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Review

Assessment of Industry 4.0 for Modern Manufacturing Ecosystem: A Systematic Survey of Surveys

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Abstract: The rise of the fourth industrial revolution aspires to digitize any traditional manufacturing process, paving the way for new organisation schemes and management principles that affect business models, the environment, and services across the entire value chain. During the last two decades, the generated advancements have been analysed and discussed from a bunch of technological and business perspectives gleaned from a variety of academic journals. With the aim to identify the digital footprint of Industry 4.0 in the current manufacturing ecosystem, a systematic literature survey of surveys is conducted here, based on survey academic articles that cover the current state-of-the-art. The 59 selected high-impact survey manuscripts are analysed using PRISMA principles and categorized according to their technologies under analysis and impact, providing valuable insights for the research and business community. Specifically, the influence Industry 4.0 exerts on traditional business models, small and medium-sized enterprises, decision-making processes, human–machine interaction, and circularity affairs are investigated and brought out, while research gaps, business opportunities, and their relevance to Industry 5.0 principles are pointed out.

Keywords: Industry 4.0; SME; digital footprint; business model; survey of surveys

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1. Introduction

At the turn of the 21st Century, a revolutionary trend was inaugurated that digitized production processes and transformed the business world. This trend triggered the onset of the fourth industrial revolution, impacting the entire production life cycle, from first-tier production and business organization to recycling processes. The "Industrie 4.0" (I4.0) initiative, coined by the German Ministry of Education and Research and presented at the Hanover Fair in 2011, constitutes a flagship concept that promotes factory digitalization and supply chain interconnection [1]. These ideas, presented in what some consider the most established German initiative, cascaded other relevant approaches around the globe, namely Smart Manufacturing, Factories 4.0, Industrial Internet, Manufacturing 3.0, and Made-in-China 2025 [2]. These ground-breaking endeavours contributed to the development of cutting-edge technologies in both the industrial sector area and major industries such as construction [3] and medical [4].

The impact of the fourth industrial revolution is reflected in the fusion of cutting-edge technologies that directly affect the operations and functions of industries. Billions of interconnected intelligent devices, edge processing power, smart storage services, self-adaptable sliced networks, and knowledge transfer platforms offer an unprecedented spread of innovation and multi-disciplinary implementation [5]. Published research and best practice reports have shown that I4.0 offers the potential to provide zero-fault production and controlled environments, as facilities and infrastructures have become more and more digitized without technological silos [6]. These advancements and increased flexibility have turned existing challenges into valuable opportunities that support the digital transition. On the other hand, innovations such as re-configurable manufacturing systems (RMSs) aim to enhance the factory's response to fluctuating markets and enable speedy and cost-effective competition in dynamic market environments [7]. During this change, in addition to the technological challenges of interoperability and compatibility issues, knowledge challenges have also arisen from organizational assemblies, such as the reluctance of manufacturers to adopt I4.0 solutions or the suitability of those in traditional business models [8–11].

The advancements and innovation provided by I4.0 should attract the attention of industrialists and decision-makers, as rapid changes are also expected to affect obsolete business and management models, based on real-time data and analysis, derived from the manufacturing facilities and the product's life cycle [12,13]. In every management stage, the decision-making process becomes more challenging, due to an abundance of available information. Note that the information validity process stands as a critical hurdle in corporate C-suite decisions, when inaccurate data can contribute to unprofitable strategic plans, costing appreciable amounts of money. As the technological dependencies of I4.0 are adopted in decision-making processes by large enterprises, business leaders can strengthen their strategies and increase their profit [14]. On a smaller scale, dominated by small and medium-sized enterprises (SMEs), data-based decisions lead to rapid tech-savvy solutions, accelerating the digital transformation and ensuring power supply safety within the factory [15], such that small and big businesses have equal opportunities to remain competitive in the global market [16].

Since the first industrial revolution, manufacturers have been challenged to produce more and more goods to meet the ever-increasing demands, initially adopting mass production techniques, while most recently, lean production schemes. As we move forward into the fourth industrial revolution, the smart factory concept has become a reality, which utilizes technologies (e.g., Industrial Internet of Things (IIoT), machine vision, digital twins) to enable holistic visibility of operations and production flexibility [14]. Fully automated facilities, machines, and material flow, within the manufacturing area, are managed by intelligent networks and smart execution systems, as a result of data exchange among all elements and intelligent functions [17]. Although a significant reduction in human intervention is to be anticipated, human–machine collaboration technologies provide the common "integration point" between workers and machines, thereby harmonizing a smooth interaction while enabling effective collaboration [18].

This new era has metamorphosed the conventional supply chain ecosystem, where stakeholders have traditionally reported to sales departments to inquire about factory supplies or customers' deliveries, into a digitally independent supply chain network, providing horizontally integrated operations between customers and suppliers [19]. Advanced planning processes and (semi-)autonomous vehicles, empowered by technological pillars (5G, big data, cloud and edge computing, IIoT, blockchain), provide intelligence and real-time traceability within the supply chain network, while adaptability, speed, and service quality are maintained [20]. As the supply chain network grows, the personalised product availability is increased, creating the need for sustainable supply chains. The key link between them is provided by the circular economy policies that have been advanced through the Industry 4.0 ecosystem [21]. The closed circular loop model and industrial symbiosis platforms are central components of I4.0 and drive the *Fifth Industrial Revolution* (Industry 5.0) [22], in which end-of-life products, scraps, or by-products are recycled to be used as raw materials in the same (or different) manufacturing processes, thereby extending a product's life cycle and reducing waste mass that is harmful for the environment [23].

Generally, the major purpose of modern manufacturing is to speed production and related industries, such as logistics, while creating new business opportunities and models by going beyond automation and optimization, taking also into account sustainability and human centring aspects. Even established sectors are expected to shift their focus from products to services for their enterprises' success [24]. For example, the growth of advanced technologies immediately fostered the buildup of subsidiary R&D capabilities, since it raised the complexity of processing processes and led to the emergence of new technological issues [25] or the employment of re-configurable ways in first-tier materials, enhanced diagnostics, and cyber–physical manufacturing systems, improving the overall design and operation of modern manufacturing [7].

Although an increasing number of surveys have been conducted on the aforementioned topics resulting in finding silos, surveys to provide multidimensional evidence are missing. Specifically, a substantial number of existing surveys examine the gaps the characteristics of I4.0 exhibit, while other surveys deal with the implementation of the fourth industrial revolution in SMEs. However, these implementation surveys miss considering the above-mentioned characteristics in conjunction with the human element, as well as with a series of critical concepts, namely sustainability, the circular economy, and supply chains. Missing such a multifaceted approach, there is no other survey in the current literature that can provide answers to the reader about how to:

- Investigate the influence in existing business models of SMEs;
- Identify the decision-making procedures within the manufacturing ecosystem;
- Clarify the interaction between humans and machines;
- Offer circularity-based insights to the stakeholders;
- Provide multidisciplinary results from existing surveys.

Having said that, it is acknowledged that there are several studies on these topics, yet a pivotal objective of the paper in hand is to strengthen the existing literature by providing answers to research questions using a fundamental systematic literature review (SLR) technique.

In an attempt to facilitate and accelerate this process, this manuscript aims to highlight the contribution of I4.0 in traditional manufacturing and smart factory schemes, by investigating high-impact journal literature. Specifically, a systemic survey of surveys' methodology [26] has been conducted to provide decision-makers and researchers in manufacturing brief insights from current systematic studies, summarising existing research or highlighting the gaps, while the PRISMA protocol has been followed [27]. By presenting and analysing the existing literature, this paper strives to offer a comprehensive compilation of relevant data that will empower both the research and business communities. This manuscript will provide insightful I4.0 knowledge, in terms of circularity, business model adaptability, and factory intelligence, for entrepreneurs and policymakers. Considering this unique opportunity to clarify the relation between the aforementioned concepts, we are attempting to answer the following research questions (*RQs*):

RQ1: How will Industry 4.0 adoption challenge traditional business models?
RQ2: Can the existing Industry 4.0 business models be applied in SMEs?
RQ3: What is the role of decision-making in Industry 4.0?
RQ4: What is the role of human–machine interaction in Industry 4.0?
RQ5: How are the circular economy, the smart factory, and the supply chain concepts connected under the framework of Industry 4.0?

The remainder of this paper is structured as follows. In Section 2, we present the SLR methodology followed to shape the paper in hand. Consequently, Section 3 contains the identified fields under discussion and the journals where the selected survey articles were published. In the following Section 4, the findings of our SLR are discussed, while in Section 5, we summarize our findings and draw conclusions.

2. Systematic Literature Review

One of the main advantages of systematic reviews over other types of literature analysis approaches is that explicit, systematic methods are utilised in order to minimize bias and provide reliable findings, from which conclusions can be drawn. In particular, a systematic review attempts to collate all empirical evidence that fits pre-specified eligibility criteria to answer specific research questions [28].

The main purpose of this manuscript is to investigate Scopus survey articles that have been reported on I4.0 between 2014 and 2022. Following the survey of surveys methodology, we intend to summarize and describe survey publications that primarily focus on key factors that should be adhered to by the modern industrial environment. There are different terms for "survey of surveys" in the literature such as overview of reviews, review of reviews, umbrella reviews, synthesis of reviews, and others, which synthesise data that are generated by other systematic reviews [28]. Furthermore, in order to build a knowledge database capable of easily locating, synthesizing, and summarizing data points, we utilized the SLR methodology based on the PRISMA protocol. SLR is considered a trustworthy tool that ensures the quality and quantity of the data being under analysis. The reliability and transparency of the SLR process are guaranteed by applying the widely accepted, five-stage methodology [29], as presented in Figure 1.

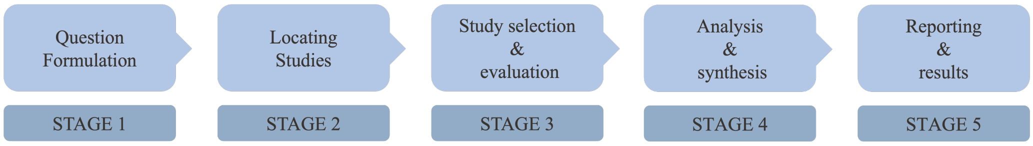

Figure 1. The figure illustrates the five sequence stages of the systematic literature review process, in which five connected blocks represent the research determination, the location of studies, the study selection and evaluation, the analysis, and the conclusion report [29].

2.1. Question Formulation

In the first stage, the scope of the literature review is defined and research questions are formulated. This manuscript explores how trending research fields are expected to affect the manufacturing I4.0 ecosystem. Consequently, the research questions were used to analyse the current technological stage, by comparing the challenges with the impact, in order to provide structured knowledge, in terms of business model adaptability, factory intelligence, human–machine interaction, and circularity.

2.2. Locating Studies

As a second step, with respect to the academic literature, a search was performed on review titles and abstracts, to gather the required publications. In order to answer the research questions with data from high-quality publications, Scopus® was used. This database includes over 34,000 peer-reviewed journals in top-level subject fields. During the collection of the publications, we selected the simple term *"Industr* 4.0 AND (Review OR Survey)"*, aiming to collect review papers that provide a mainstream overview of I4.0 and do not concentrate on highly technical topics. The research protocol and the selection criteria are presented in Table 1.

Table 1. Summary of the literature search protocol including inclusion and exclusion criteria.

Research Protocol	Details Description
Research databases	Scopus®
Publication type	Peer-reviewed papers (indexed by Scopus®)
Language	Only papers in English
Time period	2014–2022
Search field	Title and Abstract
Search term	*Industr* 4.0 AND (Review OR Survey)*
Criteria for inclusion (SC)	Articles exclusively referred to Industry 4.0
Criteria for exclusion	Articles not referring to Industry 4.0
"	Articles using Industry 4.0 as a supportive concept
"	Conference proceeding papers
"	Non-English text

2.3. Study Selection and Evaluation

The following stage involved the selection and evaluation of the collected papers. To ensure the dependable evaluation of the survey articles, inclusion and exclusion criteria were applied to exclude the ones not being relevant for our analysis or of low scientific quality. The specific criteria are described in Table 1. Surveys that did not focus on the fourth industrial revolution specifically or referred to it as future research were excluded as well. The criteria also led to the exclusion of articles that did not address technological pillars, enablers, or concepts and did not provide innovative knowledge to readers, as presented in Figure 2.

Especially, during the abstract analysis, attention is placed on identifying surveys that are focused on the basic concepts of Industry 4.0, but not on specific technology enablers. This approach aided our study by highlighting crucial information and technologies that are widely referredto in surveys. Our SLR criteria yielded a total of 511 survey articles published between January 2014 and July 2022. After the first screening of the titles, 127 papers were excluded as referring to other domains (such as Construction 4.0 [30] and Health 4.0 [31] initiatives, among others). As a next step, we utilised our university's network to discover the accessible manuscripts, except the public ones, excluding the 45 manuscripts that we were unable to locate. After applying the exclusion criteria, articles that did not pertain to Industry 4.0 exclusively, were not peer-reviewed, or were not written in English were also eliminated. Finally, 59 academic literature publications were selected for analysis. A graphical representation of the review process based on the PRISMA methodology is shown in Figure 2.

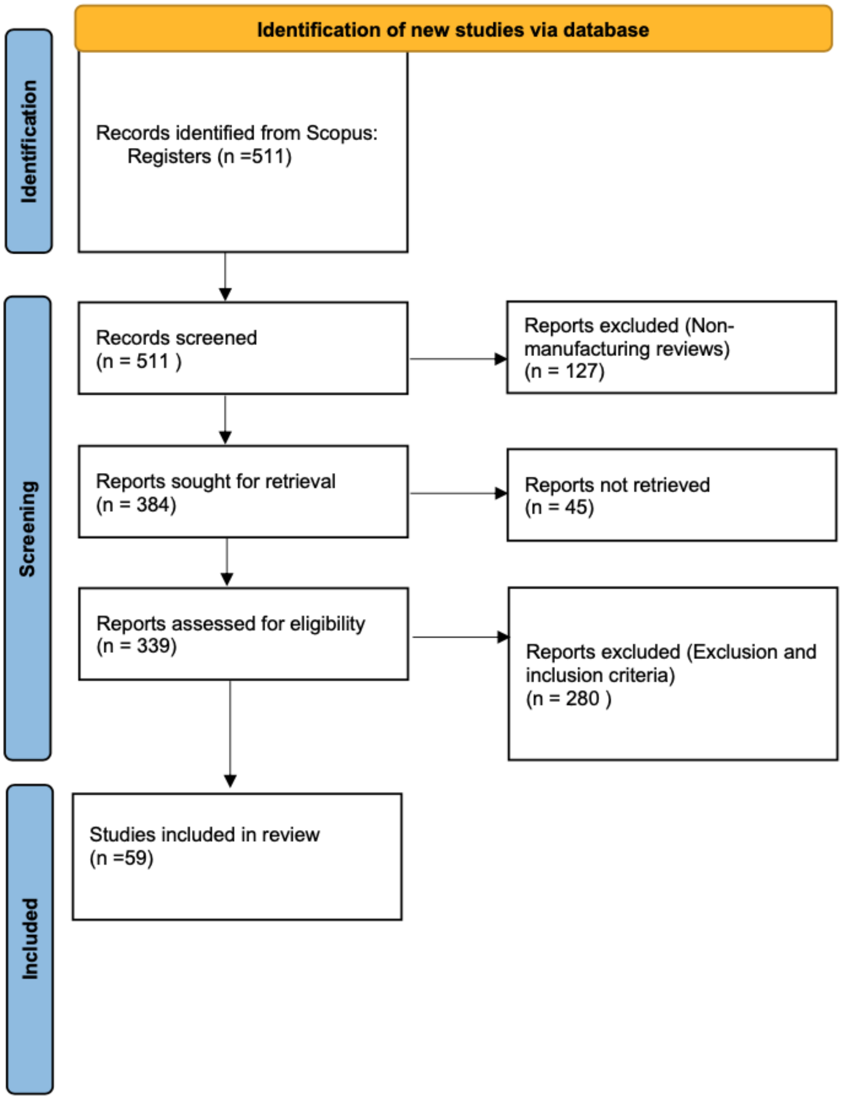

Figure 2. The figure shows different blocks being connected of the PRISMA methodology and represents how articles are decreased at each stage of the SLR process, selecting 59 out of 511 survey articles [27,32].

2.4. Analysis and Synthesis

In the data analysis and synthesis stage, the publications' content should be presented according to PRISMA in a way that answers the formulated research questions. In this paper, we firstly identified the key enablers and concepts of I4.0 that are totally related to the formulated question, as described in Section 3.1, and then identified the presence of these enablers in each analysed article, as shown in Table 4. The first high-level analysis proved the most famous technologies and concepts within the examined surveys. After that, in order to extract information regarding the research journal trends, we structured the selected survey articles into categories according to the thematic region and their occurrence (Table 3). In addition, the statistics of the publication dates were extracted, to identify the trend in which researchers tend to publish I4.0-related research according to our research questions.

2.5. Reporting and Using the Results

Thereafter, the results were categorized and discussed in the context of *traditional business models* (Section 4.1), *SMEs* (Section 4.2), *decision-making* (Section 4.3), *human–machine interaction* (Section 4.4), and *circularity* (Section 4.5). The aforementioned sections answer the research questions based on the identified key enablers and provide strong research guidance for researchers and entrepreneurs. These opportunities and suggestions are further described below in Section *Findings* (Section 4.6), specifically as it pertains to research and business opportunities, as well as the relevance to Industry 5.0 principles. In this manuscript, the occurrence of the fields under investigation is collocated in Table 2, while relationships between the survey articles and the fields are described in Table 4.

Table 2. Distribution of concepts and technologies obtained by survey articles.

Field	Number	Occurrence	Reference
Advanced Manufacturing Systems	26	44.83%	[5,8,10,14,33–54]
Artificial Intelligence	24	41.38%	[5,8,14,34,35,38–40,46,47,49,52,54–65]
Sustainability	20	34.48%	[10,37,43,45,48,59,61–74]
Challenges	16	27.59%	[8,11,14,39,47,48,50,51,60–62,65,66,75–77]
Impact	15	25.86%	[11,13,39,42,47,49,60,61,64–67,75,76,78]
Supply Chain	15	25.86%	[14,34,52,58,61–66,70,74–77]
SME	13	22.41%	[11,13,14,46,49,50,56,62,70,76,79–81]
Circularity	10	17.24%	[37,48,50,52,57,59,63,64,72,78]
Business model	10	17.24%	[11–13,34,37,53,76,80–82]
Decision Making	9	15.52%	[10,11,46,49,63,65,66,80,83]
Human-machine Collaboration	7	12.07%	[35,38,43,49,60,61,78]
Maturity	3	5.17%	[56,62,79]

3. Results

This section provides an overview of the most common areas identified in the selected publications, as well as an inspection of the journals in which researchers tend to publish I4.0-related research.

3.1. Research Field

During the full corpus investigation phase, several aspects affecting I4.0 adoption were encountered. We decided to use these as categories, around which we could structure our literature analysis, by investigating the impact of each category in I4.0. In order to cluster different aspects, we organized the key information in a contextual database, as presented in Table 4, while the survey articles were sorted by publishing date. The database contains technologies and concepts selected according to their direct or indirect reference to, and their importance in, the fourth industrial revolution, while a short description of their contribution is as follows:

- **Advanced manufacturing systems:** These survey articles promote cutting-edge technologies facilely adaptable to factory facilities, bringing about a broader transformation in operations and enterprises.

- **Artificial intelligence:** These survey articles address applications and scenarios influenced by digital transformation, as well as traditional concepts enhanced by artificial intelligence, which act as enablers for smart factories, products, networks, and production.
- **Industry 4.0 impact:** The survey articles falling into this field include analyses and conclusions concerning the positive or negative impact of the fourth industrial revolution in sectors such as business, supply chains, and management.
- **Sustainability:** These survey articles describe the concept and implementation procedure frameworks of sustainability, highlighting the benefits, value, and importance of the I4.0 ecosystem.
- **Human–machine collaboration:** The survey papers of this category discuss developments and applications that enhance human–machine collaborations in the I4.0 era, including Research and Development (R&D) and safety aspects.
- **Circularity:** These are survey articles that mention the concept and the transition of the circular economy in horizontal and vertical planes, as well as methodologies and techniques in the context of I4.0.
- **Business model:** The updated business models generated by the ongoing industrial transition, as well as their impact on the traditional models and the operations of the worldwide markets are mentioned in this cluster of survey articles.
- **Challenges:** The updated business models generated by the ongoing industrial transition, as well as their impact on the traditional models and the operations of the worldwide markets are mentioned in these survey articles.
- **Supply chain:** These survey articles analyse the role of the supply chain within the frame of I4.0, as well as the effect, challenges, and characteristics of the interconnected network.
- **Small and medium-sized enterprises:** The survey articles in this field include information about the current factory level and the requirements for their transition to the I4.0 ecosystem.
- **Decision-making:** These survey articles analyse how the data-driven, decision-making processes empower the strategic and management policies and drive the innovation research communities in the digital factories.
- **Maturity models:** These survey articles discuss innovative and upcoming maturity models, influenced by the context of smart manufacturing and factory of the future concepts.

The aforementioned topics constitute the smart factory and the level of their adoption should be considered in order to advise researchers and entrepreneurs. As the academic community can discover the research gaps through this manuscript, innovative business personnel are informed by the analysis of the value and opportunities provided by the aforesaid topics. Table 2 provides a summarised view of the examined survey articles regarding the aforementioned topics' occurrence in their full corpus, while the published journals and the detailed analysis is presented in Tables 3 and 4 accordingly.It is important to note that each topic was discussed in more than one survey article, with some topics being addressed more frequently than others. Therefore, Table 2 is sorted by topic, in descending order of occurrence and visualised in Figure 3.

From a high-level analysis viewpoint, we observed that advanced manufacturing systems and artificial intelligence technology were the fields appearing more often, as they are referred to in the biggest proportion of the selected papers in comparison to other concepts and technologies. Specifically, 15% of the papers included advanced manufacturing enablers, while artificial intelligence concepts appeared in 14% of the surveys. Discussions regarding the challenges and impact of I4.0, in terms of sustainability, circularity, human–machine collaboration, business models, etc., appeared to be less relevant. More specific, concepts such as maturity, human–machine collaboration, and decision-making were included in 2%, 4%, and 5% of the selected papers, respectively, while the frequency percentage of others such as business models, circularity, SMEs, supply chains, and impact was slightly increased at 6%, 6%, 8%, 9%, and 9%, respectively. Besides advanced manufacturing systems and artificial intelligence technology, only challenges and sustainability passed 10% in terms of frequency.

Table 3. This table includes the research areas of the journals and their occurrence.

Journal	Number	Research Area	Occurrence	Reference
Journal of Cleaner Production	6	Sustainable and environmental production	10.34%	[37,43,48,68,70,71]
Journal of Manufacturing Systems	5	Applied manufacturing system-based research	8.62%	[47,49,54,56,83]
International Journal of Production Research	4	Production ecosystem advancements	6.9%	[44,52,55,59]
Sustainability	4	Environmental, cultural, economic sustainability	6.9%	[65,67,72,73]
Applied Sciences	3	Applied natural sciences	5.17%	[14,69,79]
Journal of Manufacturing Technology Management	3	Digital operations management	5.17%	[12,57,62]
Benchmarking	2	Quality management	3.45%	[66,76]
Benchmarking: An International Journal	2	Operations and organization management	3.45%	[39,58]
Computers in Industry	2	Industrial ICT innovation and application	3.45%	[34,78]
Journal of Enterprise Information Management	2	Information systems	3.45%	[63,64]
Business Process Management Journal	1	Business process management	1.72%	[11]
Cogent Engineering	1	Engineering and technology	1.72%	[10]
Designs	1	Engineering design	1.72%	[41]
Economies	1	Economics, macroeconomics	1.72%	[13]
Electronics	1	Electronics advancements	1.72%	[46]
Electronics (Switzerland)	1	Science of electronics	1.72%	[80]
Engineering Science and Technology, an International Journal	1	R&D engineering advancements	1.72%	[40]
Enterprise Information Systems	1	Information systems and management	1.72%	[77]
Future Internet	1	Internet technologies	1.72%	[82]
IEEE Communications Surveys & Tutorials	1	Telecommunication research	1.72%	[38]
Industrial Robot	1	Industrial engineering, design, and manufacturing	1.72%	[60]
International Journal of Automation Technology	1	Engineering	1.72%	[35]
International Journal of Industrial and Systems Engineering	1	Industrial and systems engineering (ISE)	1.72%	[53]
International Journal of Precision Engineering	1	Green Technology aspects of precision engineering	1.72%	[61]
Journal of Engineering	1	R&D engineering advancements	1.72%	[42]
Journal of Industrial Information Integration	1	Industrial ICT innovation and application	1.72%	[8]
Journal of Industrial Integration and Management	1	Innovation and entrepreneurship	1.72%	[75]
Journal of Intelligent Manufacturing	1	Intelligent digital manufacturing	1.72%	[5]
Journal of Science and Technology Policy Management	1	Technology management/strategy	1.72%	[81]
Jurnal Teknologi	1	Industrial ICT innovation and application	1.72%	[33]
DAAAM International Vienna	1	Manufacturing	1.72%	[36]
Metals	1	Metallurgy engineering	1.72%	[45]
Supply Chain Forum: An International Journal	1	Supply chain management	1.72%	[74]
The International Journal of Advanced Manufacturing TecN.	1	Advanced manufacturing applications	1.72%	[50]
The Royal Society	1	Mathematical, physical, and engineering sciences	1.72%	[51]

Table 4. Overview of the review papers about Industry 4.0, while their impact on the identified concepts and technologies is marked. The acronyms AMS, AI, I, and S reflect Advance Manufacturing Systems, Artificial Intelligence, Impact, and Sustainability. The terms Sustainability Human Machine collaboration, Circularity, Business Model, and Challenges are described as S, HM, Ci, BM, and Ch. Lastly, the columns SC, SME, DM, and MM refer to the Supply Chain, Small–Medium Enterprises, Decision-Making, and Maturity Models.

Title	Year	AMS	AI	I	S	HM	Ci	BM	Ch	SC	SME	DM	MM
Industry 4.0: A review on industrial automation and robotic [33]	2016	yes	no	no	no	no	no	no	no	no	no	no	no
Understanding the implications of digitisation and automation in the context of Industry 4.0: A triangulation approach and elements of a research agenda for the construction industry [34]	2016	yes	yes	no	no	no	no	yes	no	yes	no	no	no
"Industrie 4.0" and Smart Manufacturing—A Review of Research Issues and Application Examples [35]	2017	yes	yes	no	no	yes	no	no	no	no	no	no	no
Industry 4.0: A survey on technologies, applications and open research issues. [8]	2017	yes	yes	no	no	no	no	no	yes	no	no	no	no
Past, present and future of Industry 4.0—a systematic literature review and research agenda proposal [55]	2017	no	yes	no	no	no	no	no	no	no	no	no	no
Industry 4.0 and supply chain sustainability: framework and future research directions [66]	2018	no	no	yes	yes	no	no	no	yes	yes	no	yes	no
A critical review of smart manufacturing & Industry 4.0 maturity models: Implications for small and medium-sized enterprises. [56]	2018	no	yes	no	no	no	no	no	no	no	yes	no	yes
Consequences of Industry 4.0 in Business and Economics [13]	2018	no	no	yes	no	no	no	yes	no	no	yes	no	no
Setting an Industry 4.0 research and development agenda for simulation-a literature review [36]	2018	yes	no	no	no	no	no	no	no	no	no	no	no
A review of emerging industry 4.0 technologies in remanufacturing [37]	2019	yes	no	no	yes	no	yes	yes	no	no	no	no	no
A Survey on Information and Communication Technologies for Industry 4.0: State-of-the-Art [38]	2019	yes	yes	no	no	yes	no	no	no	no	no	no	no
Exploring Industry 4.0 technologies to enable circular economy practices in a manufacturing context [57]	2019	no	yes	no	no	no	yes	no	no	no	no	no	no
Industry 4.0: Emerging themes and future research avenues using a text mining approach [78]	2019	no	no	yes	no	yes	yes	no	no	no	no	no	no
Industry 4.0: key findings and analysis from the literature arena. [39]	2019	yes	yes	yes	no	no	no	no	yes	no	no	no	no
Key ingredients for evaluating Industry 4.0 readiness for organizations: a literature review [58]	2019	no	yes	no	no	no	no	no	no	yes	no	no	no
Scanning the Industry 4.0: A Literature Review on Technologies for Manufacturing Systems [40]	2019	yes	yes	no	no	no	no	no	no	no	no	no	no
A review of research relevant to the emerging industry trends: Industry 4.0, IoT, blockchain, and business analytics [75]	2020	no	no	yes	no	no	no	no	yes	yes	no	no	no
A Strategic Roadmap for the Manufacturing Industry to Implement Industry 4.0 [41]	2020	yes	no	no	no	no	no	no	no	no	no	no	no
A survey on decision-making based on system reliability in the context of Industry 4.0 [83]	2020	no	no	no	no	no	no	no	no	no	no	yes	no
Analysis and synthesis of Industry 4.0 research landscape: Using latent semantic analysis approach [12]	2020	no	no	no	no	no	no	yes	no	no	no	no	no
Exponential Disruptive Technologies and the Required Skills of Industry 4.0 [42]	2020	yes	no	yes	no	no	no	no	no	no	no	no	no

Table 4. *Cont.*

Title	Year	AMS	AI	I	S	HM	Ci	BM	Ch	SC	SME	DM	MM
Impact of Industry 4.0 on Sustainability— Bibliometric Literature Review [67]	2020	no	no	yes	yes	no	no	no	no	no	no	no	no
Industry 4.0, digitization, and opportunities for sustainability [68]	2020	no	no	no	yes	no	no	no	no	no	no	no	no
Industry 4.0: How it is defined from a sociotechnical perspective and how much sustainability it includes-A literature review [43]	2020	yes	no	no	yes	yes	no	no	no	no	no	no	no
Literature review of Industry 4.0 and related technologies [5]	2020	yes	yes	no	no	no	no	no	no	no	no	no	no
Literature search of key factors for the development of generic and specific maturity models for Industry 4.0 [79]	2020	no	no	no	no	no	no	no	no	no	yes	no	yes
Production scheduling in the context of Industry 4.0: review and trends [44]	2020	yes	no	no	no	no	no	no	no	no	no	no	no
Supply chain integration and Industry 4.0: a systematic literature review [76]	2020	no	no	yes	no	no	no	yes	yes	yes	yes	no	no
Systematic Literature Review: Integration of Additive Manufacturing and Industry 4.0 [45]	2020	yes	no	no	yes	no	no	no	no	no	no	no	no
A review of data-driven decision-making methods for industry 4.0 maintenance applications [46]	2021	yes	yes	no	no	no	no	no	no	no	yes	yes	no
A Systematic Literature Review of Successful Implementation of Industry 4.0 Technologies in Companies: Synthesis of the IPSI Framework [69]	2021	no	no	no	yes	no	no	no	no	no	no	no	no
Big Data analytics in Smart Grids for renewable energy networks: Systematic review of information and communication technology tools [10]	2021	yes	no	no	yes	no	no	no	no	no	no	yes	no
Cyber-physical systems architectures for industrial internet of things applications in Industry 4.0: A literature review [47]	2021	yes	yes	yes	no	no	no	no	yes	no	no	no	no
Effective cloud resource utilisation in cloud ERP decision-making process for industry 4.0 in the united states [80]	2021	no	no	no	no	no	no	yes	no	no	yes	yes	no
Industry 4.0 and business models: a bibliometric literature review [11]	2021	no	no	yes	no	no	no	yes	yes	no	yes	yes	no
Industry 4.0 and sustainability: Towards conceptualization and theory Industry 4.0 and sustainable development: A systematic mapping of triple bottom line, Circular Economy and Sustainable Business Models perspectives [70]	2021	no	no	no	yes	no	no	no	no	yes	yes	no	no
Industry 4.0 smart reconfigurable manufacturing machines [49]	2021	yes	yes	yes	no	yes	no	no	no	no	yes	yes	no
Industry 4.0 technologies as enablers of collaboration in circular supply chains: a systematic literature review [59]	2021	no	yes	no	yes	no	yes	no	no	no	no	no	no
Industry 4.0 ten years on: A bibliometric and systematic review of concepts, sustainability value drivers, and success determinants [71]	2021	no	no	no	yes	no	no	no	no	no	no	no	no
Industry 4.0, transition or addition in SMEs? A systematic literature review on digitalization for deviation management [50]	2021	yes	no	no	no	no	yes	no	yes	no	yes	no	no

Table 4. *Cont.*

Title	Year	AMS	AI	I	S	HM	Ci	BM	Ch	SC	SME	DM	MM
Making smart manufacturing smarter—a survey on blockchain technology in Industry 4.0 [77]	2021	no	no	no	no	no	no	no	yes	yes	no	no	no
Six-gear roadmap towards the smart factory [14]	2021	yes	yes	no	no	no	no	no	yes	yes	yes	no	no
Stochastic model predictive control framework for resilient cyber–physical systems: Review and perspectives [51]	2021	yes	no	no	no	no	no	no	yes	no	no	no	no
The applications of Industry 4.0 technologies in manufacturing context: a systematic literature review [52]	2021	yes	yes	no	no	no	yes	no	no	yes	no	no	no
Towards a conceptual development of Industry 4.0, servitisation, and circular economy: A systematic literature review [72]	2021	no	no	no	yes	no	yes	no	no	no	no	no	no
Twin transition through the implementation of industry 4.0 technologies: Desk-research analysis and practical use cases in Europe [73]	2021	no	no	no	yes	no	no	no	no	no	no	no	no
Adopting open innovation for SMEs and industrial revolution 4.0 [81]	2022	no	no	no	no	no	no	yes	no	no	yes	no	no
An overview of Industry 4.0 in manufacturing industries [53]	2022	yes	no	no	no	no	no	yes	no	no	no	no	no
Augmented reality—an important aspect of Industry 4.0 [60]	2022	no	yes	yes	no	yes	no	no	yes	no	no	no	no
Business Models for the Internet of Services: State of the Art and Research Agenda [82]	2022	no	no	no	no	no	no	yes	no	no	no	no	no
Cyber-Physical Systems as an Enabler of Circular Economy to Achieve Sustainable Development Goals: A Comprehensive Review [61]	2022	no	yes	yes	yes	yes	no	no	yes	yes	no	no	no
Drivers and barriers of Industry 4.0 technology adoption among manufacturing SMEs: a systematic review and transformation roadmap [62]	2022	no	yes	no	yes	no	no	no	yes	yes	yes	no	yes
Integrating Industry 4.0 and circular economy: a review [63]	2022	no	yes	no	yes	no	yes	no	no	yes	no	yes	no
Mapping the links between Industry 4.0, circular economy and sustainability: a systematic literature review [64]	2022	no	yes	yes	yes	no	yes	no	no	yes	no	no	no
The Application of Industry 4.0 Technological Constituents for Sustainable Manufacturing: A Content-Centric Review [65]	2022	no	yes	yes	yes	no	no	no	yes	yes	no	yes	no
The individual and integrated impact of Blockchain and IoT on sustainable supply chains:a systematic review [74]	2022	no	no	no	yes	no	no	no	no	yes	no	no	no
Towards edge computing in intelligent manufacturing: Past, present and future [54]	2022	yes	yes	no	no	no	no	no	no	no	no	no	no

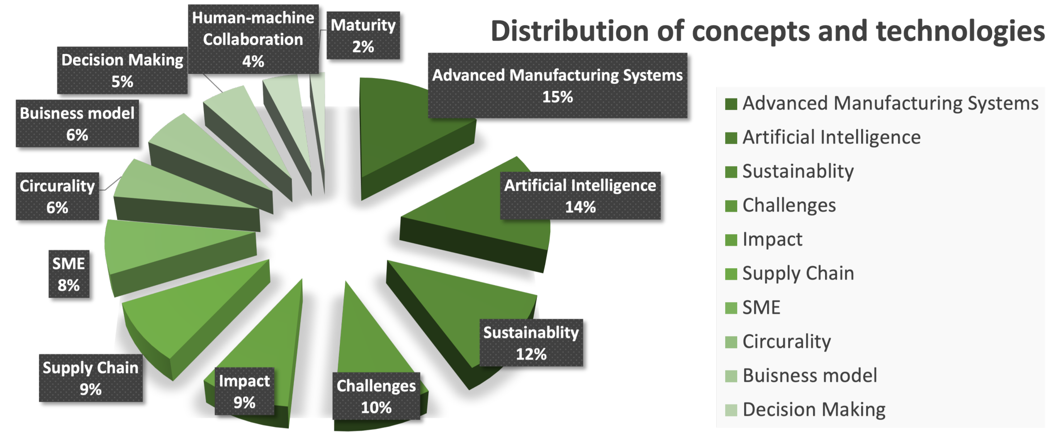

Figure 3. The figure presents the occurrence of the technologies and research fields within the 59 reviewed surveys.

This low percentage of survey articles is justified, as the aforementioned fields depend not only on the developments provided by advanced manufacturing technologies, but also on multi-disciplinary areas, such as financial and social sciences, which all need to be taken into consideration in order to extract accurate and valuable data. Lastly, our SLR confirms the trend towards the limited use of the I4.0 schema in the management of the factory and supply chain, as fields such as SMEs, decision-making, maturity models, and supply chains have not been well analysed, which resulted in the occurrence rates below 15%.

3.2. Journal Publication

Due to the plethoric availability of journals, researchers publish manuscripts with various publishers. Thus, in order to extract information regarding the research journal trends, we structured the selected survey articles into categories according to the journal during the analysis phase. The occurrence and their research area are shown in Table 3. It is easily distinguished that journals devoted to industry-related topics scored at the top of the preference, while sustainability, economic, engineering, and information journals have also attracted a great number of Industry 4.0 survey journal papers. A timeline analysis of the publications that were chosen for the study is visualised in Figure 4. During the period under investigation (2016–2022), there was an increasing research interest and activity compared to previous years. The proportion of publishing surveys climbed steadily over the course of the five years, beginning at four percent in 2016 and reaching a high of thirty-two percent in 2021. Besides, by the end of 2022, we expected to have an increase in published journals, as shown in Figure 4. This verifies the argument that, as time passes, the research community is able to provide much more information, while researchers massively review them, in order to summarise the knowledge within review journals, thus providing well-defined answers and results.

The distribution of the publishers taking into account the research results are illustrated in Figure 5. It is clear that the ranking is topped by Elsevier Ltd. , Emerald Group Holdings Ltd., and Multidisciplinary Digital Publishing Institute (MDPI). Despite the fact that there are more publishers, it is evident that the three at the top of this list are the most sought-after by authors for publishing Industry 4.0 review journals. It is remarkable that just two of the remaining twelve publishers indicated in Figure 5, notably Taylor & Francis Ltd. and Springer, are the most popular inside the subset. Finally, the rest of them show no difference as far as their distribution.

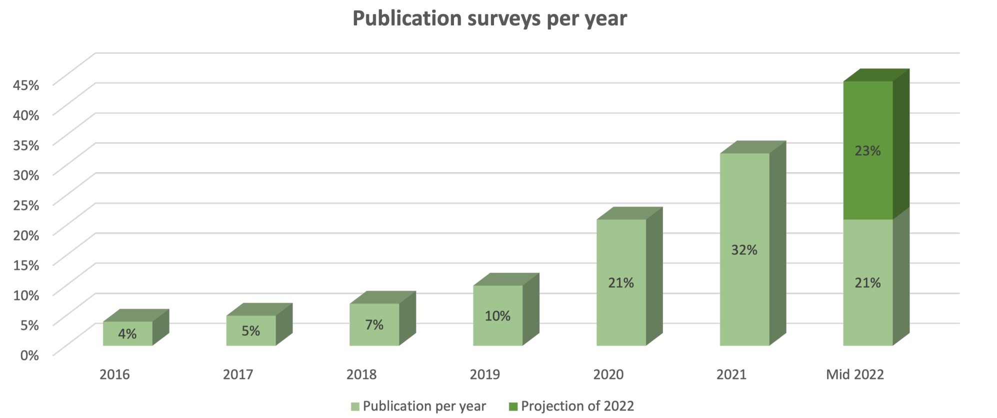

Figure 4. The figure presents the occurrence of the publication years within the examined period.

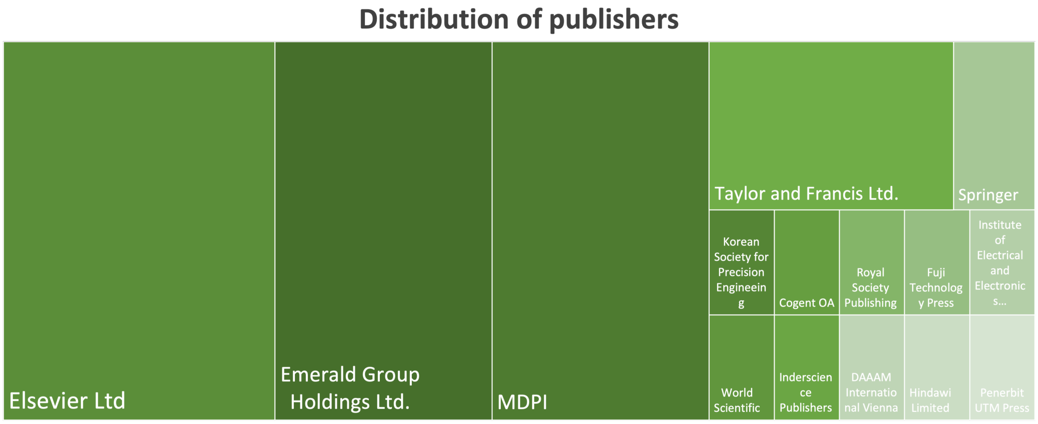

Figure 5. Distribution of publishers.

Our SLR identified that the majority of the published articles appeared in the *Journal of Cleaner Production* [37,43,48,68,70,71], the *International Journal of Production Research* [47,49,54,56,83], the *International Journal of Manufacturing Systems* [44,52,55,59] and *Sustainability* [65,67,72,73], with more than four articles in each of them. On the other hand, *Applied Sciences* [14,69,79] and the *Journal of Manufacturing Technology Management* [12,57,62] journals accounted for six publications. As concerns the research interests of these journals, the analysis revealed that the most preferable is focused not only on applied manufacturing [36,47,49,54,56,83] and the production ecosystem [44,51,52,55,59], but also on sustainability areas [37,43,48,65,67,68,70–73].

A significant number of I4.0 survey papers [35,40–42] were submitted in engineering-related journals such as *Engineering*, *Designs*, and the *Journal of Engineering* among others, which are mainly attracting R&D engineering advancements, architectures, and methodologies. In addition, industrial-based journals (*Computers in Industry*, *Industrial Robot*, *Jurnal Teknologi*) were identified, which are mainly focused on ICT design [34,53,78] and related manufacturing operations [33,60]. Apart from them, industry-related organisational [39,58], economic [13], and digital quality management [50,66,76] journals are also interesting to the researchers as proven by our analysis, while there is an increased interest in business and technology management journals [11,77,81].

However, there are also influential journals such as the *International Journal of Advanced Manufacturing Technology* [50], the *Journal of Intelligent Manufacturing* [5], and the *IEEE Communications Surveys* [38], the main theme of which lies in industrial electronics, intelligent manufacturing, and telecommunication topics, respectively. It is noteworthy to highlight that there is a number of Industry 4.0 survey papers in the computer science [10], integration [8], and Internet [82] areas in some dedicated journals such as *Computer Science Review*, *Journal of Industrial Information Integration*, and *Future Internet*. As a last observation, we identified some manuscripts being published in journals with a broad spectrum of topics, such as *Expert Systems* [75], *Electronics* [80], the *Journal of Precision Engineering* [61], or in journals with themes not directly related to I4.0, such as *Metals* [45], *Supply Chain Forum: An International Journal* [74], and *Electronics* [46].

Summarising, our study identified the trend that the academic community provides developments in the industrial manufacturing landscape with a close look into environmental and sustainable aspects. Furthermore, it is noticeable that our SLR confirms the global direction that Industry 4.0 papers are not only published in production-related journals, but in ones covering the whole spectrum of the value chain and business topics, including journals in financial, organizational, and management areas.

4. Discussion

The SLR has highlighted some aspects that help to clarify how I4.0 is transforming the existing manufacturing environment and how cutting-edge technologies are employed in the new era. These indications are grouped and generated based on identified research fields and formulated research questions. The relevance among them, as well as the findings of this survey of surveys procedure are visualised in Figure 6, while they are further described by focusing on the effects of I4.0 on traditional business models, the transformation of SMEs, the decision-making process, the human–machine interaction, and the circularity aspects.

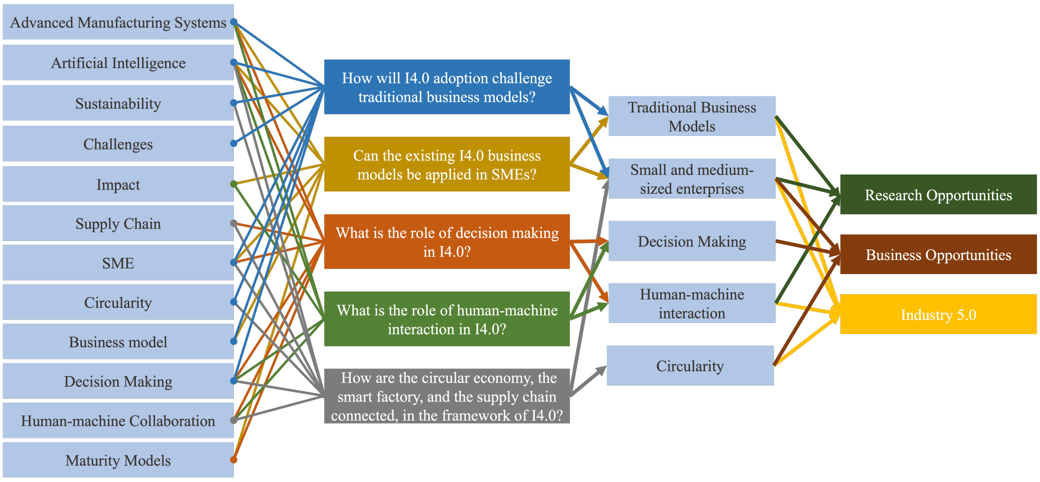

Figure 6. In this figure, the relation among identified research fields, research questions, and discussion points, in addition to the findings are visually represented.

4.1. Traditional Business Models

During the adoption of the Industry 4.0 schema in the production environment, several challenges have arisen either as obstacles to the implementation phase or as enablers that were eventually partnered with the innovations, thereby expanding the technological capabilities [47]. Ten percent of the survey articles refer to the challenges of I4.0 or significant advanced technologies and factors involved. The challenges of technological pillars, such as the Internet of Things, big data, etc., were mentioned [10], while the parameters of the achievements of Industry 4.0 have also been explored [39]. The interdependence between the level of business model adoption and actual deployed technologies was spotted by Nayernia et al. [73]. The horizontal and vertical integration capabilities through interoperability was highlighted by Lu et al. [8], who proposed a conceptual evaluation framework. In other disciplines, issues related to the circular economy and sustainable production were reported, while the challenges of Industry 4.0 in relation to business models were reported by [10,11].

Business models are heavily influenced by I4.0, and this trend will facilitate the creation of collaborative environments, interconnecting humans, processes, and production [53].

These new business models are mainly derived from organizations that adopt I4.0 to utilize more efficient and reliable production systems and innovative technologies [12,50]. Customers benefit from the fourth industrial revolution by improving their experience, as Industry 4.0 improves integration and collaboration across the value chain, which are key factors in all business models [13]. The Internet of Services (IoS) could be characterized as a new ecosystem where service providers and consumers explore their business networks for service provision and consumption. In the research community, though, there is a lack of a detailed view of an IoS-based business model to support the concept in creating, delivering to, and capturing value for customers [82]. Business models are key pillars of success in many areas such as the circular economy. More specifically, the success of a circular economy depends on new business models, which are built upon reusing the value of products at the end of their life cycle [37]. Different business model proposals consider additive manufacturing as a factor of sustainable technology that supports the circular economy [45]. Especially, additive manufacturing technology transforms the traditional sectors (footwear, textile, and wood industries), reducing the material that would be wasted otherwise [65]. More circular-based business models provide high-quality services or solutions to achieve technology cycles exceeding their life expectancy and, finally, allowing them to offer both short-lived and durable products through "*remedial methods*" [37]. In business models, sustainability plays an important role as well. In order to achieve it, organisational capabilities and corporate social responsibilities must be seriously taken into account [70]. Last, it is worth noting that despite the emergence of new business models, due to I4.0, challenges affecting traditional business models, such as interconnection, personalisation, pricing, smart services, value chain fragmentation, decentralized facilities, integrated production, and human ingenuity, have yet to be completely addressed and cannot be ignored [11].

4.2. Small and Medium-Sized Enterprises

According to the European Commission, enterprises with less than 250 employees and an annual turnover of less than EUR 50 million are classified as Small and Medium-sized Enterprises (SMEs) [56]. Due to the limited financial budget and the knowledge gap about the benefits provided by I4.0 technologies, SMEs' innovation investments are limited. As a result, multinational corporations are still pioneers in the adoption of emerging technologies, and SMEs should learn from their paradigms to quickly start their journey into smart manufacturing and Industry 4.0 [56]. Apart from the technological effects, SMEs are also facing organisational challenges, such as competitive strategies, business models, organizational architecture, etc. [79], which should be solved by embracing digitalisation and having an open mindset.

The literature study revealed that I4.0-related standards, architectures, and business models for the industrial management of SMEs have already been proposed. They are supported by technical transformation solutions from existing companies or new start-ups, which provide more flexible and interoperable systems when compared to those offered by traditional enterprise IT [13]. However, the existing industrial production assets, manufactured in the past 25 years, cannot completely support the new opportunities, in terms of scheduling and production control. The challenges and deployment constraints were explored by [50], concluding that SMEs invest in digital transformation without being fully aware of the value of the digital shift. As a consequence, the development of maturity models is a challenging task, creating barriers to the assessment of the factory's effectiveness and the development of strategic management to achieve its goals [79].

The need for a dedicated future model for SMEs was highlighted by [56], indicating that the existing maturity models have been developed for general purposes and are difficult to apply in SMEs. The dedicated maturity model would demonstrate the organization's readiness for smart production and would provide a tailored strategic plan to enable the realization of the factory of the future [56]. In addition, it would also provide specific tools and technologies to enrich the organizational dimensions, thereby guiding

SMEs into the fourth industrial revolution. Open innovation is also extremely important. Having collaboration as the main component is actually considered a new paradigm of a business innovation model that allows SMEs to reduce cost and time [81]. SMEs, though, surely struggle with a variety of problems such as upskilling challenges or poor cybersecurity regulations. That is why it is time for the research community to focus more on explaining how governments can speed up, simplify, and assist with SMEs' Industry 4.0 transformation [62].

4.3. Decision-Making

Decision-making constitutes a cornerstone process, upon which any production system is based. Automation systems gather information, assess situations, and proceed to specific actions, according to predefined procedures. As the volume of uncertain and incomplete information increases, decision support systems mainly utilize statistical, machine, or deep learning techniques to provide decision support, across a wide range of areas [83]. In an I4.0 ecosystem, decision support systems' technology is a vital enabler, as it empowers not only automation, but managers and strategy makers as well. Big data, in combination with artificial intelligence technology, analyses available data in a way that helps the system to proceed with more accurate, data-driven decisions, reducing the need for human experience in the decision-making process [83]. Besides, blockchain technology secures the data transactions used for decisions while the data costs are decreased [74]. Within the manufacturing ecosystem, intelligent data-based systems are used to investigate existing or upcoming problems in the whole value chain (viz. defective products, equipment failures, resource allocation, and energy needs) [75]. There are also enablers derived from IT (e.g., law and policy regarding employment, improved IT standards and security, corporate governance, etc.), which will actually help to streamline information flow across the supply chain network. Information flow and transparency will aid in better decision-making [66]. The decision-making process varies between an SME to a large company. The SMEs tend to adopt a quick and straightforward decision as the ownership lies in one person's hands, while the complexity of ERP in a large enterprise requires a more in-depth analysis supported by an analysis of different options and choosing the best alternative [80].

Based on the systematic, bibliographic review by Osterrieder et al. [14], a smart factory research model was proposed, which identifies the research pillars capable of enabling and improving the smart factory concept. One such pillar is the decision-making procedures, which include data-driven decisions that occur in manufacturing and rely on visualization, machine learning, and storage techniques. In particular, maintenance-based decision-making methods were investigated by [46] emphasizing the importance of cyber–physical systems in facilitating preventive and reliable decisions. Among other manufacturing-based decisions, the main ones are resource optimization, process planning, production equipment control, quality control operations, organizational-based predictions, and performance measurement [14].

4.4. Human–Machine Interaction

I4.0 aims to develop a work environment where teamwork is a key feature, not only for businesses, but also for individuals, allowing collaboration throughout the entire production ecosystem [38]. As the I4.0 and smart factory concepts unfold, human operators face increasing complexity in their day-to-day tasks, which illustrates the need to be extremely flexible and adaptable in this dynamic work environment [78]. The smart factory is a highly flexible and intelligent factory that actually empowers human–machine interaction since humans, machines, sources, and products communicate just like a social network [60]. In order to empower the operators, tools and approaches should be developed that should be easily: (i) integrated into existing everyday practices and (ii) combined within complex methodologies with high usability [78]. In the I4.0 ecosystem, humans and assets will collaborate using cognitive technologies in industrial environments, with smart machines being able to assist personnel with most of their daily tasks, by using speech recognition, computer vision, sensing systems, and machine learning techniques [54].

Augmented Reality (AR) technology is used in a wide variety of applications within the digital factory, allowing operators to stay informed about critical events and collaborate with digital assets [43]. For instance, in the maintenance procedures, operators use their mobiles to allocate and monitor their jobs throughout the day, interact with production equipment [84], and read step-by-step digitized procedures using AR architectures [18]. Besides, mechanical intelligence, enabled by artificial intelligence technologies, plays an important role in supporting human–machine collaboration. This way, machines' ineptitude in understanding and managing their environment can still be of use in a modern manufacturing environment. Moreover, advanced learning models for machines, such as robots, are needed so that humans and machines can develop complementary skills [54]. Even machine learning facilitated by CPSs provides a new means of people–machine interactions in the effort to create a smoother and more friendly user experience [61].

Human–machine collaboration belongs in a zero-fault environment, where human flexibility in combination with machine accuracy can achieve error-free and maximized production performance [35]. This should be considered a valuable enabler to accelerate the adoption of the factory of the future in the most complex production operations [54]. However, the overall performance of human–machine interaction applications can be improved by integrating environmental information and interaction models into a decision-making element that acts as a monitoring process for interaction control [51]. In addition, smart technologies should be employed to track humans in the manufacturing environment and notify stakeholders in the event of an emergency, creating a safer working environment [85]. Nevertheless, the safety principles and regulations should be taken into comprehensive consideration when adopting the human–machines collaboration techniques [73].

4.5. Circularity

The circular economy focuses on environmental performance improvements rather than taking a holistic view of sustainability dimensions. Among the various definitions of the circular economy, an insightful one is an *industrial economy that is restorative or regenerative by intention and design* [57], emphasizing the society-based economic methodology that restores waste and uses it as feedstock in circular chains. However, the large-scale implementation of the circular economy cannot be achieved since cultural, technical, marketing, and regulatory barriers need to be overcome [72]. The Circular Economy (CE) is considered a critical solution to global problems because of the considerable adverse effects of the current linear economic models [64]. Adopting combined factors of I4.0 and CE such as barriers, drivers, and enablers plays a vital role in decision-making and effective implementation [63].

One of the most critical enablers is information and communications technology, which provides interaction and integration capabilities in both existing and new applications, such that customers, organizations, and enterprises can economically benefit from the waste and unused resources [37]. In order to move forward for efficient and widespread implementations, forums, forces, and industrial symbiosis initiatives should be expanded, such that participants embrace innovative goals, key activities, and methodologies, to gain an advantage in the competitive, global market [33,78].

In the I4.0 ecosystem, where digitization and cyber–physical systems are ubiquitous throughput the value chain, the circular economy has also benefited and circular-based management models have been developed [58,71]. As stated in [78], there is a clear trend towards promoting sustainable production and consumption reduction, given the role of supply chain networks in sustainability. In spite of the low integration of I4.0 technologies in the circular economy, the limited adoption provides positive results when used to address sustainability issues, while more impressive results, such as economies of scale and knowledge transfer, can be obtained using technological advancements [59,67]. For instance, blockchain technology has offered valuable opportunities to promote the sustainability of the energy sector [68,86] and the traceability of the supply chain. It is worth mentioning that [37,43] also highlighted important sustainability issues, in relation to I4.0, such as its *consciousness* and the level at which it is implemented. The concept of the smart factory is evolving alongside the smart supply chain, which is also activated by the implementation of I4.0 [52,59], in favour of a circular economy. This transformation has led to a growing emphasis on customer importance and environmental sustainability, promoting a focus on *customer centricity* [52].

4.6. Findings

This SLR analysis spotlighted evidence that helps to provide an overview of the opportunities generated by the I4.0 ecosystem. We identified how the fourth industrial revolution affects the current state-of-the-art in production and circularity issues, while the main technological enablers were identified as contributing to the transformation of manufacturing operations and management. It is worth noting that the examined topics were directly or indirectly related to at least a third one. This relation confirms the importance of horizontal and vertical integration when using technological pillars in the context of smart manufacturing. In addition, the study proved that trending technology topics, such as artificial intelligence or advanced manufacturing systems (Table 2), are comprehensively addressed by scholar survey articles, providing a stable sense of I4.0 outcomes. Nonetheless, despite the fact that experts are continuously contributing to the I4.0 research area, some topics have not progressed as much as the aforementioned ones (viz. artificial intelligence) and should be further explored in the near future. These opportunities and suggestions are further described below, specifically as it pertains to research and business opportunities. The limitations of our SLR are also discussed.

4.6.1. Research Community

One of the most critical issues that requires further exploration is the interpretation of the term "Industry 4.0", based on its contribution at the manufacturing and business level, the value of the futuristic use cases, and the available technological enablers. It is widely known that different technological initiatives, developed around the globe, have been described as I4.0 advancements. These various forms of ingenuity have obscured the original I4.0 inspiration, and as a result, the methodology needed to achieve key developments and business visions has not yet been clearly defined. Despite the fact that the first definition of I4.0 promotes horizontal and vertical integration, by utilizing through-engineering solutions [1], the proposed concept is not fully applied in other disciplines that are directly related to the factory, such as sustainability, management policies, and product distribution, as well as those within the manufacturing area. In addition, we believe that future research will showcase the application of new technology enablers, such as blockchain or edge computing, and their impact on smart factories, circularity, and SMEs [54].

An opportunity for further research into the adoption of I4.0 in SMEs was observed. As the latest factories facilitate the I4.0 solutions [13], a vast number of traditional plants cannot support them due to their ageing infrastructure. Nevertheless, a limited number of add-on systems have been developed (e.g., product tracking [87], image-based vibration monitoring [88], etc.) in order to retrofit the aged machines and assets, thereby providing integration and cognitive capabilities. Furthermore, the existing shop floors are in need of systems and architectures that enable data sharing, not only for the in-house assets and departments, but also for collaborative factories, such as first-tier suppliers and wholesale customers. As we identified a lack of survey articles that referred to retrofitting policies and systems, we believe that future research should be conducted to provide opportunities and insights for the implementation of I4.0 add-on systems.

The interplay between technological pillars used in smart manufacturing, across the value chain, including the supply chain and circularity, is not fully understood. Our SLR identified that artificial intelligence technology and advanced manufacturing systems were discussed in the majority of the survey articles, highlighting the capabilities of the digital brain in the manufacturing ecosystem [10] (Table 2). On the contrary, technologies such as machine vision, digital twins, and additive manufacturing have not been analysed, in spite of their value. For example, machine vision is used not only to identify the quality of the products, but also to guide unmanned vehicles inside and outside the factory [89]. Additive manufacturing promotes sustainability by reducing the volume of raw materials, while digital twins predict upcoming production faults, allowing the machines to undergo self-configuration. Furthermore, the adoption of 5G in manufacturing networks via the tactile Internet has been analysed in existing case studies [90], but the regulatory framework should be further explored. The analysis and discussion of such technologies, in the entire value chain, through survey papers, will be valuable for researchers and technology adopters.

The regulatory and governmental perspectives of I4.0, especially for circularity and sustainability topics, have not been clearly addressed by recent survey articles. While regulatory directions have already been stated for trending technologies (i.e., artificial intelligence) [91]), a systematic review analysis to correlate the regulatory directions and provide meaningful insights has not been performed yet. Furthermore, an interesting, yet unexplored, topic is the barriers and challenges of current regulations in the adoption of I4.0, when humans are called to collaborate and interact with machines [73]. Generally, the regulatory and government states stand as a barrier to the success of the upcoming revolutions, and their comprehensive analysis, through future studies, would greatly contribute to this complex field.

A lack of review papers regarding educational strategies to prepare industrial workers for revolutionary changes, especially in human–machine collaboration, was observed [68,71]. Until now, the published literature has covered technologies that empower the worker and enable the Operator 4.0 concept [43,54,84], such as augmented reality, the Internet of Things, and artificial intelligence. It is widely accepted that the ongoing digital transformation has created new jobs, which require data-centric soft skills, open mindsets, and digital awareness [24]. Nevertheless, education and human-centred upskilling procedures have not been identified, which will allow us to reduce the skills gap and provide practical insights.

4.6.2. Business Community

From a business community point of view, the present manuscript summarizes the results of high-impact I4.0 survey articles that assist entrepreneurs in their understanding of the influence of digital transformation in factory and business operations. It is essential for entrepreneurs to grasp the potentialities of the technologies provided within the I4.0 bunch before adopting them within their facilities. For example, as discussed in Sections 4.1 and 4.2, recently developed business models also take into account sustainable production policies, combined with circularity-based techniques and technology enablers across the value chain [37]. The adoption of these models in SMEs requires careful consideration of the maturity level of the existing infrastructure [56], maximizing the strategic impact, and reducing non-profitable investments. Apart from that, their retrofication strategy should be also explored in other disciplines of the value chain such as warehouses, where intelligent techniques started to be used to automate packaging- or human-related procedures [92,93].

Decision-makers in business and technology adoption should prioritize horizontal integration, with the aim to remove silos and enable interoperability [8]. The interconnected factory provides zero-fault operational management, as the decision-making processes rely on real-time data streams [83]. Apart from that, new technologies, namely artificial intelligence, digital twins, edge computing, and cloud computing, can be broadly implemented in the factory, as the interconnections provide accessible and structured data [40,54,94]. For instance, as stated in Section 4.4, the interaction between a smart machine and a human requires data from the management system and the surrounding environment. Finally, advanced techniques, such as speech recognition and computer vision, analyse humans' movements and the machine acts in tandem, based on the system's state, enabling human–machine collaboration.

4.6.3. Industry 5.0

This survey of surveys study demonstrates that, over the past several years, a substantial number of surveys have been conducted on the technological elements, productivity, and flexibility, as well as the difficulties and consequences associated with their implementation (Figure 3). This result validates the design concepts and aims of the German Industry 4.0 strategy [1]. In contrast, during the past two years (Table 4), the sustainability element has attracted a great deal of attention from the academic community, which is attempting to discover methods for implementing circular policies and mapping the relationships among circularity, Industry 4.0, and sustainability. This trend aligns with the *Fifth Industrial Revolution* (Industry 5.0) strategy of the European Commission, which promotes sustainable, human-centred, and resilient aspects [22]. Nevertheless, as stated in Section 4, some aspects have already been mentioned in surveys without being noted as Industry 5.0 principles, highlighted as follows:

The *human-centric* aspect places the human at the centre of manufacturing activities, utilising technology solutions and innovative approaches to upskill and reskill them. According to Agostini et al. [11], open innovation initiatives democratise human knowledge, hence decreasing the cost and implementation time for SMEs. In another study, cognitive technologies such as voice recognition and computer vision can be utilised to increase cooperation between humans and machines by boosting their complementary skills [54], while augmented reality assists humans in their everyday operations in a user-friendly manner [60,95].

The *resilience* aspect focuses on the production's adaptation and resilience in the face of crucial unforeseen changes. Intelligence can be added to traditional systems through the use of flexible, interoperable technologies and new solutions developed by startups or established enterprises [13]. Big data and artificial intelligence enable machines to manage accurate decisions by merging data from multidisciplinary sources, such as urban demands, supply chains, and environmental changes [62]. On the manufacturing site, the application of predictive maintenance solutions extends the life of machines, decreasing direct expenses [46], which can further be invested in the digital transformation.

The *sustainability* aspect refers to the effectiveness of the circular economy through the manufacturing and supply chain processes. According to Kerin et al. [37], business models based on reused products enhance the reusability of natural resources. Societies play crucial roles in this principle by promoting waste restoration policies to collect waste for reuse as feedstock in circular chains [57]. Reliable communication technologies provide interconnections among stakeholders (customers, organisations, and businesses) in order to collect data, hence facilitating the effective management of waste and underused resources [63]. This change emphasises the value of humans, promoting *customer centricity* in favour of environmental sustainability [52].

4.6.4. Limitations

The time limitations in this research could be characterized as non-critical, as I4.0 encompasses relatively new, constantly evolving concepts, which is evident from the general research activity—most of which was published in recent years. The main limitations were in the coverage of topics and selected sources, as the selection process and the criteria that were defined at the beginning of this meta-analysis of the review articles limited its scope to journals written in English that were archived in the Scopus® database.

Although the time limitation may not have been a critical issue, other limitations, such as the breadth of coverage, may have had a substantial impact on our analysis. Survey articles published between January 2016 and July 2022 that addressed important I4.0-related problems were the focal point of our investigation. To access the information that we needed regarding the digital footprint of Industry 4.0, we followed a survey of surveys approach based on PRISMA guidelines, as explained in Section 2. The different stages are illustrated in Figure 1. During those stages, the inclusion and exclusion criteria further limited the number of articles that could enter the analysis phase. These decisions were based mostly on practical considerations, which, in many cases, were unavoidable. As a result, some very recent and interesting publications were excluded.

5. Conclusions

Industry 4.0 is expected to give rise to various changes in different areas. Based on our analysis, we should note that the I4.0 initiative started as an enabler to digitise industrial-related operations, but advanced technologies have already been adapted in several sectors, developing a I4.0 philosophy that composes a world view for tomorrow's society. Within the SMEs, it is evident that a powerful interaction between I4.0 and concepts such as decision-making, supply chain, circular economy, and business models exists. Actually, the 59 academic publications (Table 4) that were selected to account for the body of our analysis prove that such concepts (e.g., cyber–physical systems, artificial intelligence, human–machine collaboration, etc.) have a strong impact on Industry 4.0. All these topics were examined by scholar articles surveying different facets of the Industry 4.0 ecosystem, thus providing a distilled concept about the fourth industrial revolution results and the need for Industry 5.0.

Specifically, circular-based business models should lead the modern manufacturing ecosystem by providing high-quality services and durable products that are driven by the Internet of Services (IoS) principles. In order to accelerate the transformation, maturity assessment models could assist SMEs in evaluating their technology level and investing in digital transformation. As a significant enabler, data-driven decision systems aid humans or robots in optimising production planning, operating equipment, predicting breakdowns, and measuring factory performance. Furthermore, human–machine collaboration enables a zero-fault environment in which human flexibility and machine precision can accomplish error-free and optimal production performance. Finally, in the modern manufacturing ecosystem, SMEs restore waste from customers and use it as feedstock in circular manufacturing chains, promoting the sustainability and circularity principles.

Moreover, opportunities and suggestions have been provided focusing on the research and business communities. Research gaps such as the adoption of Industry 4.0 in SMEs, the regulatory and governmental policies, as well as the educational strategies and managerial insights such as sustainable-based and human centring strategies were highlighted in Section 4.6. Yet, this is not enough, since continuous uninterrupted effort is surely needed. Sustainability, business models, and the adaptation of advancements to humans should be further analysed so as for Industry 4.0 to grow further and be transmitted to the Industry 5.0 era. This in turn should result in new challenges and prospects that shall enrich future studies, which will be based on developing transition frameworks.

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Abbreviations

The following abbreviations are used in this manuscript:

Abbreviation	Full Form	Definition
I4.0	Industry 4.0	Industry 4.0, which refers to the fourth industrial revolution, is the cyber–physical transformation of manufacturing. The name is inspired by Germany's Industrie 4.0, a government initiative to promote connected manufacturing and a digital convergence between industry, businesses, and other processes
I5.0	Industry 5.0	The Industry 5.0 term, known as the fifth industrial revolution, referring to the development of a more human-centric, sustainable, and resilient industry. This is linked with the upcoming development of novel technology, industrial or supply chain processes, or new business models
SMEs	Small and Medium-sized Enterprises	According to the European Commission, enterprises with less than 250 employees and an annual turnover of less than EUR 50 million are classified as small and medium-sized enterprises
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses	PRISMA is an evidence-based minimal set of components for the systematic review and meta-analysis reporting. It is primarily intended for the reporting of reviews assessing the effects of interventions, but it may also be used to record systematic reviews with goals other than evaluating intervention effects
SLR	Systematic Literature Review	The SLR is a sort of literature review that collects and critically examines various research projects or publications in a systematic manner. The SLR's objective is to give a comprehensive overview of the existing literature related to a research issue
RMS	Re-configurable Manufacturing System	The RMS is a system that is intended from the start for rapid modification of its structure, as well as its hardware and software components, in order to rapidly adapt its production capacity and functionality, in reaction to market changes
IoS	Internet of Services	The IoS could be characterized as a new ecosystem where service providers and consumers explore their business networks for service provision and consumption
IoT	Internet of Things	The IoT refers to physical items equipped with sensors, processing power, software, and other technologies that connect to and exchange data with other devices and systems over the Internet or other communications networks
CE	Circular Economy	The CE is a production and consumption paradigm that emphasises sharing, leasing, reusing, repairing, refurbishing, and recycling of existing resources and goods for as long as feasible

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