resilience. Self-resilience emphasizes human sustainability from biological, physical, cognitive, and psychological dimensions and focuses on human-centricity in the technological transition, i.e., work ethics, social impacts, legal issues, etc. [38,71–73]. System resilience, however, signifies the functional collaboration between humans and machines in terms of sharing and trading control [74].

Human–robot collaboration in Industry 5.0 also plays a vital role in reacting to highly unexpected events, e.g., the COVID-19 pandemic, which requires high production agility and flexibility to fulfill the rapidly increasing demands of medical supplies [70,75,76]. In this regard, collaborative robots (cobots) are one of the most discussed enabling technologies in Industry 5.0. However, two important issues, namely the human skills and the behavior of cobots, need to be taken into account when cobots are integrated into a production or logistics system. As the main lever of Industry 5.0, through proper training, humans must be capable of working together with cobots [31,73,77–79]. For this purpose, the use of several supportive technologies, i.e., virtual reality, augmented reality, and simulation, has been extensively investigated [3,76,80]. For instance, operators can learn and understand the cobot motions under specific conditions without compromising safety measures and productivity [3,76]. On the other hand, cobots can be programmed or trained to establish a lean collaboration with the operators, which may lead to an increase in the productivity and efficiency of the workflow [81]. Human–robot collaboration not only requires hardware capabilities, i.e., sensors, etc., but also implies the essence of cognitive and intelligent behaviors of the cobot [81]. In this regard, the latest computation methodologies, i.e., machine learning (ML), deep learning (DL), clustering, regression, etc., have become increasingly important for the development of versatile applications [3,76,82–86].

6.2.2. Intelligent Devices

Machines, robots, and other facilities that are used in the production and logistics systems must be improved and equipped with smart technologies to maximize functionality and performance through physical and cyber connections with high monitoring and controlling capacities [87–90]. Considering the scopes of Industry 5.0, this objective signifies the interaction between humans and robots/machines. On the one hand, these intelligent devices, e.g., intelligent machines, smart robots, cobots, etc., require cognitive capabilities for decision-making by themselves to not only perform operations alongside the humans but also actively prevent undesired incidents. On the other hand, due to the operators' inherent physical and intellectual limitations, the shortcomings for accessing the information flow and augmented functional abilities can be resolved by intelligent devices [77]. The collaboration between robot and operator raises concerns about human constraints as opposed to machines, which requires extra effort to resolve their integration issues. In this regard, operators' conditions need to be constantly traced with capture motion and eye-tracking devices, wearable biometric equipment, etc., under various workload conditions from both physical and cognitive perspectives [91–93]. This helps to facilitate a resilient workplace in which the environment adaptability can be improved in varied conditions [92].

In addition, Industry 5.0 emphasizes human-centricity through the use of technologies and hardware to improve and support the operators' performance in logistics systems and supply chain operations. In this regard, human wearable devices that boost cognitive and operational capacities are increasingly being utilized and improved in manufacturing industries [93]. Exoskeleton refers to augments equipment that gives extra strength and physical capabilities to protect the operator from the adverse effects of heavy workloads [94–97]. Benefiting from virtual technologies, i.e., smart AR glass, spatial AR projector, etc., are viable and novel gadgets that facilitate flexible operations and technical guidance through information transmission and virtualization [70].

Moreover, the latest improvements in unmanned aerial vehicles (UAVs) have radically altered the intralogistics and material handling systems in a highly novel manner, and this additionally represents significant potential for personalized delivery systems [56,98,99]. Furthermore, Auto Identification (Auto-ID) and RFID have been extensively investigated in smart logistics and supply chains, which support traceability, warehouse operations, and inventory management [78,100].

6.2.3. Intelligent Systems

The systematic approach of Industry 5.0 requires information transmission for individualized and case-based tasks in the production system and enhanced interaction with better decision-making processes throughout the whole supply chain [101–105]. This characteristic urges improved data and information exchange among different stakeholders, which largely affects the agility and intelligence of a smart logistics system. This aim can be realized by a network of data interoperability, where sensors exchange and process information in a big data environment [3,56,106–109]. In the context of Industry 5.0, a Smart Cyber–Physical System (SCPS) can be established for promoting data transmission and the sustainability of production and logistics systems [110,111]. This digital transformation, however, must be energy-efficient by taking into account green procedures, i.e., green production, green recycling/disposal, green IoT (G-IoT), etc., to facilitate a lean circular economy (CE) [112,113].

A digital transition to Industry 5.0 and Society 5.0 triggers the development of blockchain computing [34,114–118]. In addition, it benefits the supply chain by enabling demand customization and personalization through recommender systems, which capture customers' preferences using social networks, text recognition, and analytical techniques [119]. Benefiting from internet-based connectivity, the transparency of information and manufacturing traceability can be drastically enhanced [56,78]. Real-time decision-making and high-quality visualization form the foundation of a virtual smart logistics

system in Industry 5.0 [120], which facilitates the emergence of the smart digital twin for logistics systems [3,108,121–123].

6.2.4. Intelligent Materials

One of the revolutionary improvements in Industry 5.0 is the development of smart materials. The characteristics of these new materials may significantly impact the supply chain activities by serving multiple functionalities and capabilities under certain conditions. For example, manipulating the shape and properties of the material and/or product according to varying physical conditions, e.g., temperature, light, stress, etc. [123–126]. The primary implication is related to additive manufacturing, where the 4D printing method strongly benefits from smart materials [36]. Compared with traditional 3D printing, 4D printing employs similar technology that fabricates parts and components through the layer-wise adhesion of a corresponding material. However, the major difference lies in the material type [124,125,127,128]. By using smart materials, the products can maintain various shapes and functionalities according to the environmental condition to improve the durability, adaptability, and reliability of the product. Various examples exist in medical science, aerospace, semiconductors, etc.

6.3. Discussions and Research Agenda

6.3.1. Analysis of Enabling Technologies

Industry 4.0 has proposed a technology-driven evolution during the last decade, with a major focus on network connectivity, intelligence, and automation. However, the autonomous attribute of this industrial revolution disregards the role of humans in the operation loops, and thus, the new concept of Industry 5.0 is developed to use the technology in favor of humans, not as a substitute. According to the established automation level and massive utilization of industrial robots in manufacturing plants, human–machine/robot collaboration offers the best potential to approach this goal. The human and robot symbiosis, however, triggers various technological, operational, and strategical challenges that require particular attention from both industrial practitioners and academia to achieve a lean collaboration. Furthermore, Industry 5.0 embraces new technologies and platforms that facilitate the achievement of socio-economic and environmental objectives. In this regard, through the analysis of the literature related to smart logistics in Industry 5.0, we have summarized the most extensively focused enabling technologies in Figure 8 and Table A1 (Appendix A).

As shown, artificial intelligence has shown remarkable viability, being addressed in 59% of the research. This innovative solution with broad applicability, i.e., human–robot collaboration, Society 5.0, etc., is one of the most promising technologies that successfully fulfills the socio-economic requirements of Industry 5.0 within the context of smart logistics. Given the human-centricity attribute of Industry 5.0 and the significance of the interaction between humans and machines/robots, 49% of the research has highlighted the advantages of cobots, which are unarguably the main technological driver in this regard. Although operators are empowered by a variety of new tools and equipment, cobots facilitate a resilient and sustainable logistics system. To improve the utilization of cobots, 24% of articles argue the importance of sensor technologies that not only favor better and safer human–robot collaboration but also improve the connectivity and intelligence of intralogistics and supply chain operations. Moreover, machine learning and deep learning methods (maintaining 16% of research activities) are emphasized methods to increase the intelligence and cognition level of either humans or cobots as well as the entire logistics system. To account for the sustainability and human-centricity features, biotechnologies have been studied in 14% of articles. This category of technologies is enriched by machine/deep learning methods for better utility and applicability. It is noteworthy that smart materials are also included in this category. Additive manufacturing and mobile transportation are the least discussed topics. Given 8% and 5% for AM and UAV/AGV, respectively, there is

a lack of attention from scholars to these categories considering their potential impact on smart logistics in Industry 5.0.

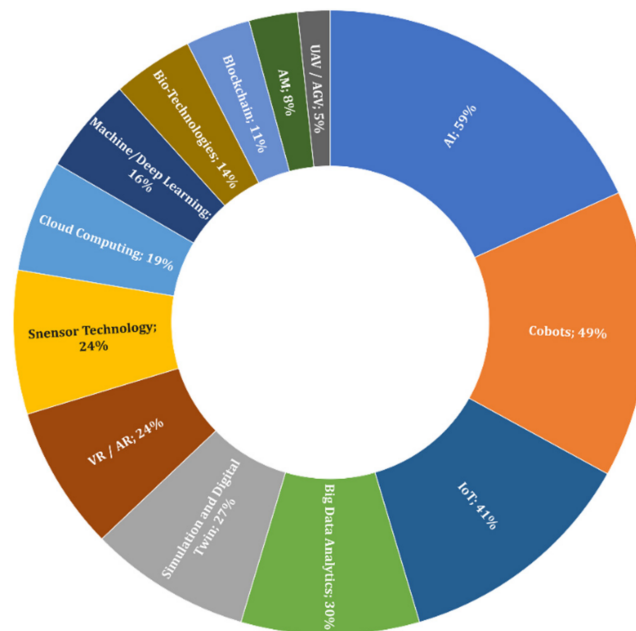


Figure 8. Supporting technologies in smart logistics of Industry 5.0.

IoT, big data analytics, and cloud computing, which are the most important Industry 4.0-enabling technologies, have drawn academia's attention by 41%, 30%, and 19%, respectively, which implies the significance of the digital transition in the fifth industrial revolution. These components, which are widely discussed in various topics, i.e., operator 5.0, society 5.0, and so forth, not only establish connectivity and intelligence but also improve the information transparency throughout different actors in a logistics system. In addition, blockchain is discussed in 11% of the research, which has a notable role in achieving socio-economic goals. Given this digital transition, smart logistics operations have shown a strong connection with virtual technologies in recent years, where 51%, 27%, and 24% of research highlights the role of simulation, digital twin, and virtual reality and augmented reality, respectively.

6.3.2. Similarities and Differences between Industry 4.0 and Industry 5.0 for Smart Logistics

Industry 5.0 is still in its infancy and under both conceptual and methodological developments by practitioners and the research community. From the conceptual development perspective, Industry 5.0 is not considered a radical technological revolution from Industry 4.0 but essentially shifts the focus from technology to the development of human and society driven by new technologies. Thus, it can be seen that Industry 4.0 technologies are still the most important technological enablers for smart logistics in Industry 5.0. For example, IoT, AI, big data analytics, simulation, and digital twin are still the focus of smart logistics transformation.

However, there are significant differences between Industry 4.0 and Industry 5.0 in their core focuses. Given human-centricity, resilience, and sustainability as the main drivers of Industry 5.0, the transition in logistics, which is a labor-intensive sector, toward a more harmonious balance among economic, environmental, and societal sustainability is crucial. For example, the focus of the smart logistics transformation in Industry 4.0 is to replace human operators and improve productivity through the adoption of new technologies. However, in Industry 5.0, the balance is shifted to human and environmental sides, and new technologies are used not to replace the human operators but to support their operations in a more effective way to better achieve highly personalized products and services. In this regard, many logistics providers are undergoing a smart transformation of Industry 4.0,

but this smart transformation should not be hindered but be repurposed to achieve better cohesion among economic, environmental, and societal sustainability in Industry 5.0.

6.3.3. Research Agenda

The following directions are raised to inspire further research of smart logistics in Industry 5.0.

- *Smart and sustainable logistics network design.* Logistics network design is one of the most important strategic decisions. The human-centric and technology-driven paradigm shift will largely affect the smart logistics operations in Industry 5.0; however, this leads to more challenges in strategic logistics network design to accommodate these configurational and operational changes within the whole planning horizon. Thus, research focus needs to be given to smart and sustainable logistics network design considering both human and technological factors in Industry 5.0.
- *Mobile transportation.* Intralogistics operations and material handling systems are some of the most significant challenges related to manufacturing logistics, which significantly impact the system's flexibility and agility. In this regard, smart mobile transportation means, i.e., UAVs, AGVs, have shown significant capabilities with intelligence and connectivity utilities. These pave the way for a smart collaboration with the operator, which not only satisfies the resilience goal but also takes human centrality into account. Given the least attention from the literature, it is of significance to devote more effort in this direction.
- *Additive manufacturing.* Due to its high adaptability and flexibility, additive manufacturing would significantly influence the sustainable supply chain and logistics operations compared with other techniques in Industry 5.0. Various logistics operations and supply chain activities can benefit. For example, in warehouse management, digital inventories of a large variety of products with low and irregular demands can be held with the help of additive manufacturing, which reduces both costs and environmental impacts. Thus, research attention needs to be given to AM in smart logistics of Industry 5.0 to improve both economic and environmental performance while maintaining a high service level.
- *Intelligent materials and supply chain.* Biotechnologies and intelligent materials are among the primary technologies for Industry 5.0. Given its low rate of attention from scholars, it is of significance to invest more research effort in this direction. In addition, it is highly beneficial to study the impact of intelligent material on smart and sustainable logistics systems, i.e., green logistics, reverse logistics, circular economy, etc.
- *Warehouse and inventory operations.* Although plenty of technological discussions exist within the context of manufacturing industries, some other logistics activities are neglected in the agenda. Warehouse and inventory operations could be investigated from various aspects considering both new technologies and human-centric operations—for instance, the use of virtual technologies to improve the information transparency and cognitive skills of warehousing or inventory activities. In addition, innovative human–robot solutions along with advances in sensing technologies potentially serve as valuable topics to be studied further in this context.
- *Human-centric manufacturing and logistics.* On the one hand, the human operator, supported by technologies, is the most important element in an Industry 5.0-enabled manufacturing and logistics system. On the other hand, the diversified human demands drive the way of technological breakthroughs and paradigm changes in manufacturing and logistics. Hence, it is substantially important to understand the interplay between humans and technologies in the transition by, for example, studying the impact of cobots and other human-centric technologies on manufacturing and logistics.
- *Smart logistics solutions for unexpected events and disasters.* Recently, the world witnessed several catastrophic events and humanitarian disasters, e.g., the COVID-19 pandemic, the war between Russia and Ukraine, etc., which require more smart and responsive logistics solutions. For example, satisfying the rapidly increasing demand for personal

protective equipment (PPE) [129] and properly dealing with infectious medical waste are among the most critical logistics challenges during the pandemic [130]. In this regard, Industry 5.0 may play an important role by providing innovative solutions through autonomous logistics solutions, human–robot collaboration, etc. Thus, future research in this direction is suggested.

It is worthwhile to mention that the above list is not a binding research agenda according to the structure of Industry 5.0; however, it seeks to highlight the most important topics in the context of smart logistics. In addition, the identified research agenda does not neutralize the significance of other technological drivers that have been extensively discussed in the literature. For instance, simulation and digital twin are inevitable parts of Industry 5.0, facilitating digital transmission.

7. Conclusions

Based on the technological breakthroughs in Industry 4.0, the emerging concept of Industry 5.0 has put forward the research frontier from technology-driven to human- and society-driven paradigm changes that will potentially and drastically influence many industries. Embedding human-centricity, resilience, and sustainability in smart logistics requires a rethinking and reconsideration of the technology matches, and in this regard, the role of the human in the technological transition needs to be predominantly focused on to ensure sustainable development in economic, environmental, and societal dimensions. To understand the implications of the coming Industry 5.0 for smart logistics, this paper presents a comprehensive analysis of the existing literature with both quantitative and qualitative methods.

We sought to answer the following research questions:

- *RQ1*: We conduct a comparative bibliometric analysis to thoroughly present the connection and differences in smart logistics between industry 4.0 and Industry 5.0.
- *RQ2*: We thoroughly evaluate the characteristics and key enabling technologies of smart logistics in Industry 5.0.
- *RQ3*: We propose a research agenda with seven directions to inspire future research on smart logistics in Industry 5.0.

The results show that smart logistics in Industry 5.0 is deeply rooted and benefited from the technological breakthroughs in Industry 4.0. However, in Industry 5.0, more emphasis has been given to the human side, with increasing research that focuses on human–machine systems, collaborative robots, and human–robot collaboration. Moreover, besides manufacturing journals, research related to smart logistics in Industry 5.0 is also published by inter-disciplinary journals that focus on the interplay among technology, society, and sustainability. Through a detailed content analysis, it is shown that IoT, cobots, and AI are the most investigated Industry 5.0 technologies in smart logistics. Finally, a research agenda is given to guide and inspire future research.

The paper has three limitations related to the sample selection. First, Industry 5.0 is a new and rapidly developing concept, so the papers presented in this review are restricted by the time of the literature search, and some important papers published after 2022 are not included. Second, some papers may be published in another language, so they are excluded from this review, but these papers may also present important information for smart logistics in Industry 5.0. Third, only the peer-reviewed papers published in scientific journals and conferences are focused on in this research, but, as an emerging topic, many studies may be published in other forms or may still be in the review process, so they are not included in the analysis of this paper. Thus, the results of this literature review are not exhaustive and are affected by these limitations.

Table A1. Cont.

Author [Ref. No]	AI ^a	Cobot	Sim. and DT ^b	Sensor Tech	Cloud. Comp ^c	Big Data	ML/DL ^d	VR/AR ^e	UAV/AGV ^f	Bio-Tech.	IoT	AM ^g	Block. ^h
Golov, Palamarchuk [111]	✓		✓		✓								
Resende, Cerqueira [71]		✓											
Ávila-Gutiérrez, Aguayo-González [92]	✓			✓			✓				✓		
Doyle-Kent and Kopacek [80]		✓											
Bathla, Singh [119]	✓					✓						✓	
Romero and Stahre [70]	✓	✓				✓	✓	✓		✓			
Jabrane and Bousmah [81]	✓	✓				✓	✓						
Fraga-Lamas, Varela-Barbeito [100]			✓	✓							✓		
Fornasiero and Zangiacomi [78]				✓				✓			✓		
Carayannis, Dezi [59]						✓					✓		
Carayannis, Christodoulou [117]	✓										✓		✓
Hol [73]	✓	✓						✓	✓			✓	
Doyle Kent and Kopacek [79]													
Longo, Padovano [93]		✓						✓					
Doyle-Kent and Kopacek [31]		✓				✓							
Martynov, Shiryaev [57]	✓												
Martynov, Shavaleeva [53]	✓					✓					✓		
Mihardjo, Sasmoko [58]											✓		
Welfare, Hallowell [72]		✓											
Rahman, Muda [118]	✓				✓	✓					✓		✓

a. Artificial Intelligence. b. Simulation and Digital Twin. c. Cloud Computing. d. Machine Learning/Deep Learning. e. Virtual Reality/Augmented Reality. f. Unmanned Aerial Vehicle/Automated Guided Vehicle. g. Additive Manufacturing. h. Blockchain Technology.

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