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Industry 4.0 Ten Years On: A Bibliometric and Systematic Review of Concepts, Value Drivers, and Success Determinants

Abstract

The fourth industrial revolution, known as Industry 4.0, and the underlying digital transformation, is a cutting-edge research topic across various disciplines. Industry 4.0 literature is growing exponentially, overexpanding the current understanding of the digital industrial revolution through thousands of academic publications. This unprecedented growth calls for a systematic review of the concept, scope, definition, and functionality of Industry 4.0 to address the existing ambiguities and deliver a clear, comprehensive, and up-to-date overview of this phenomenon. Consistently, the present study carried out a systematic literature review of related articles, published online within the Industry 4.0 discipline until November 2020. The systematic literature review identified 745 eligible articles and applied extensive qualitative and quantitative data analysis to methodically answer the four research questions proposed. The study provides a descriptive assessment of eligible articles' properties and offers a unified conceptualization of Industry 4.0 and the underlying building blocks. The study further describes the value drivers of the fourth industrial revolution and identifies the conditions on which digital industrial transformation's success lays. The study also draws on the findings and offers important theoretical and practical implications, highlights the existing gaps within the literature, and discusses the possible future research directions.

1. Introduction

Industry 4.0 is becoming popular exponentially among industrial, political, scientific, and academic communities (Beier et al., 2020; Rosa et al., 2020). Industry 4.0 involves the promise of a new industrial revolution, commonly labeled as the fourth industrial revolution (Mahmood and Mubarak, 2020; Wang et al., 2020). The first reference to Industry 4.0 occurred in 2011, yet, it is misleading to assume that Industry 4.0 is a sudden revolution utterly unaware of the industrial and technological revolutions that arose earlier (Liao et al., 2017; Oesterreich and Teuteberg, 2016). The first industrial revolution occurred by the end of the 18th century, which centered around introducing machines into production. The second industrial revolution dates back to the early 19th century, which involved the electrification of factories and the introduction of production lines. The third industrial revolution, also known as the digital revolution, is characterized by the introduction of digital technologies in production during the 1960s and 1970s. In reality, Industry 4.0 builds entirely upon the foundations of previous industrial revolutions (Culot et al., 2020). However, Industry 4.0 is expected to deliver the highest degree of digitalization, automation, virtualization, and decentralization across all industries, when coming to its maturity (Bordeleau et al., 2020; Theorin et al., 2017). The disruptive force of Industry 4.0 is argued to be massive, impacting the rules of competition, value delivery functions, labor market, socioenvironmental norms, and even educational priorities (Matthyssens, 2019; Sony and Naik, 2020). It is why international associations, governments, industrial communities, and academia have valued and prioritized the understanding of Industry 4.0 functions, capabilities, driving force, socioeconomic impacts, and future trends.

The amount of hype surrounding Industry 4.0 has led to the overwhelming growth of academic publications during the past few years, from a handful of articles in 2014 and 2015 to the thousands of academic contributions in 2020. The sheer academic contributions have significantly advanced the current understanding of Industry 4.0 along with all its capabilities. The richness of Industry 4.0 literature has called for review studies to identify, synthesize, and categorize the existing scholarly literature on Industry 4.0 phenomenon and make the existing findings and evidence more comprehensible and accessible to industrialists, academicians, and decision-makers. The existing Systematic Literature Review (SLR) studies have strived to provide an overview of contributions done to various aspects of the Industry 4.0 phenomenon and address research gaps left unintended, enabling the scientific community to develop and propose more relevant and rigorous research agendas. Table A1 provides a concise review of the selected SLR articles published in the field of Industry 4.0. Previous SLR articles have addressed a wide variety of issues within the Industry 4.0 context, from broadly reviewing the Industry 4.0 phenomenon (e.g., Hoyer et al., 2020; Klingenberg et al., 2019; Liao et al., 2017; Nazarov and Klarin, 2020) down to the implication of Industry 4.0 digital technologies in the fields of Lean thinking (Bittencourt et al., 2020; Núñez-Merino et al., 2020; Pagliosa et al., 2019), industrial maintenance management (Dalzochio et al., 2020; Silvestri et al., 2020; Zonta et al., 2020), sustainability (Kamble et al., 2018; Rosa et al., 2020; Tirabeni et al., 2019), production management (Bueno et al., 2020; Felsberger and Reiner, 2020; Usuga Cadavid et al., 2020), manufacturing systems (Hoffmann Souza et al., 2020; Vrchoťa et al., 2020; Zheng et al., 2020), and supply chain management (Abdirad et al., 2020; Barata et al., 2018; Dallasega et al., 2018).

Despite the valuable contribution of existing SLR studies to the advancement of Industry 4.0, the question of "what is the current status quo of Industry 4.0 literature?" remains unanswered. Liao et al. (2017) conducted a comprehensive SLR to provide an in-depth understanding of enabling features, application fields, and ongoing

research themes of Industry 4.0. However, Industry 4.0 literature has gone through revolutionary changes since 2017, mainly because of the dynamism of the digital industrial revolution and the ever-increasing theoretical and empirical contributions of academicians and industry practitioners. Therefore, there is still a prevalent need for a holistic SLR on the concept, scope, definition, and functionality of Industry 4.0 to deliver a clear, comprehensive, and up-to-date overview of this phenomenon. To fulfill this objective, the current study designs and executes a comprehensive SLR to address the following research sub-questions:

- RQ1: What are the demographic properties of Industry 4.0 literature?
- RQ2: What are the current trends on the conceptualization and scope of Industry 4.0?
- RQ3: What drives the digital transformation under Industry 4.0?
- RQ4: What are the most critical determinants of Industry 4.0 digital transformation success?

2. Review methodology

The study applies SLR to systematically obtain a rigorous and objective summary of the Industry 4.0 phenomenon and identify existing trends, practical implications, and future digital transformation opportunities under Industry 4.0. To ensure the robustness and reliability of SLR procedure, the study strictly follows the systematic review guideline within the literature (e.g., Booth et al., 2016; Tranfield et al., 2003), and more importantly, Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocols. Consistently, SLR in this study involves resource identification principles and data collection processes.

2.1 Resource identification principles

Following PRISMA protocols, SLR methodology starts with establishing eligibility criteria. Table 1 lists the inclusion and exclusion criteria developed for the present study. This table explains that eligible resources in this study include journal articles published in academic journals that employ a rigorous peer review system. To ensure this requirement, being published in journals indexed in Clarivate Analytics (Social Sciences Citation Index® or Science Citation Index®) was defined as one of the inclusion criteria.

Table 1. Inclusion and exclusion criteria developed for the present SLR.

Criteria	Description
<i>Exclusion</i>	
EXC1*	The document does not categorize as a journal article (e.g., editorials or white papers).
EXC2	The main body of text for the article is not written in English
EXC3	The full text of the article is not accessible
EXC4	The article has been published in a journal that is not indexed in Clarivate Analytics (Social Sciences Citation Index® or Science Citation Index®)
EXC5	The article uses the search keywords merely in the title and provides no insight into the Industry 4.0 phenomenon or its applications whatsoever
<i>Inclusion</i>	
INC1**	The article is formally published in open access or subscription-based journals
INC2	The article is formally accepted for publication in open access or subscription-based journals (forthcoming, ahead-of-print, or in press variants)
INC3	An article of any acknowledged categories (e.g., original research, review, letter, case study)
INC4	Industry 4.0 is the central theme of the article
INC5	Industry 4.0 is only one of the several topics addressed within the article
*EXC: Exclusion criteria	
**INC: Inclusion criteria	

2.1.1 Article collection

The study developed and applied a straightforward search scheme to identify the initial pool of articles. The search scheme included using three discrete search terms of "Industry 4.0," "Industrie 4.0," and "fourth industrial revolution." SLR in the present study used the *Scopus* online database to identify the initial pool of articles and further benefited from the *Web of Science* online database for applying execution criteria EXC4. In the *Document Search* page within the *Scopus* online database, three search lines with operator 'or' between them were constructed. In the Search Field Type, *Article title* was selected for each of the search fields from the drop-down list, and each of the "Industry 4.0," "Industrie 4.0," and "fourth industrial revolution" terms were placed in each of the *Search terms lines* separately. In the *Refine results* section and under the Document type subsection, results were limited to the *Article* and *Review* types. The search strategy did not apply any restrictions in terms of the year, subject area, or region. A similar search strategy was also employed within the *Web of Science* database to complement the *Scopus* search.

As explained in Figure 1, the search strategy employed in the present study involved two separate search attempts. The initial search was conducted on August 10, 2020, which resulted in identifying 1442 articles for the search term "Industry 4.0," 258 articles for the search term "Industrie 4.0," and 193 articles for the search term "fourth industrial revolution," leading to the initial pool of 1893 articles. Articles shortlisted as the initial pool was further subjected to the exclusion criteria (listed in Table 1), which resulted in removing 1256 articles. Consistently, 637 eligible articles were shortlisted for content-centric analysis. Industry 4.0 literature constantly evolves, continually introducing new articles. Therefore, the SLR was updated via a complementary search conducted on November 10, 2020. This complementary search followed the procedure applied within the initial search (Figure 1), which identified 358 new articles. The newly identified articles were subjected to exclusion criteria, as a result of which 108 new eligible articles were shortlisted to be included in the content-centric assessment.

Overall, the initial and complementary search attempts identified a total of 2251 articles, out of which 1506 articles were removed due to the exclusion criteria (Figure 1). By the end of search attempts, 745 eligible articles were shortlisted to go through the content analysis procedures.

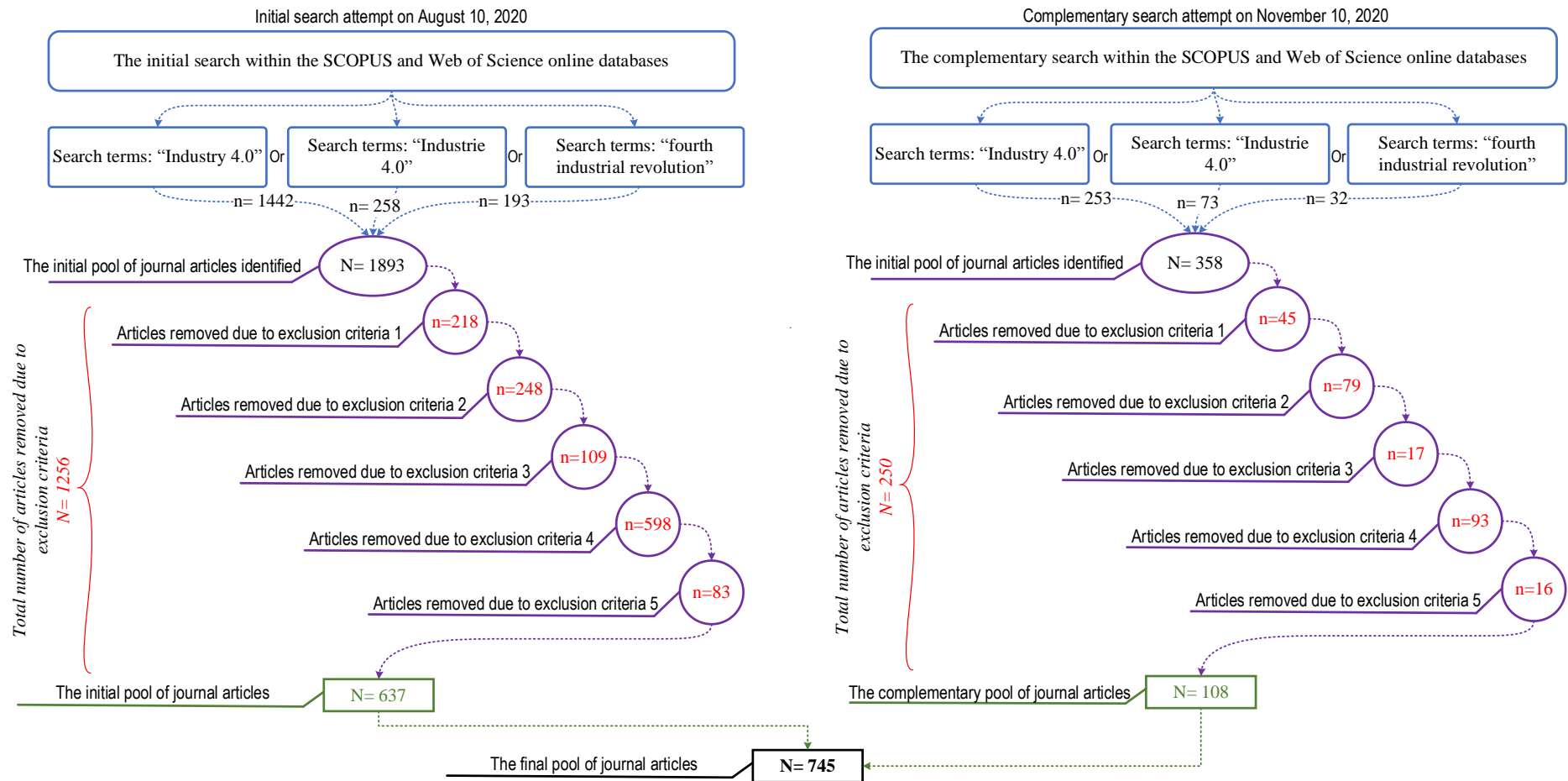


Figure 1. SLR procedure for article selection.

2.2 Data extraction and collection

Content analysis of the eligible articles in the present SLR involved the qualitative and quantitative assessment of each article to identify and collect two categories of information. The first category comprised demographic information, including title, keywords, journal name, abstract, and publication year. EndNote, MS Excel, and VOSviewer were used collectively to collect, manage, and analyze the demographic information of the eligible articles. The second category included the information on the definition, scope, technology trends, design principles, drivers, implications, and ongoing trends of Industry 4.0, which are necessary for answering the study's research questions.

Two investigators conducted data collection procedures independently. A review protocol was designed and executed to standardize the review process and minimize the threat of investigator's bias while collecting data. An MS Excel-based database was created to manage data and records throughout the review. The review protocol followed a comprehensive contextual text denoising procedure to ensure that variations in naming, abbreviations, format, and synonyms of a particular concept are accounted for. For example, the text denoising procedure ensured that expressions such as cyber-physical systems, cyber-physical system, cyber-physical systems (cps), cyber physical systems, cyber physical systems (cps), cyber-physical system (cps), cyber-physical systems, cyber-physical systems (cps), and (CPS) are not regarded as different terms, particularly while using the text processing software. Overall, the data collection procedure involved the following two phases:

Phase 1: To address RQ1, the assessment of eligible articles was conducted quantitatively, mainly with the use of EndNote and VOSviewer. The type of information collected included the title, abstract, journal name, country of contributors, and publication year.

Phase 2: To address the remaining research questions, the investigators conducted a content-centric review of eligible articles qualitatively and quantitatively. The investigators analyzed the main body of each article qualitatively and extracted the necessary information. To simplify and standardize information extraction and archival, a standard recording form was developed inside the MS Excel database and uniformly used for all articles. The study also benefited from IBM's natural language processing service for advanced text analytics to review the overall sentiment of eligible articles and identify key terms, concepts, and categories of interest. This service also allowed the investigators to understand better the emotion associated and the overall negativity and positivity of articles.

3. Data analysis

Consistent with the data collection procedure that involved two different phases, data analysis in the present SLR is bisectonal. Section one involves a basic data analysis based on the descriptive statistical assessment of the 745 eligible articles' demographic information. The data analysis in section one satisfies RQ1. Section two of data analysis includes the in-depth content assessment of 745 eligible articles, qualitatively and quantitatively, to satisfy RQ2 to RQ4.

3.1 An overview of demographic properties

The analysis of the demographic properties of 745 eligible articles offers exciting results. Figure 2a explains that the earliest publication dates back to 2016, meaning the Industry 4.0 discipline is in its embryonic stage. However, the publication growth rate of this discipline has been staggering, as the number of publications has doubled since 2016 each year. Over 50% of 745 eligible articles have been published during 2020 (Figure 2b), showing the exponential growth in popularity of Industry 4.0-related topics in recent years.

Figure 2c explains the occurrence rate of keywords within the 745 eligible articles. Overall, the 745 eligible articles included 2106 typographically unique keywords. Figure 2c ranks the most frequently occurred keywords after applying the denoising procedure. For the sake of conciseness, keywords with the occurrence of at least five have been listed. As expected, Industry 4.0 holds the highest occurrence rate, respectively, followed by popular terms such as the Internet of things, sustainability, smart factory, and cyber-physical system. The majority of highly occurred keywords are concerned with the digital technologies of Industry 4.0. Interestingly, the popularity of keywords such as sustainability, circular economy, and sustainable development highlights the importance of sustainable thinking in the Industry 4.0 discipline. This trend is supported by Figure 2d showing that the *Sustainability* journal ranks 1 by a significant margin regarding the frequency of publication in the Industry 4.0 discipline. Overall, the 745 eligible articles have been published across 179 unique journals. Figure 2d ranks the journals based on the publication occurrence while including journals with the publication occurrence of at least 5. As expected, most of the Industry 4.0 literature contribution belonged to the journals from sustainability, operations management, and operations research disciplines.

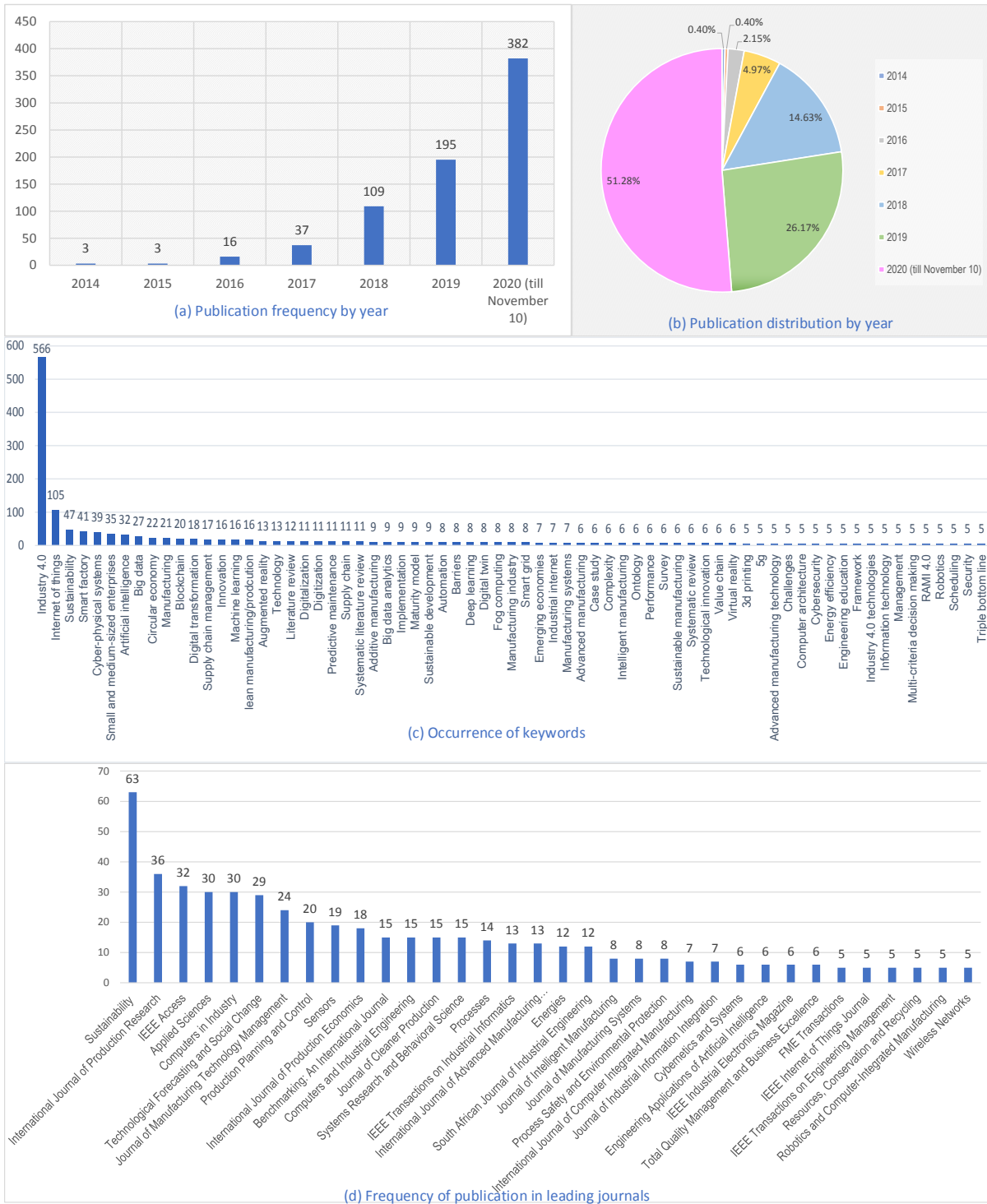


Figure 2. Demographic assessment of eligible articles.

Figure 3 provides exciting insights into the geographical properties of the eligible articles. Figure 3a shows that within the present SLR, Germany, Italy, United Kingdom, India, and the United States, respectively, account for the highest number of publications within the Industry 4.0 discipline. Overall, Industry 4.0 literature involves the contribution of 109 countries, as observed across the 745 eligible articles. Figure 3b explains the geographical distribution of citations within the Industry 4.0 background, indicating that scientific contributions from Germany, the United States, China, United Kingdom, and Italy have received almost 50% of all citations across the literature. Figure 3c offers a network visualization of co-authorships with countries as the unit of analysis for the 745 eligible articles, with the number of documents for each country limited to 5. This figure clearly shows that Germany is regarded as the origin of the Industry 4.0 research discipline, offering the earliest

and most profound contributions. Besides Germany, industrialized countries such as Austria, Switzerland, Japan, Taiwan, and Singapore were among the earlier contributors to the Industry 4.0 literature. Nevertheless, transitioning countries such as China, India, and Brazil account for a significant portion of recent, especially 2020, contributions to the Industry 4.0 literature.

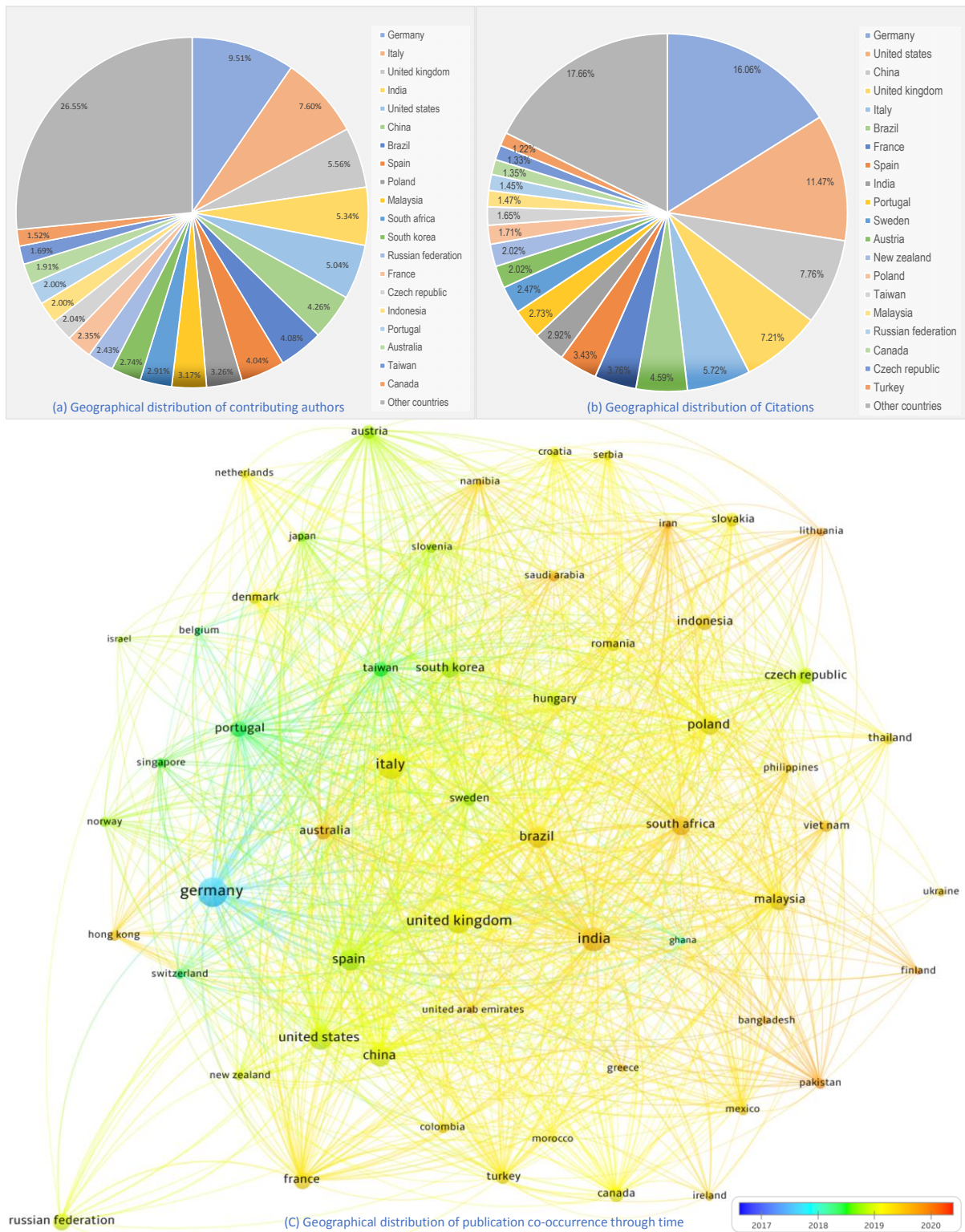


Figure 3. Assessment of the geographical distribution of eligible articles.

3.2 Industry 4.0 definition and scope

The content analysis of 745 eligible articles reveals that scholars have been struggling with offering a unified definition of Industry 4.0. The earlier studies tend to narrate Industry 4.0 as the digitalization of manufacturing processes, limiting it to factories (Lasi et al., 2014; Stork, 2015; Strandhagen et al., 2017), mainly in the form of implementing advanced digital manufacturing technologies such as 3D printing, modeling, simulation, virtualization, and data management technologies (Fatorachian and Kazemi, 2018; Kerin and Pham, 2019; Neal et al., 2019; Theorin et al., 2017). More recent articles, mainly published in 2019 and 2020, regard Industry 4.0 as the digital transformation of industrial value chains, a paradigm shift across various industries (e.g., Ghobakhloo, 2020a; Rahman et al., 2020; Ramakrishna et al., 2020). Figure 4 displays the literature transition from manufacturing-oriented definition to the industrial value chain-oriented definition of Industry 4.0. Comparing the trendlines in Figure 4 shows that more recent papers are proportionally less concerned with defining Industry 4.0. Nonetheless, the industrial value chain-oriented definition of Industry 4.0 outscores the manufacturing-oriented definition in 2020.

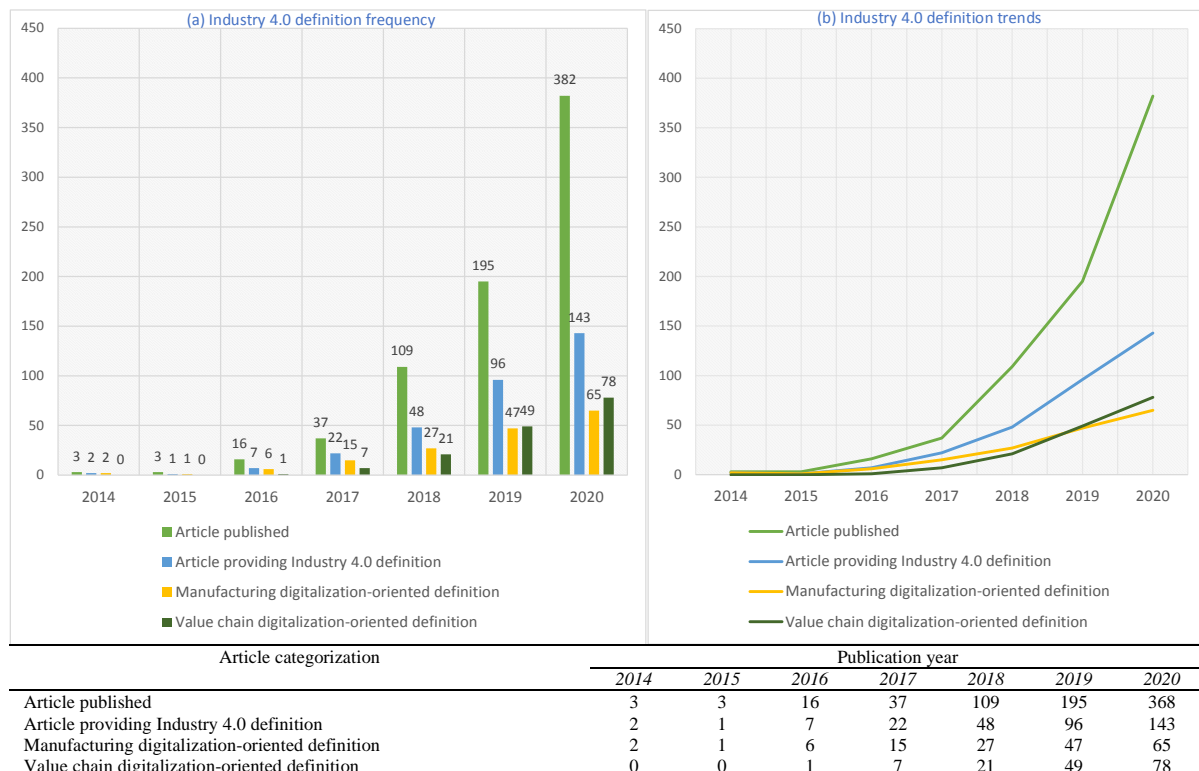


Figure 4. Industry 4.0 definition categorization.

3.3. Building blocks of Industry 4.0

To address the elusive nature of Industry 4.0 and the underlying digital transformation, the literature commonly characterizes Industry 4.0 based on a wide variety of underlying technology trends and design principles (Castelo-Branco et al., 2019; Derigent et al., 2020; Lu, 2017). The technology trends and design principles, collectively, explains that the technology trends of Industry 4.0 are advanced digital, information, and operations technologies that are indeclinable to shaping the undergoing digital industrial transformation (Alcácer and Cruz-Machado, 2019; Ghobakhloo and Fathi, 2020; Liao et al., 2017; Sackey et al., 2017). Ghobakhloo (2018) Design principles are desirable conditions that enable industrial entities to achieve digital transformation success and unlock the potential benefits of Industry 4.0 technology trends.

3.3.1 Technology trends of Industry 4.0

The review of eligible articles reveals that the contribution of existing studies to the technology level of Industry 4.0 has been staggering. Nonetheless, much fuzziness exists around the classification of Industry 4.0 technology trends, mainly because of the diversity of approaches coming from scholars among different disciplines, and industrial actors that have addressed this paradigm based on their particular values, and interests. The content analysis of 745 eligible articles showed that the technology trends of Industry 4.0 could be categorized into two clusters, termed *core technologies* and *facilitating technologies* clusters in the study.

The *core technologies* of industry 4.0 are the modern technological innovations that have been in development within the past few decades but have matured enough to become commercially available within the last decade.

Figure 5 lists the core technologies of Industry 4.0 identified across the content analysis of eligible articles, along with the frequency of occurrence. The frequencies listed in Figure 5 do not represent the mere occurrence of these keywords among the eligible articles. Instead, the numbers represent the articles that have allegedly acknowledged these technologies as building blocks of Industry 4.0, as identified via content analysis of 745 eligible articles. Internet of things and cyber-physical systems have been the two most hyped components of Industry 4.0 within the industrial and academic communities (Ghobakhloo, 2018; Liao et al., 2017; Manavalan and Jayakrishna, 2019; Villalonga et al., 2020), and a similar pattern is observed in Figure 5.

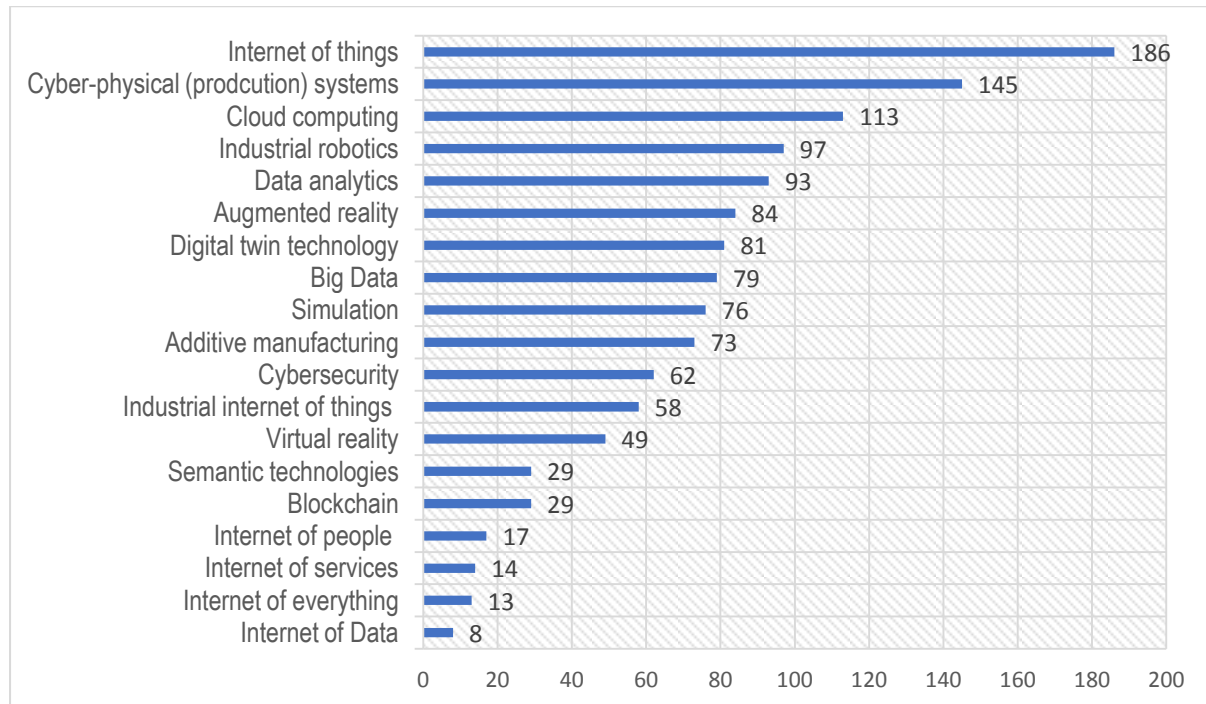


Figure 5. Core technologies of Industry 4.0.

The majority of core technologies listed in Figure 5, such as additive manufacturing, augmented reality, Cloud computing, and virtual reality, are highly elaborated and well-studied within the literature (Liao et al., 2017; Lu et al., 2017). For example, several articles have addressed the industrial applications of augmented reality (Blanco-Novoa et al., 2018; Bruno et al., 2019; Gattullo et al., 2019), surveyed the challenges and drivers of augmented reality industrial applications (Masood and Egger, 2019), and discussed its advantages in the real industrial scenarios (van Lopik et al., 2020). The industrial internet of things, cyber-physical (production) systems, and digital twin technology are higher-tier controversial technologies causing debates, out of the 18 core technologies of Industry 4.0. literature,

The literature offers two perspectives on the industrial internet of things (IIoT) concept. From the generic perspective, IIoT refers to an umbrella term for the industrial application of the IoT technology outside the consumer market (Kabugo et al., 2020; Nicolae et al., 2019; Yli-Ojanperä et al., 2019). However, the more practical perspective regards IIoT as the new vision of IoT in the industrial sector characterized by unique functions and diverse core objectives. IIoT, within this perspective, is not limited to the implementation of industrial sensors and interconnectedness, as it may involve various functions such as data processing, real-time communication, and even decentralized decision-making of smart components for better process monitoring, operation efficiency, and interaction management of industrial assets (Aazam et al., 2018; Posada et al., 2015; Wan et al., 2016). From this perspective, IIoT and CPS are highly intertwined and overlapping. Within the Industry 4.0 literature, when IIoT is mentioned, the CPS concept usually follows, and vice versa (Ghobakhloo, 2018). Figure 6a offers a simple graphical presentation of IIoT-CPS interaction. Although the literature does not offer a standard definition for IIoT or CPS, the reference architecture model developed for these technologies offers similar functions (e.g., Lins and Oliveira, 2020; Mosterman and Zander, 2016; Neal et al., 2019; Wan et al., 2016).

The content analysis of eligible articles also shows that the literature characterizes IIoT, CPS, and digital twin technology as higher tier technology trends of Industry 4.0. These technologies are not something that industrial

entities can achieve overnight. They severely rely on the integration of various *facilitating technologies*, sensors, networking processes, protocols, Cloud, operations technologies, and even human components (Karnouskos et al., 2020; Tran et al., 2019; Wan et al., 2016). Consistently, the deployment of higher tier technologies of Industry 4.0 relies on a strategic and staged roadmap complemented with a certain degree of digital transformation maturity and readiness (Ghobakhloo, 2018; Mittal et al., 2018; Santos and Martinho, 2019; Wagire et al., 2020).

As shown in Figure 5, the literature recognizes the concept of the *internet of everything* (Klingenberg et al., 2019; Sanchez et al., 2020) that emerge from CISCO defined as the interconnectedness of networked connection of people, process, data, and things. Expanding this idea, the Industry 4.0 literature conceptualizes IoE as Figure 6b, a networked connection that facilitates the integration of physical objects (machines, equipment, and smart gadgets), human workforce, smart products, smart consumers, and intelligent processes. Similar to IIoT, Internet of Data (IoD), Internet of People (IoP), and Internet of Services (IoS) represent the specialized applications of IoT in various fronts of Industry 4.0. IoP, for example, exploits the legacy IoT infrastructure to enable humans (workforce on the industrial side and consumer on the market front) and their smart devices to become the active elements of the Industry 4.0 environment (Conti et al., 2017; Molano et al., 2018). Overall, the emergence of the IoE concept aligns with the value chain digitalization-oriented definition of Industry 4.0.

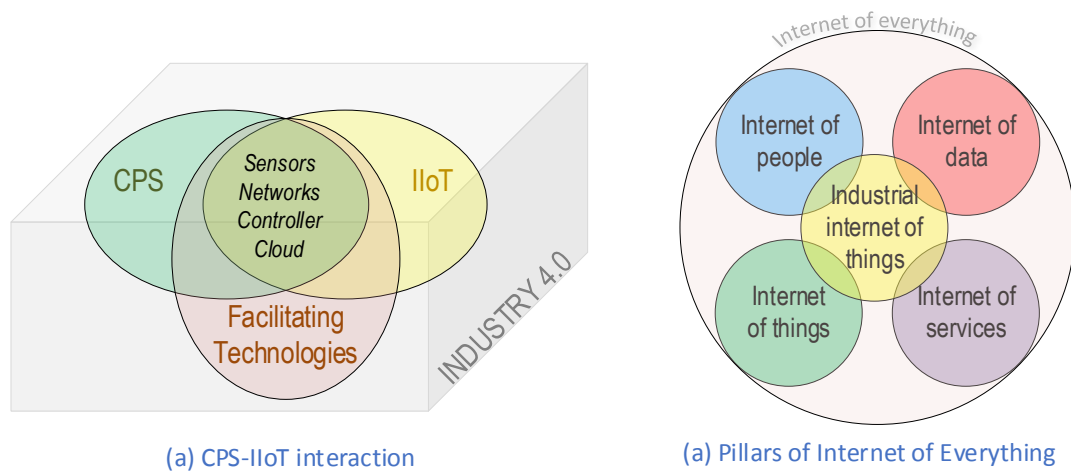


Figure 6. Industry 4.0 and the interaction of major technology trends.

The *facilitating technologies* of Industry 4.0 are the more traditional, prevailing, and mature information and operations technologies that enable the *core technologies* of Industry 4.0 to deliver their intended functions. Figure 7 lists the 11 facilitating technologies of Industry 4.0, as recognized by the eligible articles. These technologies have been commercially available and commonly in use across industries within the past few decades. Nonetheless, the literature commonly uses the prefix *smart* or *intelligent* while listing these technologies, explaining that these core technologies should be nowadays developed fundamentally different from the ground up to support a certain degree of integrability. For example, the so-called intelligent ERP should be developed Cloud-native and architected to interact with application programming interfaces for entities of a smart system securely in real-time, which may involve interacting with entities of an industrial value chain via IIoT, IoP, and IoS.

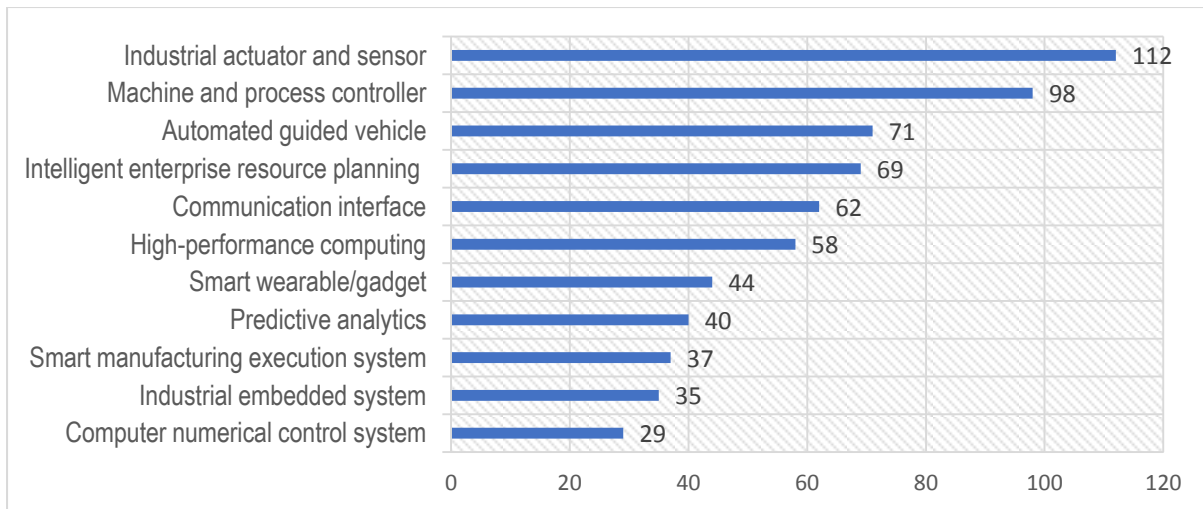


Figure 7. Facilitating technologies of Industry 4.0.

3.3.2 Design principles of Industry 4.0

The literature offers diverse insights into the categorization of the Industry 4.0 design principles. The content assessment of eligible articles in the present study and the application of denoising leads to the classification of Industry 4.0 design principles presented in Figure 8, along with the frequency of direct contributions done to each concept. The section offers a unified definition of each concept concisely to address the ambiguity around each design principle's understanding. *Real-time capability* means every smart component of an Industry 4.0-based ecosystem should be able to communicate with other smart components in real-time (Lu, 2017; Pollak et al., 2020). In turn, each intelligent sub-ecosystem should analyze the data collected in real-time and facilitate concurrent decision-making (Terziyan et al., 2018). *Vertical integration* concerns the integration and networking of all logical layers of an industrial organization, from smart production systems and machinery at the field level through production management, sale and marketing, customer service, and research and development departments (Dalenogare et al., 2018; Wang et al., 2016). Alternatively, *horizontal integration* involves the hierarchical integration of multiple production facilities for a multifaceted manufacturing system, extending to integrating various entities across value-creation networks, including suppliers, manufacturing networks, delivery channels, and consumers (Ghobakhloo, 2020b; Veile et al., 2020). *Customer orientation* refers to placing customer centricity as one of the core digital transformation objectives under Industry 4.0 (Ghobakhloo, 2018). This principle entails the goal-oriented application of Industry 4.0 digital technologies for strengthening the customer experience via delivering individualized products and services associated with unique and memorable experiences (Tien, 2020; Wang et al., 2017).

The *virtualization* principle values the replication of Industry 4.0 physical components via merging sensor data acquired from the physical world into a virtual instance known as the digital twin (Qi and Tao, 2018). The virtualization of Industry 4.0 components such as new products, processes, and even smart factories would enable engineers and designers to optimize Industry 4.0 components' functionality in complete isolation, reducing the risk of design failure or disrupting the physical processes (Santos et al., 2020; Schluse et al., 2018). *Interoperability* refers to the ability of Industry 4.0 sensor-equipped micro components such as equipment, tools, machines, processes, human workforce, parts, and products to communicate with each other through the IoE (Lu, 2017; Pedone and Mezgár, 2018). *Modularity* denotes the ability of manufacturing value chains, involving factories, upstream supply chains gathering materials and services, and downstream distribution chains delivering goods to adapt to the new market preferences rapidly (Yin et al., 2018). A modular manufacturing value chain in Industry 4.0 setting is usually characterized as a digital process enabling flexibility, dynamic material flow systems, agile product development, modular decision-making procedures, and agile procurement planning (Ghobakhloo, 2018; Maganha et al., 2018). *Decentralization* refers to the ability of Industry 4.0 components, particularly intelligent control mechanisms and self-regulating systems such as CPS, to make independent yet informed decisions (Huang et al., 2017). Decentralization enables the smart components of Industry 4.0 to operate as autonomously as possible. Under decentralization, autonomous tasks are delegated to a higher level, merely when control mechanisms observe abnormalities or conflicting goals (Koh et al., 2019; Neal et al., 2019).

Service orientation in Industry 4.0 environment entails the application of digital technologies for shifting toward the *as-a-service-based* business models (Frank et al., 2019). The product-as-a-service business model is among the main principles of information-driven service-oriented monetization in Industry 4.0 (Veile et al., 2020; Xu et

al., 2018). The product-as-a-service business model seeks for leveraging pay-by usage schemes or manufacturing-as-a-service business model for turning machinery from capital expenditures to operating expenses for manufacturers. The least acknowledged principle, *technical assistance*, denotes the paradigm shift in human resources' role in the Industry 4.0 context (Lin et al., 2017). This paradigm involves the gradual transition of the workforce from machine operators to problem-solvers and decision-makers via empowering them by providing aggregated and visualized information in real-time. Technical assistance also involves supporting the workforce through the industrial automation of unsafe, unergonomic, and exhausting tasks (Golan et al., 2020; Longo et al., 2017).

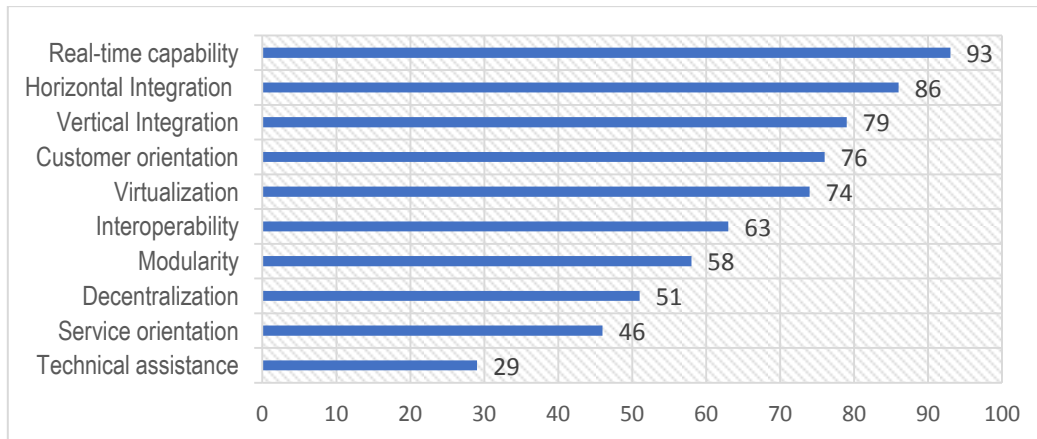


Figure 8. Industry 4.0 design principles and mention frequency within the literature.

3.4. Industry 4.0 value drivers

The literature offers different perspectives on the possible benefits of Industry 4.0 that drive the digital industrial revolution. The content analysis of 745 eligible articles and denoising procedure identified three major categories of Industry 4.0 benefits, termed economic benefits, social benefits, and environmental benefits in the present study. As shown in Figure 9a, the literature mainly acknowledges the economic benefits of Industry 4.0, which itself comprises two clusters of opportunities for manufacturing productivity and opportunities for business competitiveness. Figure 9b lists the eight manufacturing opportunities that Industry 4.0 may offer, along with the frequency of appearance among the 745 eligible articles. Not surprisingly, the manufacturing productivity opportunities listed in Figure 9b, such as labor productivity and reduced time to market, are comparable with the benefits of intelligent (smart) manufacturing frequently discussed within the existent literature. Figure 9c lists the business competitiveness opportunities of Industry 4.0, which shows that organizational agility is the most prevailing advantage that Industry 4.0 may offer to business. Unexpectedly, and despite being less recognized, improved corporate image is among the economic benefits of Industry 4.0. The social benefits of Industry 4.0, as shown in Figure 9d, involves five different functions. Product individualization is the most recognized advantage that, along with the reduced cost of consumer products and better customer experience, Industry 4.0 offers to consumer society. Although the literature recognizes the disruptive force of Industry 4.0 for the labor market (Abdul-Hamid et al., 2020), the consensus is that the digital industrial transformation would improve labor conditions and create more new job opportunities than it eliminates (Ghobakhoo, 2020a). Figure 9e explains that the literature, sustainability discipline in particular, holds high hopes for the contribution of Industry 4.0 to environmental preservation, mainly through resource consumption efficiency along with energy consumption, waste, and emission reduction. Industry 4.0 is also believed to offer unique opportunities to integrate renewable energy sources into the energy distribution and transmission systems. Finally, the environmental benefit of Industry 4.0 also involves applying underlying digital technologies for developing and producing more sustainable products and services.

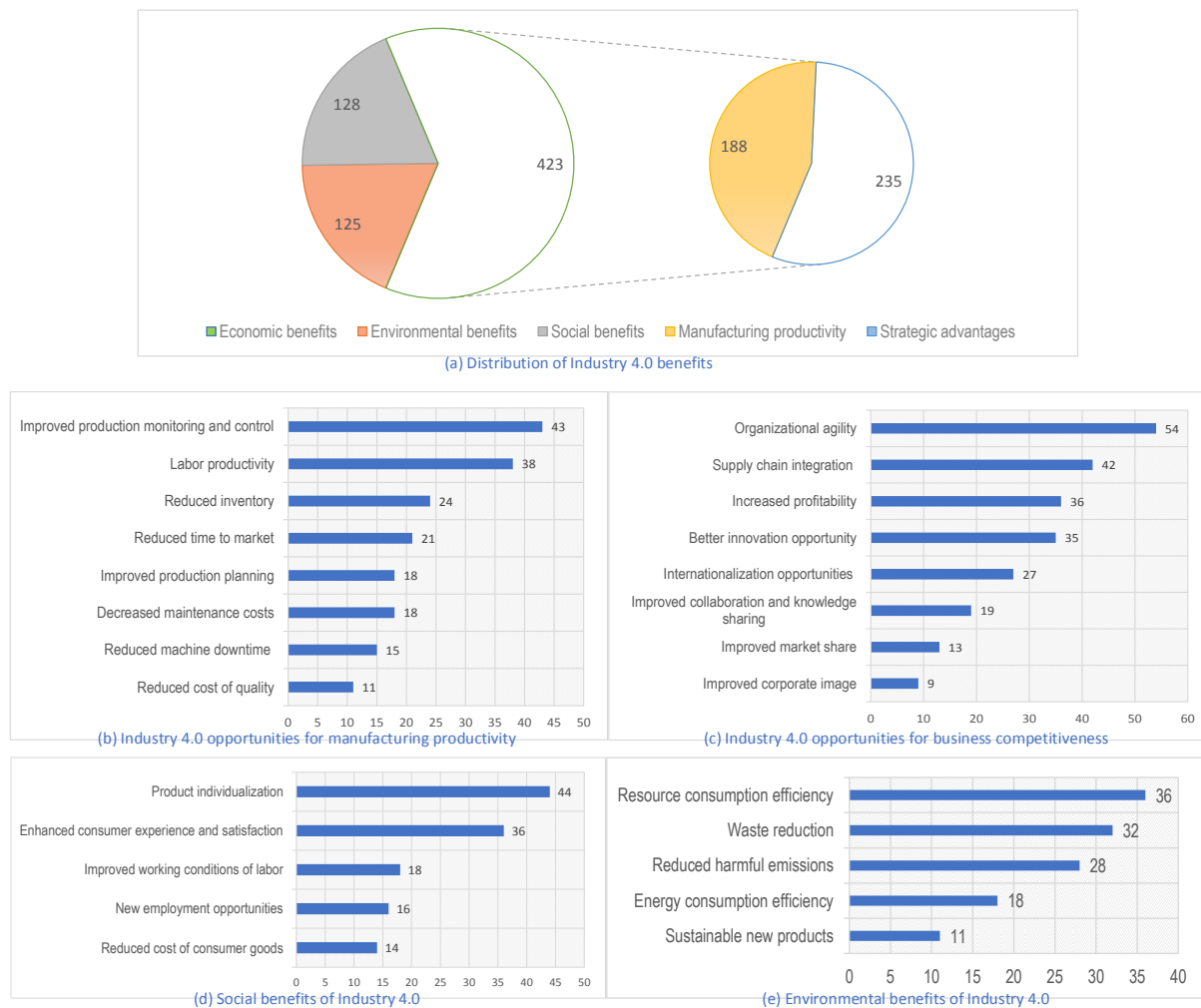


Figure 9. Benefits of Industry 4.0 and the mention patterns within the literature.

3.4.1 Industry 4.0 disadvantages

The SLR reveals that literature is largely over-optimistic regarding the economic and socioenvironmental impacts of Industry 4.0. The SLR did not find a single article dedicated to the possible disadvantages of Industry 4.0. Nonetheless, literature widely acknowledges the drawback of Industry 4.0 in terms of possible job loss due to automation (Birkel et al., 2019) and severe cybersecurity risks associated with digitalization (Lezzi et al., 2018). The more recent literature is also beginning to express concerns regarding the negative impacts that Industry 4.0 might introduce, such as the energy rebound effect, widening the digital divide, and intensifying corporate and social inequality (Ghobakhloo, 2020; McCredie et al., 2019).

3.5 Industry 4.0 digital transformation determinants

The factors that may impact the success or failure of digital transformation under Industry 4.0 have received considerable more attention within the Industry 4.0 literature (e.g., Bilbao-Ubillos et al., 2020; Bhatia and Kumar, 2020; Moeuf et al., 2020; Park and Huh, 2018). These factors, which are termed determinants in the present SLR, can act as enablers of digital transformation when favorably presented or barriers when undesirably lacking. The content analysis of eligible articles identifies numerous determinants of Industry 4.0 digital transformation. After applying the denoising procedures and accounting for overlaps, Industry 4.0 digital transformation determinants are listed in Figure 10. This figure sorts the determinants based on the total number of mentions among the eligible articles, including mentions as both drivers and barriers. Financial resource availability is the most frequently mentioned determinant of digital transformation, mainly viewed as a barrier. This finding indicates that the literature has been deeply concerned with the lack of capital for fueling Industry 4.0 digital transformation. A closer look at Figure 10 reveals that technological determinants have been mentioned more frequently compared to the organizational determinants. Among the 13 determinants listed in Figure 10, external support for digitalization and data security, ownership, and regulation are the only two environmental determinants of digital transformation. The literature mainly regards the external support for

digitalization as the governmental policies for Industry 4.0, and to a lesser extent, the digital readiness of value chain partners (Castelo-Branco et al., 2019; Lin et al., 2017; Stentoft et al., 2020).

A narrow stream of research addresses the complexity of the relationships among the determinants of Industry 4.0 digital transformation and argues that the complex relationships among determinants and the order in which they should be present have a massive impact on the quality of advantages offered by the digital transformation under Industry 4.0 (Stentoft et al., 2020; Türkeş et al., 2019).

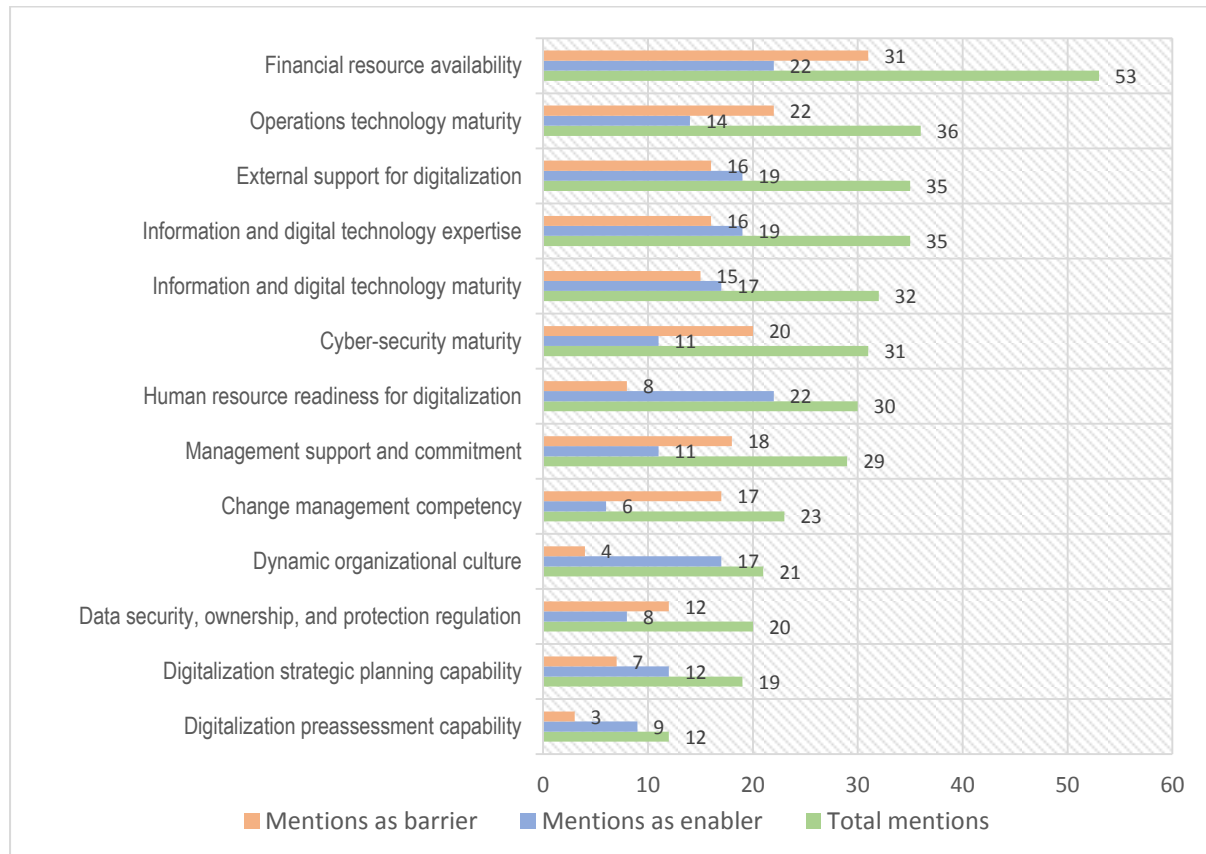


Figure 10. Determinants of Industry 4.0 digital transformation.

4. Discussion

The first research question within the present SLR concerned the popularity and ongoing trends within the Industry 4.0 literature. The descriptive assessment of 745 eligible articles revealed that the growth rate of Industry 4.0-related academic publications appears to be doubling yearly. In particular, more than 50% of all the contributions done to Industry 4.0 literature belongs to the year 2020. Although scholars from industrial economies such as Germany, Italy, and the US are starkly ahead in contributing to the Industry 4.0 literature, scholars from more than 80 countries have contributed to the development of the eligible articles reviewed in the study. The technology and economic aspects of digital transformation are the leading topics within the Industry 4.0 discipline. Nonetheless, previous studies have addressed countless aspects of Industry 4.0 at the micro, meso, and macro levels of analysis, involving the most specialized contribution such as protocol development for wireless sensors up to the broadest agendas such as digitalization policy-making. Undoubtedly, Industry 4.0 and the underlying digital transformation has become one of the most popular and cutting-edge research topics across a wide variety of research disciplines.

The second research question of the study concerned the ongoing trends in the conceptualization and scope of the Industry 4.0 phenomenon, and the SLR provided exciting insights in this regard. The early literature thought of Industry 4.0 as the digitalization and automation of traditional manufacturing processes. However, the literature is witnessing a paradigm shift in the definition of Industry 4.0, from a factory-oriented definition to a value chain-related definition. Academia nowadays regards Industry 4.0 as the digital transformation of industrial value chains. From this perspective, Industry 4.0 translates into the smartization of all manufacturing and value creation processes, involving the digitalization of plants, suppliers, customers, and distribution channels. Consistently, the literature widely acknowledges that Industry 4.0 and the underlying digital

transformation is no longer limited to the manufacturing industry, as the implications of Industry 4.0 in agriculture (Lele and Goswami, 2017; Trivelli et al., 2019), construction (Dallasega et al., 2018; Oesterreich and Teuteberg, 2016; Patrucco et al., 2020), healthcare (Aceto et al., 2020; Pace et al., 2019), tourism (Bilotta et al., 2020) and energy (Kabugo et al., 2020; Scharl and Praktiknjo, 2019; Su et al., 2020) industries account for a significant portion of the literature. Overall, Industry 4.0 involves the digital transformation of industrial organizations. Industry 4.0 digital transformation is a complex phenomenon, expanding beyond discrete digitalization projects. The literature attempts to address the elusiveness of this perspective by describing Industry 4.0 based on its two building blocks, namely technology trends and design principles. Technology trends of Industry 4.0 consist of core technologies and facilitating technologies. Core technologies are modern and iconic digital technologies that have become commercially available within the last decade, such as augmented reality, additive manufacturing, Cloud data, and blockchain technology. The core technologies of Industry 4.0 come in two different tiers in terms of complexity and overall integrability requirements. Facilitating technologies include a wide variety of mature and sometimes called legacy information and operations technologies that allow the core technologies to integrate, operate, and function properly. The second building block, the design principles of Industry 4.0, includes ten favorable conditions, the existence of which is vital to the Industry 4.0 digital transformation success.

The third research question addressed the driving force behind the digital transformation under Industry 4.0. The present SLR revealed that three major categories of economic, environmental, and social benefits are the value drivers fueling the accelerating advancement of Industry 4.0. The SLR results showed that more than 60% of Industry 4.0 benefits mentioned within the literature are classified as economic benefits. The economic benefits of Industry 4.0 include two major clusters, including the opportunities offered for manufacturing productivity (such as labor productivity or improved production planning) and opportunities offered for overall business competitiveness (such as organizational agility and innovation opportunities). The literature also believes that Industry 4.0 offers relatively equal opportunities for environmental and social development. Product individualization and enhanced customer experience are among the more prevailing social benefits of Industry 4.0. The environmental benefits of Industry 4.0 involve various eco-efficiency functions, such as resource consumption efficiency and sustainable product development.

The fourth research question concerned identifying the determinants of Industry 4.0 digital transformation. The SLR identified 13 determinants that may positively or negatively impact digital transformation success under Industry 4.0. Determinants identified fall into three clusters of technological, organizational, and environmental determinants. Information, digital, and operations technology maturity is the most emphasized technological determinant of Industry 4.0 transformation. Financial resource availability is the most critical organizational determinant, and the literature generally is concerned with the undesirable lack of capital for investing in and progressing digital transformation. Environmental determinants involve conditions that fall outside organizational and industrial boundaries, such as supportive policies for digitalization or data security, ownership, or protection regulations. The literature commonly labels the determinants as *drivers* when favorably presented or *barriers* when undesirably lacking.

4.1 Theoretical implications

The present study addressed the ambiguity surrounding Industry 4.0 definition, concluding that Industry 4.0 is the digital transformation of value creation and delivery channels across various industries. It is not merely limited to the digitalization of production processes within the manufacturing industry. The study further revealed that the underlying digital transformation of Industry 4.0 involves the implementation of core digital technologies such as IIoT, AI, and additive manufacturing while simultaneously developing the design principles of Industry 4.0, such as vertical integration, interoperability, and real-time capability. Consistently, Industry 4.0 should not be simplified as merely implementing digital solutions that are defined as discrete organizational information system projects. Industry 4.0 is a novel paradigm in the management and control of the industrial value chains, requiring value members to endure gradual and comprehensive change processes. Consistently, caution should be exercised when using the fuzzy term 'Industry 4.0 implementation'.

4.2 Practical implications

The present SLR and underlying findings may provide industrialists, practitioners, and academicians with practical implications listed below:

- Industry 4.0 digital transformation is a gradual and complicated process involving implementing many technologies and developing several design principles. Many determinants may impact the digital transformation processes positively or negatively. The previously referred determinants are interrelated; meaning the order at which they should be developed may significantly impact the effectiveness of digital transformation efforts. For example, the literature infers that capital availability

is the building block of digitalization efforts, enabling the development of other favorable determinants such as digitalization knowledge and expertise. Given the complexity of Industry 4.0 digital transformation, devising a detailed strategic plan for micromanaging countless Industry 4.0 transformation requirements is a strategic priority for industrial organizations.

- The majority of Industry 4.0 advantages are categorized as manufacturing-economic benefits. Industry 4.0 also offers significant socio-environmental benefits; nonetheless, these are the more remote opportunities that Industry 4.0 may offer. The manufacturing-economic growth opportunities of Industry 4.0 are expected to enable higher employment opportunities in the long run, increase worker wages, improve working conditions, and address the corporate inequality issue via promoting internationalization. Alternatively, manufacturing efficiency, cost-saving, and manufacturing profitability functions of Industry 4.0 are expected to gradually promote the large-scale development of energy and resource efficiency capabilities across value networks, leading to waste reduction and resource and energy efficiency. Therefore, the socio-environmental opportunities of Industry 4.0 should be interpreted in light of the manufacturing-economic benefits of the digital industrial transformation.

6. Conclusion and future directions

The present SLR addressed the cutting-edge topic of the fourth industrial revolution and attempted to offer a clear picture of the Industry 4.0 concept, scope, value drivers, and critical determinants. To achieve its core objectives and answer the four research questions designed, the SLR identified a vast pool of 745 eligible articles and proceeded with the necessary demographic and content-centric assessments. Consistently, the study addressed the ambiguity surrounding the definition of Industry 4.0, delivered a comprehensive assessment of Industry 4.0 building blocks, explained the main reasons for the accelerating growth of the digital industrial revolution, and explained what factors might determine the success or failure of digital transformation efforts under Industry 4.0.

The present SLR followed the necessary standard procedures, yet, the results should be interpreted in the light of existing limitations, such as English language or journal article exclusivity, which can be addressed by future researchers. More importantly, the study could not verify the possibility of Industry 4.0 negative impacts, mainly due to the lack of evidence within the eligible articles. The academic literature holds an overoptimistic view of Industry 4.0, promising an ideal digitalized ecosystem that offers 'clean' economic growth and socio-environmental prosperity. The hype surrounding idealized benefits of the fourth industrial revolution and the overexcitement of academia are somewhat expected, given Industry 4.0 is in its infancy, and the real economic and socio-environmental impacts of the digital industrial revolution have not been empirically measurable in practice. Industry 4.0 will gradually alter the world of business, value delivery channels, and how people work and live. Similar to any significant breakthrough in the history of humankind, Industry 4.0 will contain side-effects. The scientific and sociopolitical communities are already questioning the disruptive force of Industry 4.0, intensifying the digital divide, data privacy conflicts, labor market polarization, and rebound effects. Future studies are consistently invited to address the concerns over the negative side effects of Industry 4.0 scientifically, identifying the transitional or large-scale undesirable consequences of the digital industrial revolution and devising necessary policies to address these pressing issues proactively.

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Appendix

Table A1. An overview of selected SLR studies in the field of Industry 4.0.

Scholars	Filed of SLR	Type of documents reviewed	Number of documents reviewed	Key research questions and contribution
Oesterreich and Teuteberg (2016)	Implications of automation and digitization in the construction industry	Journal articles in English and German	149	Type of Industry 4.0 digital technologies, level of implementation, and their possible implications
Liao et al. (2017)	Overall allocation and status of Industry 4.0 phenomenon	Conference and journal article	224	Application fields, research directions, and enabling features of Industry 4.0
Kamble et al. (2018)	Technologies, process integration, and sustainability impacts	Journal articles	85	Research approaches and current status of Industry 4.0
Mariani and Borghi (2019)	Emerging intellectual structure and potential service industry evolution	Articles, books, conference papers, and reports	757	Intellectual structure of Industry 4.0, especially in the service industry
Tirabeni et al. (2019)	Digital industrial revolution and implications for the sustainable society	Journal articles	42	Emerging features of Industry 4.0 and dimensions of sustainability
Abdirad and Krishnan (2020)	Electronic logistics and smart supply chain	Journal articles	56	Supply chain management trends in Industry 4.0
Belinski et al. (2020)	Dimensions of organizational learning	Journal and conference articles	50	Organizational learning concept in Industry 4.0 and nine underlying dimensions
Bittencourt et al. (2020)	Synergy between lean thinking and Industry 4.0	Journal papers, conferences, and book chapters	33	Lean manufacturing and Industry 4.0 interactions and possible barriers
Bueno et al. (2020)	Smart production control and planning, performance and environmental implications	Journal articles	102	Production planning and control smart capabilities in Industry 4.0
Hoyer et al. (2020)	Potential determinants of Industry 4.0 implementation	Book chapters, journal papers, and conference proceedings	64	Reasons for organizational implementation of Industry 4.0
Núñez-Merino et al. (2020)	Taxonomy of research on digital industrial revolution and supply chain management	Journal articles	78	Interaction of digital technologies, Industry 4.0, and lean supply chain management
Osterrieder et al. (2020)	Smart factory concepts, perspectives, and future directions	Journal articles	106	Perspectives on smart factory concept under Industry 4.0
Rosa et al. (2020)	The association of Industry 4.0 and the circular economy	Book chapters, journal and conference papers, proceedings	158	Circular Industry 4.0 and interactions with the digital circular economy
Vianna et al. (2020)	Crowdsourcing in supporting the implementation of Industry 4.0	Articles published in scientific periodicals	31	The role of crowdsourcing in Industry 4.0
Zonta et al. (2020)	Challenges and limitations in predictive maintenance	Journal and conference articles	47	Models, methods, and architecture for predictive or monitoring under Industry 4.0
Rauch et al. (2020)	Paradigms in anthropocentric production caused by Industry 4.0, focusing on humans and machines	Journal and conference publications	58	The anthropocentric perspective of production within the Industry 4.0 setting