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The fourth industrial revolution of supply chains: A tertiary study

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ABSTRACT

This paper unfolds the ongoing fourth revolution of supply chains (4SC) and proposes guidelines for future research. The review of sixty-five literature reviews follows three stages: bibliometric analysis of Industry 4.0, its synergies with supply chain transformation, and state-of-the-art assessment. 4SC is a context-bound technological change driven by organizational and cultural priorities, aiming to create more sustainable networks to serve the customers and support responsible decisions in the supply lifecycle. The proposed framework can assist future literature reviews and digital transformation proposals for 4SC that need to frame their context and incorporate functions to endure change.

1. Introduction

The Fourth Industrial Revolution (4thIR) is a global and unstoppable movement that "*will affect governments, businesses and economies in very substantial ways*" (Schwab, 2015). Comprehensive digital agendas for the interconnected, rapidly changing, and socially disruptive industry of the future are put in place. For example, in Europe, Industry 4.0 was launched in late 2011 as part of the high-tech strategy of the German government to transform the industry using cyber-physical systems. Their aim was to make factories "smarter" and apt to respond to the growing demands of the society (Lasi et al., 2014; Xu et al., 2018). However, the transformation of production systems goes beyond the organizational borders to ensure horizontal, vertical, and end-to-end digital integration (Brettel and Friederichsen, 2014). Currently, the most advanced economies in the world (Moeuf et al., 2018; Schneider, 2018), global industries (Isaka et al., 2016), and consulting companies shift supply chain transformations to the top of industrial priorities. Two reasons that justify this importance are the increasing amount and potential of data (Waller and Fawcett, 2013) and the innovations in the supply chain (Sabri et al., 2018).

The term Supply Chain 4.0 is now commonly used in academia (da Silva et al., 2019; Frederico et al., 2019) and industry (Alicke et al., 2016), referring to the ongoing sociotechnical transformations that Industry 4.0 brings to supply chains (Frederico et al., 2019). The need to understand the trends in this field emerges from the increasing adoption of digital technologies. For example, cloud computing, mobile platforms, augmented/virtual reality, simulation, internet of things (IoT), autonomous robots, or additive manufacturing (Alicke et al., 2016; da Silva et al., 2019; Frederico et al., 2019). Rather than being seen in isolation, these technologies must be combined to make Industry 4.0 a reality, taking advantage of the knowledge obtained from diverse disciplines (Xu et al., 2018). Nevertheless, technologies are pointless if their adoption does not lead to new business models, redesigned business processes and services, and work systems that adhere to the characteristics of each business or sector of the economy (Moeuf et al., 2018). Consequently, researchers also face the managerial challenges of digital transformation (Schneider, 2018), logistics (Hofmann and

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Rüsch, 2017), and sustainability (Nascimento et al., 2019), making evident that interdisciplinary approaches are vital.

This paper adopts the abbreviation 4SC to integrate (1) the important contributions in Supply Chain 4.0 literature, (2) the profound transformations in "*velocity, scope, and systems impact*" that shapes the 4thIR (Schwab, 2017), and (3) the inevitability of initiatives such as Industry 4.0. Therefore, 4SC is addressed in this study as (1) a process of change and (2) a new instantiation of industrial supply chains.

The popularity of digital transformation in industry and its supply chains is exponential in many research areas. For example, business, operations, technology, and work and skills (Galati and Bigliardi, 2019). Despite its youth, several "4th/4.0" industrial systematic literature reviews can be found in prominent databases (e.g., Scopus, Web of Science, or Google Scholar, among others), with remarkable citation records. Systematic literature reviews, also known as secondary studies, are essential to consolidate knowledge in a particular field and should follow specific guidelines to ensure rigor and validity (Tranfield et al., 2003; Webster and Watson, 2002). Sound literature reviews can help the development of emerging areas in the Fourth Industrial Revolution, allowing the identification of opportunities for future research (Tranfield et al., 2003).

A tertiary study is a form of review that considers secondary studies as its main source (Kitchenham et al., 2010). The review of literature reviews offers an integrative and broader understanding of the field under investigation. Previous tertiary studies in supply chain make recommendations on how systematic reviews should be conducted (Hochrein et al., 2015) and there are influential examples in technological areas such as software engineering (Kitchenham et al., 2010). However, as secondary reviews flourish in the context of supply chain in the Industry 4.0 era, tertiary studies are still rare. This paper aims to address this gap introducing two research objectives:

- *RO1. Understand the current landscape of 4thIR, Industry 4.0, and Supply Chain 4.0 research;*
- *RO2. Carry out an integrative tertiary study to classify the contributions in 4SC and develop a framework for future research.*

The remainder of this paper is presented as follows. Section 2 describes the research approach that includes bibliometric analysis and a systematic review of literature reviews. Next, the results for the initial research objective (RO1) are presented. Subsequently, Section 4 presents a concept centric appraisal of sixty-five literature reviews and a framework to guide new advances in 4SC. The paper closes summarizing the main conclusions, implications, and suggestions for literature reviews in 4SC.

2. Research approach

Six main steps are generally accepted for conducting systematic literature reviews: "*(1) defining the research question, (2) determining the required characteristics of primary studies, (3) retrieving a sample of potentially relevant literature, (4) selecting the pertinent literature, (5) synthesizing the literature, and (6) reporting the results*" (Durach et al., 2017). The same sequence can be adopted in tertiary studies, although using secondary studies as the primary source. As stated by Tranfield et al. (2003), "[f]*or academics, the reviewing process increases methodological rigor. For practitioners/managers, systematic review helps develop a reliable knowledge base by accumulating knowledge from a range of studies*". This research evolved in two stages subsequently presented.

First, a bibliometric analysis was selected to address RO1. The research started with a global evaluation of papers published in Web of Science (WoS) using the keyword "Industry 4.0" OR "fourth industrial revolution" in the topic (title, abstract, author keywords, and keywords plus), since 2012: 8553 papers found. Web of Science was selected because it is one of the most important scientific databases, indexes important publications in both social and technical areas, and provides an interface for preliminary analysis of the results and exporting to different formats (e.g., text formats suitable for further evaluation in bibliometric tools).

Second, RO2 included a concept-centric review (Okoli and Schabram, 2010; Webster and Watson, 2002) of the most representative secondary studies identified in the bibliometric analysis for 4SC. The selection was made as follows: First, a search in the topic (("industry 4.0″ OR "fourth industrial revolution") AND ("supply chain" OR logistics)), refined by: DOCUMENT TYPES: (REVIEW), timespan: All years. Indexes: SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI, CCR-EXPANDED, IC. A total of 92 papers corresponded to the criteria with a surprising average citation of 17.92 per item. However, some papers were not classified as "review type" and the search continued using ("industry 4.0" OR "fourth industrial revolution") refined by: TOPIC: ("literature review" AND ("supply chain" OR logistics)), timespan: All years, same indexes presented above. This search yielded 102 hits. In a subsequent stage, the author checked title and abstract to exclude articles that were not in the scope of the study, resulting in a total of 65 secondary studies that was possible to access the text (included in Appendix A).

3. Results of the bibliometric analysis

There is a drastic evolution in Industry 4.0 publications when contrasting to previous bibliometric analysis included in Galati and Bigliardi (2019) and Muhuri, Shukla, and Abraham (2019). Bibliometric analysis performed in different moments, using distinct databases, can contribute to our understanding of research in one of the most exciting areas in the 4thIR: transforming the flow of products and services. The next subsections present the findings for RO1.

3.1. Industry 4.0 – a comprehensive analysis

A total of 8553 papers fit the topic Industry 4.0 in WoS (since 2012, all indexes) according to the chronology presented in Fig. 1. The first year (2012) includes two conference papers and one editorial, increasing to 29 in 2013, reaching three digits in 2015 (151) and 2065 papers in 2020 (24,14 % of the publications). Over 57 % of the papers indexed in WoS for Industry 4.0 were published in the past two years. The tree view map of the publication categories is presented in Fig. 2.

Engineering and automation (on the left of the tree map) are leading the research, as expected, considering the focus of Industry 4.0 in proposing new technologies. Computer science follows with over 1/3 of the publications and the distance increases for the areas of business, management, and economics (bellow 7% each).

The citations for this sample of papers start in the year 2013 (3) but the increase between 2016 and 2020 is vertiginous, shifting from 537 to 23194. In January 2021, the h-index is 84 and the average citation is 5,53.

Most papers were presented in conferences (48 %) when comparing with articles (over 43 %) and 319 editorial material (almost 4%). The expressive number of 411 reviews (near 5%) supports the need to summarize the findings in this vibrant field. The selection of 411 review papers in Industry 4.0 is detailed with VoSViewer v 1.6.11 (van Eck and Waltman, 2010) and summarized in Fig. 3.

Fig. 3 involved a pre-preparation of data using a thesaurus file (remove duplicates, integrate similar concepts, discard generic terms such as “challenges”, “future”, or “systems”). Three clusters emerge on the left (clustering parameters of 1 for resolution and 2 for minimum cluster size; scale weighted for occurrences; normalization method: association strength) with supply chain management associated with innovation and smart factory keywords. The green cluster also reveals several contributions aiming at the creation of research agendas, supporting the emergent nature of the field and the need to consolidate existing research. On the right, it is possible to identify leading economies (blue), more specific clusters in the European Union (green), Australasian networks of research (red) and sub-networks of countries that are not typically linked with high Industry 4.0 maturity (e.g., the emergent economies of India, or Brazil). The concept landscape of Industry 4.0 reviews becomes clearer in Fig. 4.

Fig. 4 reveals five main clusters (resolution 2 and minimum cluster size of 3). The blue and purple clusters include more technical studies (e.g., blockchain, cloud, and related security aspects) that shape the infrastructure of Industry 4.0. The yellow and the red clusters representing respectively the design-time and the run-time of industry transformation establishes a bridge to the supply chain green cluster. The green cluster is particularly interesting to our research purpose, highlighting the role of sustainability and smart factories, but also the highest connections with research agendas and literature reviews.

The next section details the bibliometric analysis for the supply chain level.

3.2. *Supply chain transformations – looking for synergies*

Fig. 5 presents a closer look at the topic of supply chain in the widest perspective of Industry 4.0 reviews (sample of 92 review papers restricted using the keywords "supply chain" OR logistics).

The supply chain management cluster in Fig. 5 suggests an emphasis in augmented reality, circular economy, and taking advantage of the increasing amount of data with analytics. These topics are distinctive when comparing to the overall scenario of Industry 4.0 literature reviews. The figure also suggests an opportunity to strengthen research on the topics of management and predictive analytics (identified in light grey). Topics with less significant link strength (measured by line thickness) include integration (which is crucial considering that horizontal and end-to-end digital integration are core principles of Industry 4.0 (Brettel and Friederichsen, 2014)), simulation (important in supply chain reconfiguration), and the assessment of technology developments in performance, optimization, and innovation. Contrasting with the model in Fig. 4, the topics of cloud, blockchain, or security are not visible (may exist but are not frequent when compared to the other concepts in Fig. 5). These results confirm the necessity to integrate the literature in engineering and technology management of supply chains.

The first citation in this sample of 92 papers appeared in 2018 but is increasing rapidly. The 1099 citations in 2020 double the sum of citations of the previous two years and, although h-index is lower (21), when compared to Industry 4.0 as a whole, the average citation per item is 1.26 higher (comparing with the 411 Industry 4.0 reviews) for papers addressing the topic of transforming industry in their boundaries and interactions with external stakeholders. India, Germany, and England exceeding 40 % of the Supply Chain 4.0 reviews are the top three countries interested in the topic.

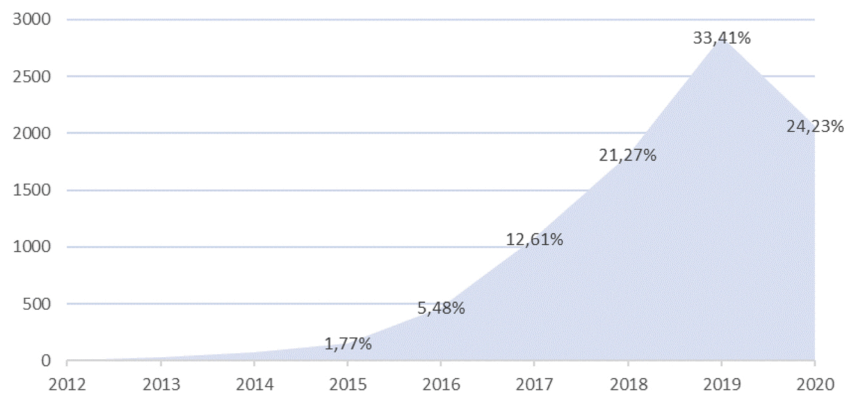

Fig. 1. Industry 4.0 publications since 2012.
(source: Web of Science).

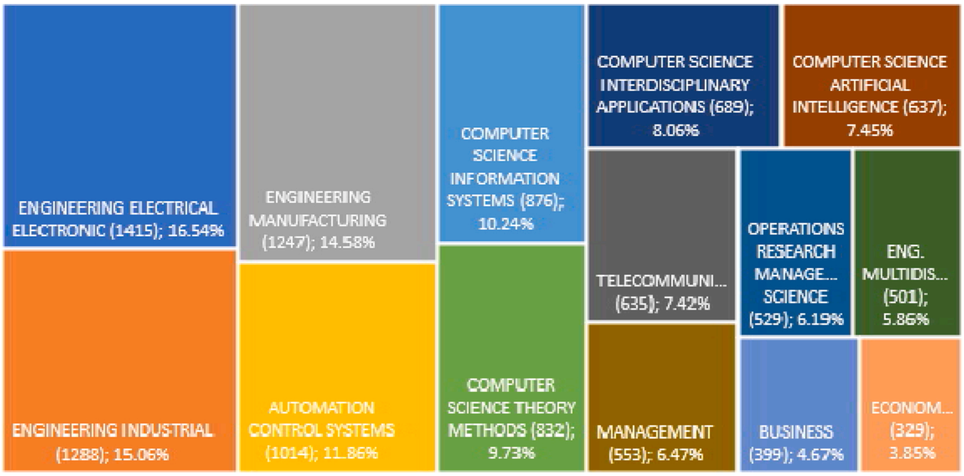

Fig. 2. Categories of publications in Industry 4.0 literature.
(source: Web of Science).

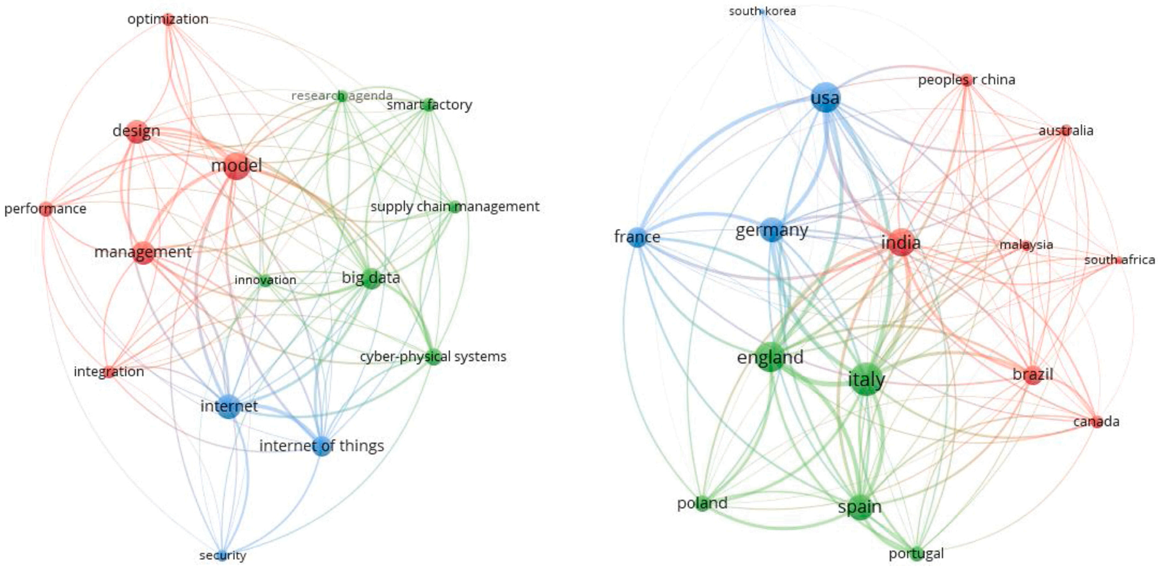

Fig. 3. Reviews in Industry 4.0: co-occurrence with keyword plus (on the left) and bibliographic coupling of countries.

Fig. 6 presents a bibliometric analysis of papers addressing supply chain and logistics in the context of Industry 4.0, not restricted to reviews.

The visualization in Fig. 6 confirms the increasing impact of managerial and organizational aspects in supply chain transformations (the size of the labels is proportional to the importance of the topic). There are also new topics emerging in this analysis of articles, namely, the topics of lean, digital twin, RFID, inventory, scheduling, circular economy, cloud, business models, and collaboration that are not yet highlighted in the sample of 92 literature reviews, revealing opportunities for additional work in this field.

The bibliometric analysis in Industry 4.0 and supply chain provided important insights to proceed to RO2. First, confirmed the fast-growing pace of Industry 4.0 research and secondary studies. Secondly, the supply chain level reveals specific concerns of resilience, circular economy, lean, or network creations that diverge from mainstream Industry 4.0 literature. This initial phase of the study (RO1) provided a high-level picture of 4SC and preliminary trends. The next section presents a concept-centric review (Webster and Watson, 2002) of the 65 literature reviews (RO2).

4. Making sense of the literature reviews

Following the recommendations made by Webster and Watson (2002), the 65 secondary studies (detailed in Appendix A) are classified into five main concepts (see Fig. 7).

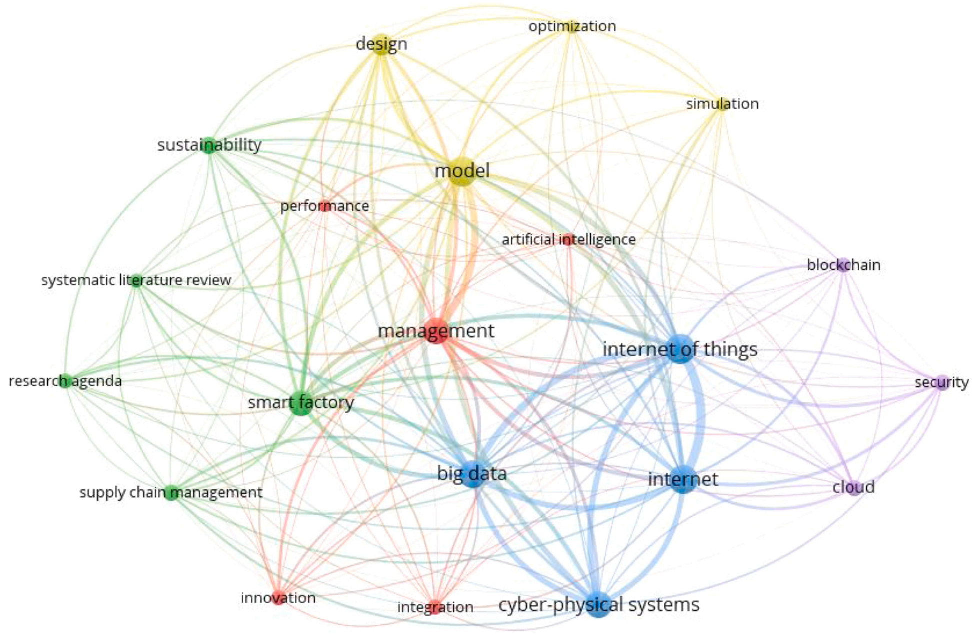

Fig. 4. Reviews in Industry 4.0: co-occurrence with all keywords (minimum of 20 occurrences).

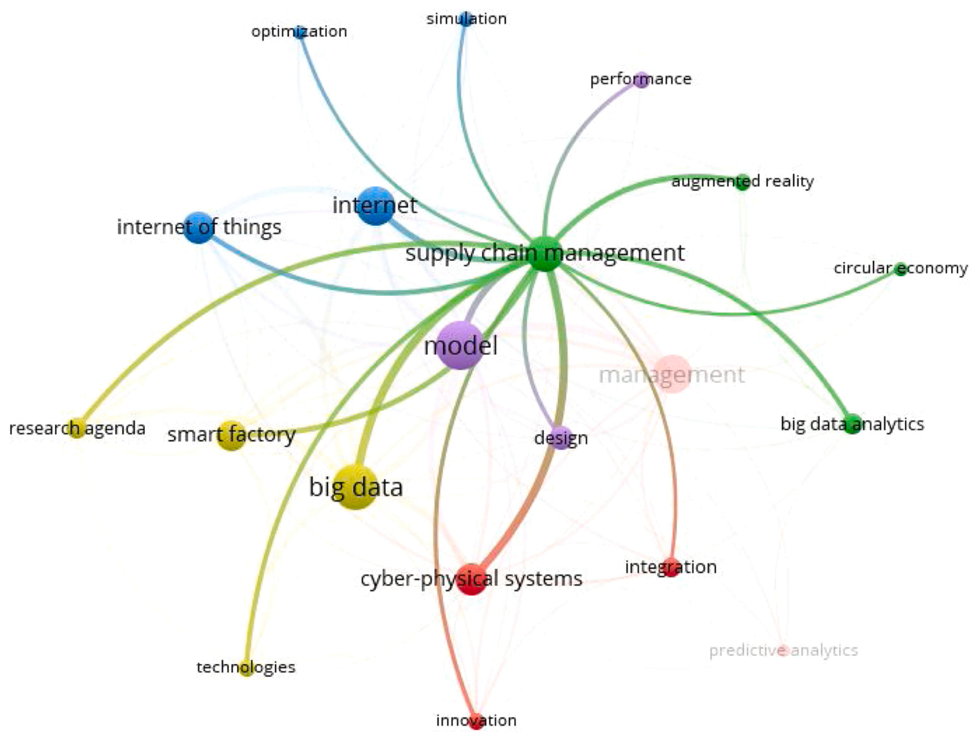

Fig. 5. Supply chain literature reviews in the context of 4thIR and Industry 4.0.

Almost half of the selected papers was published in 2020 (30), with a steady expansion since 2016. C1 includes papers with a core focus in Industry 4.0 (supply chain appearing as one of its dimensions) or the parallel between Industry 4.0 and supply chain. Next, C2 comprises reviews addressing more specific supply chain transformations (e.g., last mile logistics, how Industry 4.0 appears in the supply chain literature), representing the highest percentage of papers. This evidence (adding that 52 % of the papers in this concept were published in 2020) suggests that 4SC has an opportunity to create its own agenda for technological change. Sector-specific supply

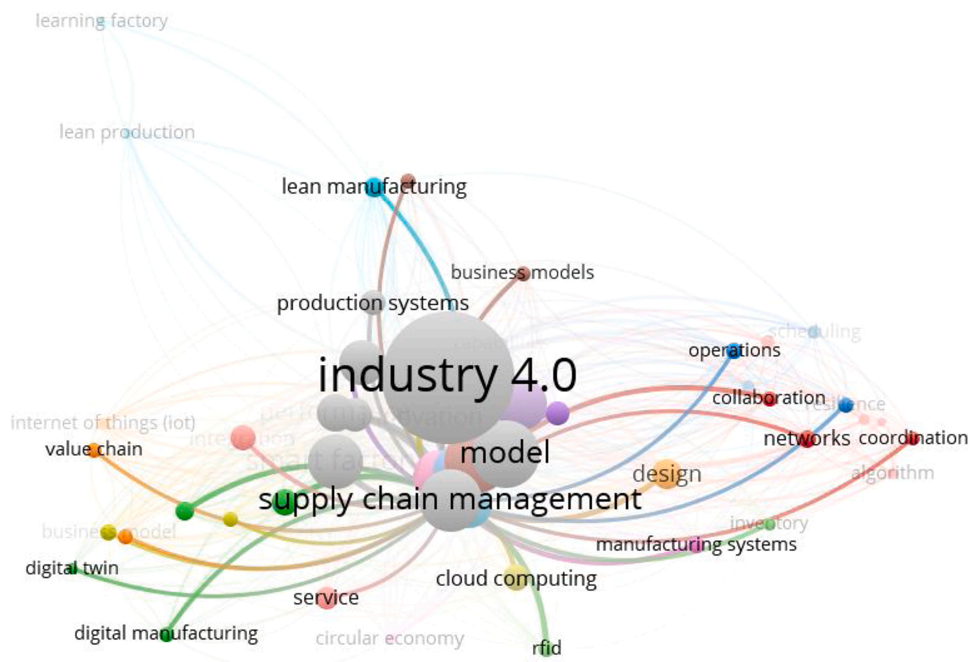

Fig. 6. Supply chain and logistics: co-occurrence with all keywords.

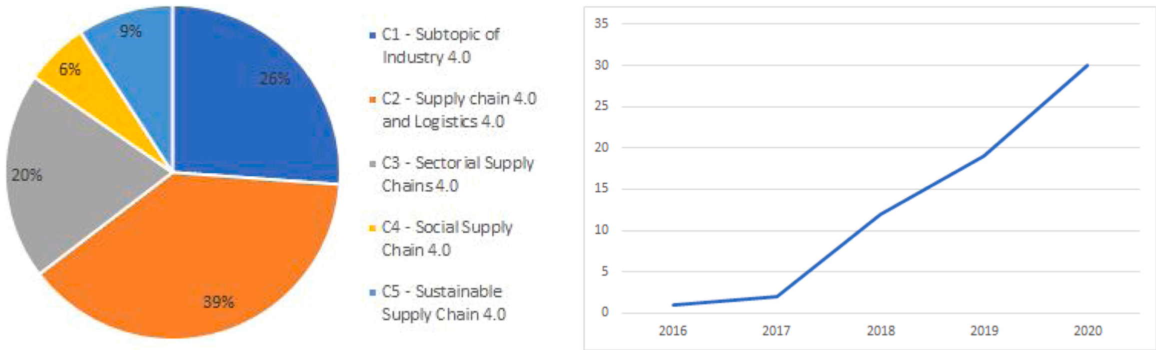

Fig. 7. Inter-related concepts of the 65 literature reviews and growth over time.

chain transformation follows (C3) and the papers revealing a higher concern in social (e.g., organization of work practices, wellbeing) and sustainability (e.g., environmental, economic) aspects are classified in C4 and C5, respectively.

The five concepts are interrelated, and many papers could fit in more than one. However, it was decided to associate each paper to the most prevalent concept to facilitate the analysis subsequently presented.

4.1. Concept 1: supply chain as a subtopic of Industry 4.0

The supply chain is a central part of Industry 4.0 research (Galati and Bigliardi, 2019). For example, Zhong et al. (2017) describes the global efforts in different areas of the globe (European Union, United States, Japan, and Chin) that enable "*physical processes and information flows to be available when and where they are needed*". The concept of supply chain reconfiguration is also included in the review of 156 primary studies found in Savastano et al. (2019), the cyber-physical transformations described by Panetto et al. (2019), or the important impact of additive manufacturing in aspects like collaboration with suppliers, logistics efficiency, or supply chain decentralization and manufacturing networks (Franco et al., 2020; Frazzon et al., 2020).

There is a mutual impact between Industry 4.0 and supply chain transformations: improving supply chain decisions, and supporting network formation via digitalization (Kamble et al., 2018). On the one hand, the impact of Industry 4.0 can occur in the decisions of reshoring ("*bring back to the home country production activities earlier offshored*"), changing global supply chains (Barbieri et al., 2018). On the other hand, supply chains can be used to transfer knowledge and technology between partners (Pfohl et al., 2017).

Supply chain particularities emerge in themes such as circular economy, decentralization of production, and the increasing uncertainty that requires agility and flexibility (Galati and Bigliardi, 2019) but also trust, transparency, and collaboration (Da Silva et al., 2020), or monitoring performance in smart manufacturing (Parhi et al., 2020). Simulation technology is a pillar of Industry 4.0 and a possible approach to improve flexibility and agility in supply chains, taking advantage of virtual reality or digital twins to implement Industry 4.0 design principles (de Paula Ferreira et al., 2020). Blockchain is being associated with a different line of studies, revealing potential application in transparency, reliability, security, accountability, or traceability (Bodkhe et al., 2020). Nevertheless, Industry 4.0 includes a plethora of technologies with different maturities that must be integrated to explore synergies towards lean supply chain management (Núñez-Merino et al., 2020). For example, IoT for real-time monitoring and big data to improve sustainability (Oztemel and Gursev, 2020).

The extension and quality of the secondary studies found in the intersection of Industry 4.0 and supply chains are remarkable. However, the impact of smart products in supply chains is understudied in our sample, as well "*the impact of smart manufacturing on supply chain networks, reverse logistics, production planning, and control of product recycling and remanufacturing*" (Kamble et al., 2018). According to Kerin and Pham (2020), flexible and "reconfigurable remanufacturing" will be essential to the future of Industry 4.0 and circular economy, involving a technological and a sustainability agenda. The opportunities for future research in closed-loop supply chains are confirmed in Ivanov et al. (2020) that also point to the importance of digitalization to mitigate risks and improve resilience in supply chains that are increasingly dynamic, when compared to the traditional "*rigid physical system with a fixed and static activities*" (Ivanov et al., 2020).

Managing and coordinating increasingly digitized and intelligent "flows" can be enriched with the smartness of the objects that move in the supply chain, at design-time (from raw materials and services to final goods), and at run-time - when the final goods are used and may provide feedback to the entire supply chain.

4.2. Concept 2: Supply chain 4.0 and Logistics 4.0

Supply chains have a societal impact, not exclusive to the participants in demand and supply processes. The pressure to digitize and optimize supply chains become more visible with the COVID-19 pandemics and vaccine delivery (and use monitoring). Therefore, Supply Chain 4.0 is not only "a state" of technology maturity, but also a long-term transformation process with different generations of stakeholders.

Concept 2 reveals that a specific supply chain transformation agenda is unstoppable and necessary. Da Silva et al. (2019) conclude that "*the supply chain will go through changes, such as real-time visibility throughout the entirety of the supply chain, continuous collaboration between the stages of the chain, among other significant changes*" and several authors support this claim (Ivanov et al., 2018; Juhász and Bányai, 2018; Maslarić et al., 2016; Saucedo-Martínez et al., 2018; Winkelhaus and Grosse, 2020). Moreover, the changes must consider knowledge management to explore new solutions (innovation) and exploit existing knowledge to improve routines, integrating both, internal and external stakeholders (Schniederjans et al., 2020a).

One of the reviews proposing a definition for Supply Chain 4.0 and a maturity assessment framework is presented by Frederico et al. (2019). The authors create a framework based in four concepts: managerial and capability supporters, technology levers, process improvement, and strategic outcomes. Although closely related, there are also differences between Industry 4.0, Supply Chain 4.0, and Logistics 4.0. For example, the higher focus in automatic identification and tracking, real time location, or transparency (Yavas and Ozkan-Ozen, 2020). These authors point to the importance of handling information, transports, and warehouses to create the future logistic centers.

Technology is an important driver for agility in supply chains but must be integrated with the development of capabilities (e.g., customer service, information sharing, or differentiation) and relational aspects that are not merely technological, as happens in supplier selection (Shashi et al., 2020). The proposal of reconfigurable supply chain networks presented by Dolgui et al. (2020) shows that four pillars are necessary, namely, digitalization, resilience, sustainability, and efficiency. These authors adopted a combination of bibliometric analysis and tertiary studies using Scopus database to address the increasing dynamic of supply chains at structural, process, and plant levels of reconfiguration. The study on smart logistics presented by Issaoui et al. (2020) also reveals the importance of sustainability, exploring areas that can be transformed, and pointing to technological trends (e.g., IoT, AI, 5G, blockchain).

Important frameworks have been proposed to redesign supply chains. For example, the framework proposed by Ghadge et al. (2020) reveals how RFID and cloud can improve operational performance. Moreover, the three main clusters in Supply Chain 4.0 literature identified by Abdirad and Krishnan (2020) also show the need to include more detailed implementations and quantitative studies. Ivanov et al. (2018) stress the importance of interdisciplinary cooperation and propose a framework for digital supply chain that includes cloud, RFID, big data, artificial intelligence, and blockchain. More recently, Woschank et al. (2020) propose a framework to create more intelligent supply chains that support forecasting, digital-twin based control, predictive maintenance, improved decision support and transport systems. Simulation tools will be essential to manage risks in complex and constantly changing supply chain networks (Vieira et al., 2020).

Directing to the last mile logistics, Juhász and Bányai (2018) present financial and environmental benefits enabled by smart technologies and information systems, while Maslaric et al. (2016) describe the vision of the physical internet "*transferring of metaphor of the (digital) Internet in the way we move, store, handle, realize, supply and use physical objects all around the world*". This proposal requires changes in the supply chain to integrate services and freights. Additive manufacturing is one of the most disruptive enablers of Industry 4.0 that can contribute to changes in planning, producing (near to the user), delivery, and recycling, as revealed by Kunovjanek et al. (2020).

Effective performance improvements depend on the capacity to integrate improvements in individual processes and explore and exploit knowledge in the organization (Fatorachian and Kazemi, 2021; Schniederjans et al., 2020b). Nevertheless, many studies in

Supply Chain 4.0 still have a focus at the firm level, as revealed by the review presented by Chauhan and Singh (2019).

Blockchain is a popular platform for the development of Supply Chain 4.0 (Junge, 2019; Schniederjans et al., 2020b), differing from other areas of the smart factory. 5G is another fast-growing technology, particularly when associated with IoT, but research is still scarce in prototypes, adoption methods, and security challenges (Taboada and Shee, 2020). More research is necessary to understand why some technologies are not evolving as fast as others, and what are the solutions needed to change the scenario in different sectors of the economy. The work of Winkelhaus and Grosse (2020) reinforces this claim and points to the importance to (1) understand the needs of different sectors and societies, (2) study technologies such as IoT (an example can be found in Ben-Daya et al. (2019)), blockchain, and augmented/virtual reality and its economic impacts (3) evaluate tasks of logistics such as packaging and truck loading, (4) redesign business models, (5) study the impact in the workers, and (6) empirically validate the theoretical proposals.

Although the benefits of emerging technologies are vast for the adoption of increasingly mobile supply chain management (Barata et al., 2018), few studies explore the problems and pitfalls of digital transformation, as the central topic. One of the examples found is presented by Moretti et al. (2019) who describe the operational, planning and employee related difficulties in RFID implementation. The important work done identifying potential benefits of technological changes need additional attention in the analysis of cases studies and challenges found during the change process, as well as the measures to increase the success of sustaining change.

4.3. Concept 3: sectorial supply chains 4.0

Some authors have focused specific sectors of the economy, namely, Ding (2018) for pharmaceutical supply chain; Dallasega et al. (2018) in construction; Mariani and Borghi (2019) in services; Müller et al. (2019) in wood supply; Reis (2019) in chemical processes; Zambon et al. (2019) in agriculture; and Cruz Introini et al. (2018) in food. The main motivation of each sector varies, for example agriculture, and food are crucial for human health, requiring technologies for traceability in supply chains: QR (quick response) codes, wireless sensors and NFC (near field communication) technology have a good potential that is not yet entirely explored (Cruz Introini et al., 2018). Other technologies like IoT, blockchain, big data, and artificial intelligence may be used to reduce uncertainty and assist decision-making in agri-food 4.0 (Lezoche et al., 2020).

The perspective of agriculture 4.0 is vast and includes the use of technology in the farm equipment, in the field, or in the effort of monitoring weather conditions and control irrigation systems (Zambon et al., 2019). These authors highlight the differences between agriculture (e.g., small farms, people developing multiple activities in the site that may benefit from new training systems based on electronic devices) and industry, suggesting that each sector of the economy can benefit from a personalized assessment of the supply chain. For example, in the case of food supply chains, technologies like IoT and digital twins can be used to minimize (e.g., thermal or biological damages) fresh food lost (Onwude et al., 2020). However, the same authors also found that "*the holistic implementation of digital twins in the entire value chain (from planting-fork) and for a wide range of fresh produce is yet to be demonstrated*". The review presented by Kayikci et al. (2020) suggests that blockchain is a potential solution to reduce food loss, while also improving transparency, stakeholders trust, and food security.

Pharmaceutical supply chains are critical for humans and require digital traceability systems. The study presented by Ding (2018) addresses sustainability, identifying enablers and inhibitors of pharmaceutical Supply Chain 4.0. This work evaluates how Industry 4.0 can improve sustainability in this "*contaminating, high waste and energy-intensive consumption industry*". A managerial perspective was selected by Mariani and Borghi (2019) to evaluate the impact of Industry 4.0 in the service industry. These authors present a comprehensive quantitative review including 765 studies identifying interesting clusters for innovation, namely, reshoring and strategic aspects of supply chain responsiveness.

In line with Zambon et al. (2019), the work of Müller et al. (2019) provides a comprehensive overview of Industry 4.0 in the wood sector. There are touchpoints between these studies considering the proximity of agriculture and wood production, from raw materials management to the moment of sale.

Complexity of chemical processing industry is explored by Reis (2019) "*with respect to several common activities, such as data integration/fusion, de-noising, process monitoring and predictive modelling, among others*" taking advantage of new sensors and the potential of big data analytics. Diverging from continuous process industries, construction industry involves multiple actors that can interact more closely. Synchronization between suppliers and the construction site, RFID, geographic information systems, monitoring systems, E-Business, BIM (building information models) and 3D printing can improve proximity in this sector that require several experts with different backgrounds (Dallasega et al., 2018).

Three recent studies addressed maritime supply chains. The work presented by Ramirez-Peña et al. (2020a) argues that sustainability and Supply Chain 4.0 should be inseparable in shipbuilding, revealing which technologies are already contributing to sustainable efforts (e.g., energy efficiency of environmental protection) and the opportunities for additive manufacturing and simulation. The other study evaluates the "4.0" transformation of ports and maritime industry (de la Peña Zarzuelo et al., 2020), identifying more mature trends (e.g., IoT, terminal operating systems, or integration) but also areas that need additional attention in terms of technologies (sharing the importance of additive manufacturing with shipbuilding industry and other less developed like blockchain or AI), going beyond isolated experiences and correcting digitalization asymmetries between large ports and smaller maritime structures. Finally, Ramirez-Peña et al. (2020b) added the aerospace and automotive to the shipbuilding sector, identifying a different sectorial focus in Industry 4.0 technologies (e.g., additive manufacturing in aerospace, cloud in shipbuilding, and AI in automotive) but also best practices that could be shared, namely, collaboration in change management that is more typical in automotive supply chains. Comparing the three studies, it is possible to conclude that supply chain revolutions must integrate digitalization of structural elements (e.g., ports, warehouses, equipment) and the "moving part" of the chain (e.g., objects, or people), at different lifecycle stages (e.g., ship/automotive production and operation), and levels of abstraction (e.g., port – ship – container - product).

Although it is possible to find studies addressing (1) traceability, (2) sustainability, (3) opportunities to innovate with specific examples of technologies (e.g., QR code, RFID, smart sensors) in each context, there are several sectors not yet well represented in current literature reviews. Some concepts allow transferability (e.g., traceability in wood and pharma industry) but others are very specific to each sector of the economy. Another shortcoming of current sectorial reviews is the comparability between sectors (e.g., evaluate applicability of solutions tested in other sectors, such as product recall in automotive industry and possible systems to warn users in food contamination).

The number of sector-specific reviews is still scarce but the scenario is likely to improve soon, not only in critical supply chains (e.g., healthcare, food). It is recommended that authors conducting sector specific SLRs provide comparisons with secondary studies made for other sectors, particularly, if the supply chains have some links to consider (e.g., similar products/services or common societal challenges). Another recommendation is to evaluate resilience of specific supply chains, for example, in case of global disruptions.

4.4. Concept 4: social supply chain 4.0

Supply chain transformation is sociotechnical. The social impact in human resources was the perspective selected by Liboni, Cezarino, Jabbour, Oliveira, and Stefanelli (2019), while Schneider (2018) evaluates the implications for managers regarding (1) strategy and analysis, (2) planning and implementation, (3) cooperation and networks, (4) business models, (5) human resources, and (6) change and leadership. Despite the social concerns also perceptible in other literature concepts (and shared by the vast majority of the literature reviews found), for example, Zambon et al. (2019), few address specifically the managerial and human resource management and more primary/secondary studies are necessary. The process of document selection and the number of the sample is illustrative: for example, Liboni et al. (2019) started with 146 papers in the selection process and Schneider (2018) with 414, comparing, for example, with starting point of 2147 papers in Juhász and Bányai (2018) or 15,000 initial results in Winkelhaus and Grosse (2019) that selected a more technological perspective.

More recently, Sgarbossa et al. (2020) argue that human concern "*in design and management of production and logistics systems is a crucial aspect for business success*" and present inspiring examples for engineering, modeling, and management of increasingly digitized systems. According to these authors, it is essential to balance efficiency, quality (e.g., human errors), and wellbeing (e.g., age-friendly modeling, psychosocial aspects of work) for long-term success.

Although it was decided to include technology transfer in C2 (da Silva et al., 2019), this is an overlapping concept. In fact, supply chains differ from single company initiatives that have a common digital infrastructure and management structures. Moreover, as supply chains move from traditional stages to distributed networks of sociotechnical elements (da Silva et al., 2019), becomes essential to evaluate the social implications of technology adoption. Digitalization is transforming supply chain infrastructures but it is equally important to include human intuition and "*hybrid decision models might be more efficient than only human- or robot-centered approaches*" (Klumpp et al., 2019).

4.5. Concept 5: sustainable supply chain 4.0

Circular economy is a major issue in manufacturing supply chain, as revealed by Nascimento et al. (2019) that suggest using web technologies, additive manufacturing, and reverse logistics to reuse scrap of electronic devices. The strategy allows to reuse waste in the supply chain producing new objects on demand. Also in sustainability, Bányai (2018) conducted a literature review to evaluate energy savings in the strategic and operational level of the supply chain elements. For example, with real-time scheduling to optimize energy resources using IoT (Bányai, 2018). The review presented by Cañas et al. (2020) highlights that social sustainability is also essential but has been scarcely studied when contrasting, for example, with the environmental perspective.

A technological viewpoint is presented by Manavalan and Jayakrishna (2019), proposing a framework to assess readiness of sustainable supply chains. Focusing the last mile logistics, Luthra and Mangla (2018) identify several Industry 4.0 technologies that can be used to reduce movements in the delivery process. However, the initiatives for supply chain in the context of Industry 4.0 also present challenges. For example, the lack of infrastructure and standards or poor data quality, particularly in the emerging economies (Luthra and Mangla, 2018).

Other authors selected specific technologies for sustainability. For example, Chiappetta Jabbour et al. (2020) reveal how big data can be used to improve sustainability in the economical (e.g., prediction of financial impact of decisions), environmental (e.g., monitoring environmental indicators) and social perspectives (e.g., prediction of social problems, assessment of compliance issues of the suppliers. Sustainability is a political priority of our era and it is expected that the topic remains in the agenda of 4SC researchers, with opportunities to be detailed for specific contexts (e.g., sectors, stakeholders, geographical regions, scarce resources).

4.6. A research framework for the fourth industrial revolution of the supply chain

In the author's view and from the concepts revised in the previous sections, the conceptualization of 4SC can be explained by *a context-bound technological change driven by organizational and cultural (civilizational) priorities, aiming to create more sustainable networks to serve the customers and support responsible decisions in the supply lifecycle*.

The proposed conceptualization is integrative but not restricted to the traditional focus of Industry 4.0. Moreover, it is inspired in the vision of technology innovation systems (TIS) proposed to analyze technological change (Bergek et al., 2015, 2008; Hekkert et al., 2007) recognizing the importance of context, the uniqueness of networks in 4SC, and the necessity to sustain change over time, within the entire lifecycle of products and services.

The TIS support that sustainable technological change (Bergek et al., 2015) must consider interactions with other TIS (e.g., maritime supply chain and international trade systems), sectors and geographical characteristics, and policies. As explained by Bergek et al. (2015), there are multiple factors affecting individual decisions and priorities that must be balanced in a changing network (e.g., the concerns of raw material producers may differ from product distributors sharing the same supply chain). The TIS have interrelated functions as stated by Hekkert et al. (2007), namely, the *entrepreneurial activities*, because innovation needs entrepreneurs and pilot projects to become reality, *knowledge development* (e.g., learning by searching and by doing), *knowledge diffusion through networks*, which is particularly challenging in distributed production settings, *guidance of the search*, establishing the priorities and focus of change that are shared by internal (e.g., shareholders plans) and external actors (e.g., societal goals such as carbon reduction), *market formation* to ensure that new technologies endure, *resources mobilization*, and finally, *creation of legitimacy* that will incorporate technological change in the incumbents or even transform the industry.

Fig. 8 integrates the priority concepts identified in the literature according to the lens of TIS (Bergek et al., 2015, 2008; Hekkert et al., 2007) and supply chain innovation (Sabri et al., 2018).

The framework maps the tertiary study findings with the context of technology change (Bergek et al., 2015) (on the top), the TIS functions presented bellow (Hekkert et al., 2007), and the need to include both product/service and process changes in supply chain transformations (Sabri et al., 2018), extending the scope of 4SC from the most basic source materials and services to the end-of-life in the supply lifecycle.

This framework reveals that some sectors of the economy and policy priorities are already in the agenda of 4SC researchers. For example, environmental protection (top-right of Fig. 8) or healthcare supply chain transformations (critical chains). However, the framework also shows opportunities to integrate different concepts in future publications. For example, there is a lack of literature reviews about the formation of markets: What are the requirements to increase the success of a specific technology? How changes in the digital supply chain promote the entrance of new suppliers and how those suppliers interact in the network? How new technology suppliers increase their power in the supply chain and how it can be balanced in different contexts? The 4SC must develop its own research agenda and the networked structure of change in market formation is an important distinction. Future 4SC publications could discuss the implications for the market formation that contribute to incorporate change in the selected supply chain and make it sustainable.

There are also areas that may be extended. For example, in the context dimensions, several sectors are still understudied in 4SC literature (e.g., water supply, renewable energy systems, technology production, several private and public services). Regional geographical contexts are also important to address because the influence in the supply chain can be significant (e.g., gas supply, oil, or lithium). The political context is well represented in the sample but there are also opportunities for other sustainable goals. For example, inspired in the United Nations sustainable goals of reducing poverty and ensuring equal opportunities, education, food and medicine supply chains in humanitarian missions, or technologies that promote responsible consumption and reduce sourcing of specific materials. Finally, although it is understandable that the term "Supply Chain 4.0" is often attached to "Industry 4.0", there are opportunities to integrate and enrich the supply chain revolution with other digital transformation initiatives, for example, "X.0",

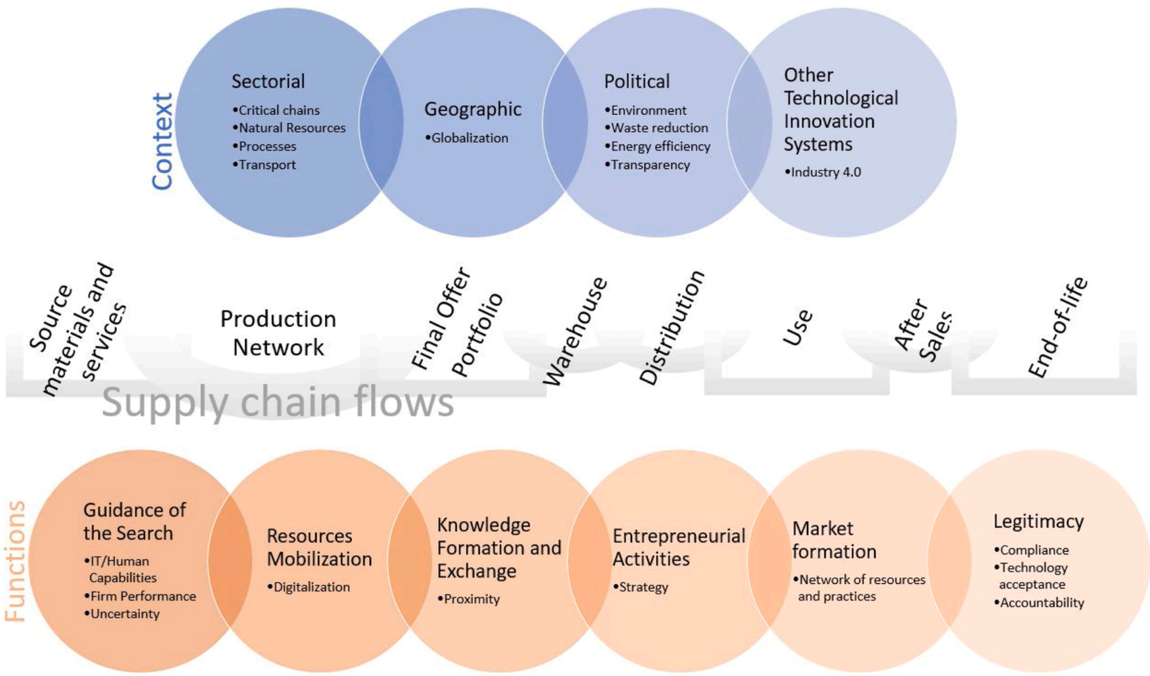

Fig. 8. Fourth industrial revolution of supply chains: a guiding framework for technological change.

Industry 5.0 (and the more human-focused Supply Chain 5.0), Society 5.0, Made in China 2025, or the Industrial Internet of Things.

The past two years of research are marked by enormous progress. Intelligent resource management is key for sustainability of supply chains. The examples are significant according to the studies presented by Bányai (2018) for energy management, and other authors for environmental impacts, or wastes, at different levels (Ding, 2018; Kamble et al., 2018). However, social sustainability in the 4SC agenda (e.g., employee rights, health and safety, diversity practices, social and product responsibility) also has a positive impact in supply chain performance (Mani et al., 2018).

Responsibility requires to ensure compliance to regulations, making companies accountable and able to prove their practices to third party entities such as customers, assessors, and inspectors. Traceability is another priority (Cruz Introini et al., 2018; Müller et al., 2019) and blockchain technologies may contribute to this aim (Winkelhaus and Grosse, 2020). Examples that fit the responsibility domain include health and safety in supply chains, security (e.g., increasing risks for cyber-attacks in critical supply chains), and privacy (e.g., data sharing via cloud computing (Novais et al., 2019)). The recent needs in the supply chain of COVID-19 vaccines (e.g., transparency, asset protection, fairness, simulation and management of raw materials/ resource scarcity and provenance, compliance with end-use) are examples of priorities for 4SC research.

Future supply chains will require the development of capabilities at different levels, namely, in the adoption of new technologies to create a resilient digital infrastructure and reconfigurable supply chains (Dolgui et al., 2020). Human capabilities (e.g., recruitment and training) must also be developed to take advantage of the new technologies and methods (Galati and Bigliardi, 2019; Liboni et al., 2019; Schniederjans et al., 2020b). Moreover, the decentralization of supply chains and the individualization of production raise new challenges when the market is constantly changing (Teece et al., 2016). Case studies about best practices of technology transfer and resilient supply chains are examples of future research possibilities, providing basis for meta-analysis.

Dealing with uncertainty is crucial in 4SC. Smarter supply chains enabled by information technologies can reduce costs, improve visibility (transparency dimension), manage risks more effectively (Rajagopal et al., 2017), increase customer proximity and be decentralized at a global scale (Brettel and Friederichsen, 2014; Butner, 2010; Dallasega et al., 2018). Additional research is necessary to anticipate demand needs of the consumers and a clearer understanding of cost reduction in 4SC (e.g., costs of transport and warehouse). The operationalization of real-time changes in manufacturing can only be accomplished with trust (Müller et al., 2019) between all the participants. However, data quality (errors in real-time information can lead to major costs in supplier/production orders) and security are new priorities.

It will be interesting to evaluate if agility promoted by Industry 4.0 technologies (e.g., simulation, cloud), may, in some cases, be also a source of supply chain rigidity. This contradictory effect may occur due to the different stages of maturity (Frederico et al., 2019) of each supply chain partner and the difficulty to find alternative partners that have the sociotechnical capabilities (Schneider, 2018) and the digital infrastructure (Winkelhaus and Grosse, 2020) to integrate the network. The necessity to ensure supply chain resilience in disruptive events is a major research theme and each sector of the economy may have particularities. For example, topics related with artificial intelligence, machine learning, and social networks are promising for future studies in 4SC. More comprehensive reviews are necessary to assist managers in the creation of contingency plans to ensure business continuity.

The proposed framework can be used as a guide for future research. The possible combinations, still unexplored, to integrate two or more concepts are significant (e.g., evaluate how technology management capabilities can improve regional supply chains aiming at sustainable production; how the intelligent management of energy can be more transparent). Moreover, it is possible to evaluate each goal in the light of a technology portfolio (e.g., IoT for sustainability) at different levels: national, sectorial, product/service, and organizational. The plurality of methods (e.g., survey, case study, action research, literature review) and the richness of possibilities included in the framework can contribute to the holistic sustainable development of supply chains enabled by disruptive technologies.

5. Conclusion

This paper presents a bibliometric analysis of recent Industry 4.0 publications and a review of 65 literature reviews on the topic of supply chain transformations.

The new era of supply chains expands the traditional focus of industry transformations to a more demanding level of societal concerns: sustainability and circular economy (Luthra and Mangla, 2018; Nascimento et al., 2019), integration, resilience, coordination, and technology transfer (da Silva et al., 2019; Pfohl et al., 2017). These intentions are difficult to achieve when multiple stakeholders participate in the physical and digital flows required by decentralization and individualization of production (Brettel and Friederichsen, 2014). The proposed framework can assist 4SC researchers (1) in the selection of essential literature reviews to support their background section, (2) framing the contribution in the wider landscape of 4SC, (3) guiding the discussion of contextual and functional elements of the research (e.g., evaluating how the proposal is addressing political concerns or organizational goals, eventually incorporated in the market, and legitimized), and anticipate future consequences and conditions that must be met to ensure more responsible use of technology.

This research has limitations that must be stated. First, although WoS is one of the most important scientific sources, the selection of databases and the search criteria can influence the results (Mongeon and Paul-Hus, 2016). Second, supply chain transformations are evolving at an accelerated pace, which mean that, even when using the same database, the results change in short periods of time. Third, the identification and classification of literature reviews is a subjective evaluation, increasing the risk of not considering all the possible literature reviews.

The review of secondary literature is essential to support an increasingly digitalized flow of (smarter) products and services. The most promising vision of 4SC must match the expectations of the entire supply lifecycle, going far beyond manufacturing.

5.1. Study implications

For theory, this paper evaluates how researchers integrate contributions in the crossroads of supply chain and Industry 4.0 transformations and presents a framework for future research. The bibliometric analysis extends recent research presented by Frederico et al. (2019) to define Supply Chain 4.0 and its maturity; Galati and Bigliardi (2019) using the Scopus database to identify themes and future research opportunities; Özdağoğlu et al. (2019) with a predictive filtering approach; Cobo et al. (2018) that analyzed WoS with a different set of keywords in 2018; and Muhuri et al. (2019) that used both WoS and Scopus. Moreover, best practice recommendations for the development of SLRs in 4SC are suggested in the next section. This paper also reveals how technology innovation systems (Bergek et al., 2015, 2008; Hekkert et al., 2007) can be adopted to map literature review studies and identify opportunities for future research that adhere to the context and the functions of change in 4SC.

For practice, this work (1) clarifies areas that already justified SLRs due to its maturity, and (2) offers a lifecycle view of underdeveloped areas in digitalized supply chains. Different supply chain actors must be involved (Liboni et al., 2019) in the achievement of more ambitious and comprehensive goals like traceability supported by blockchain technologies (Longo et al., 2019) and big data analytics to reduce all forms of waste and disruptions in intelligent, capable, responsible, and efficient supply chains. The proposed framework can be used to evaluate technologies or approaches (e.g., machine learning, self-healing or self-adjusting systems) that are not yet sufficiently developed to address the various contexts and the extended links made possible by digitalization of supply chains.

5.2. Suggestions for future literature reviews in supply chain

Tertiary studies in supply chain management literature have excellent examples such as the work presented by Giunipero et al. (2008) to evaluate a decade of research. More recently, Hochrein et al. (2015) analyzed the state of the art of literature reviews in this field and also propose recommendations for future SLRs - suggested reading for future 4SC literature reviews. The authors stated that "[a]*s best-practice guidelines for LRs in the field of SCM* [supply chain management] *are still in their infancy* (…), *we finally make a plea for the development of further recommendations, for example, via tertiary studies*". The important lessons are (Hochrein et al., 2015): *(1) link to other secondary studies and (2) sound methodological references, (3) properly explain the search process (4) and the selection of articles, (5) extract data based in concepts (e.g., using a framework), (6) increase meta-analytic studies, and (7) detailed lessons for reporting the results*. The evaluation of the 65 secondary studies according to the lessons presented by Hochrein et al. (2015) highlights the following aspects more related to 4SC literature reviews:

5.2.1. Identify methodological guidance and compare the review with other SLRs in the same context (if available)

On the one hand, foundational references to SLR provide the sequence of steps and the quality requirements for the review process. For example, the reference to Tranfield et al. (2003) was found in 10 of the SLRs but there other important methodological articles. On the other hand, presenting SLRs that adopted the same methodological guidance can strengthen the choice of the approach, particularly if it was conducted in the same field of research (e.g., Ding (2018)).

Some authors, for example Winkelhaus and Grosse (2020) or Ben-Daya et al. (2019) discuss related systematic literature reviews. There are advantages in including a subsection with this aim to (1) ensure that the SLR has a different scope, (2) understand gaps for research in early stages of the SLR development, and (3) contrast the findings. This recommendation is aligned with lessons presented by Hochrein et al. (2015). However, considering the technological focus of Industry 4.0, it is also advised to include SLRs on the target technology.

5.2.2. Ensure that the SLR is repeatable and clearly identified

Most studies have identified the source databases (>80 %), the most relevant keyword combinations (>80 %), the process of selection, and the number of papers in each step. A vast majority of selected publications present the total number of primary studies. The identification of the paper as a review in the title can also assist in the immediate identification of the method. This recommendation is aligned with the lesson 3 (Hochrein et al., 2015), assisting in the identification of the selection process and the global sample involved in the topic. More meta-analysis are necessary (lesson 6) in the intersection of Industry 4.0 and supply chain issues.

5.2.3. Mix graphical and textual analysis techniques

The use of bibliometric tools such as VoSViewer is becoming common (Ben-Daya et al., 2019; Dolgui et al., 2020; Galati and Bigliardi, 2019; Mariani and Borghi, 2019) and can support the report of SLRs (lesson 7) with bibliometric networks. Visual presentations, particularly in initial sections of the results, can be used to frame the topic or guide the review process.

5.2.4. Report the network addressed in the review and the recommendations to endure change

The clear identification of the context can contribute to create a solid body of knowledge in 4SC, allowing the identification of new contexts for future studies and reusing previous SLRs contributions. Moreover, the focus of change can affect only a part of the supply chain (e.g., inventory), a set of links, or the extended supply chain (e.g., use phase or end-of-life). Finally, the system needed to promote and endure change can be explained in the discussion section and/or suggestion for future work of 4SC. This recommendation can also be adopted in primary studies to improve background sections.

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Appendix A. Supplementary data

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