Digital supply chain model in Industry 4.0

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Abstract

Purpose – The purpose of this paper is to present a conceptual model that defines the essential components shaping the new Digital Supply Chains (DSCs) through the implementation and acceleration of Industry 4.0.
Design/methodology/approach – The scope of the present work exposes a conceptual approach and review of the key literature from 1989 to 2019, concerning the evolution and transformation of the actors and constructs in logistics and Supply Chain Management (SCM) by means of examining different conceptual models and a state-of-the-art review of Industry 4.0's concepts and elements, with a focus on digitization in supply chain (SC) processes. A detailed study of the constructs and components of SCM, as defined by their authors, resulted in the development of a referential and systematic model that fuses the inherent concepts and roles of SCM, with the new technological trends directed toward digitization, automation, and the increasing use of information and communication technologies across logistics global value chains.
Findings – Having achieved an exploration of the different conceptual frameworks, there is no compelling evidence of the existence of a conceptual SCM that incorporates the basic theoretical constructs and the new roles and elements of Industry 4.0. Therefore, the main components of Industry 4.0 and their impact on DSC Management are described, driving the proposal for a new conceptual model which addresses and accelerates a vision of the future of the interconnectivity between different DSCs, grouped in clusters in order to add value, through new forms of cooperation and digital integration.
Originality/value – This research explores the gap in the current SCM models leading into Industry 4.0. The proposed model provides a novel and comprehensive overview of the new concepts and components driving the nascent and current DSCs. This conceptual framework will further aid researchers in the exploration of knowledge regarding the variables and components presented, as well as the verification of the newly revealed roles and constructs to understand the new forms of cooperation and implementation of Industry 4.0 in digitalized SCs.

Keywords Digitization, Supply chain management, Technological change, Value chain, Industry 4.0, Supply networks

Paper type Research paper

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1. Introduction

Supply chains (SCs) and production logistics processes are an important part of the daily enterprises of many professional and personal activities in modern life, and they are highly significant for global development (Min *et al.*, 2019). The great speed of the changes in the different markets and in the economic, financial, social and technological aspects results in SCs being in a state of constant movement and evolution. SCs do not remain static, but evolve and change in their size, shape, configuration and the manner in which they are coordinated, controlled and managed (MacCarthy *et al.*, 2016). The impact of the new digital era on the fourth industrial revolution, the Information and Communication Technologies and the Internet of Things (IoT)-based cyber-physical system (CPS) architecture for production logistics and SC applications have led to the implementation and acceleration of innovations that are required for the digitization of the industry (Tu *et al.*, 2018a).

The objective of this research is to contribute to the understanding and evolution of SC models, both conceptual and structural, by means of a literature review; and subsequently, to present a detailed analysis of the principal models, in order to create a well-founded proposal for the evolution for these conceptions, through a new Digital Supply Chain (DSC) model which considers new actors and roles together with the principal constructs and elements of Industry 4.0. Therefore, the purpose of this prospective model could be a starting point in order to continue explaining and observing the best way to accelerate and implement Industry 4.0 practices for digitalized SCs.

The present work addresses the following main research question:

RQ1. Does a conceptual model of supply chain management (SCM) exist that includes basic, previously validated elements/constructs, and that also integrates the components and elements of Industry 4.0 for the new digitalized SCs?

These questions are based on the work of MacCarthy *et al.* (2016) who presented the idea that the new SCs may emerge for many reasons; and now we are experiencing the ascent and development of new actors, elements, concepts and models into these current value chains, such as new intermediaries and multi-sided business platforms.

Moreover, the research work accomplished by Hofmann and Rüsch (2017) proposed that future research should investigate and explore the effects of Industry 4.0 on organizational and operational structures firms. Another significant work, from which this investigation's query arose, was done by Ben-Daya *et al.* (2017), who through a current literature review on digital technology applications in SCM, identified the following gaps: a lack of solid frameworks that provide guidance for IoT and CPS adoption in a SC context with clear guidelines and a roadmap; a lack of models that address SC problems in an new technological environment; and several barriers against the implementation of Industry 4.0 concepts and features in SCM from both a technological and a managerial perspective.

Section 2 presents methodology via a systematic literature review in two parts: the first part studies conceptual models, frameworks for SCM, whereby 18 models were selected for a full descriptive analysis, which allows an understanding of the findings and the theoretical concepts or constructs derived from these models. The second part systematically reviews the Industry 4.0 state of the art to identify a summary of the emergent elements and technological constructs used in the nascent digitalized SC. Section 3 shows the findings of the literature review to support in Section 4 a proposal for a DSC model that includes the validated – through a literature review – traditional SC actors and constructs, as well as the new and emergent elements inherent in the Industry 4.0 era. Section 5 Discusses the practical implications for the DSC model. Conclusions, limitations and recommendations for future work are provided in the final section.

2. Methodology

In this section, a systematic literature review is presented in two parts: the first part identifies the main, previously published conceptual SC models, and the second part is a systematic search for the state of the art with regard to the nascent elements and constructs of Industry 4.0, and its enablers within SCM and production logistics processes. An inductive focus is applied to study the main constructs defined by the science of SCM. In addition, evidence is gathered for the purpose of conceptualizing management research that is not only of high academic quality, but also practical and context sensitive to facilitate the development of valid and reliable knowledge (Tranfield *et al.*, 2003).

The methodology for the literature review is based on the recommendations for a successful systematic review by Webster and Watson (2002), Tranfield *et al.* (2003), Cooper and Hedges (2009), Seuring and Gold (2012) and Saenz and Koufteros (2015). The objective is to present a formal methodology based on meta-analysis, as presented in Preferred Reporting Items for Systematic Reviews and Meta-Analyses (Moher *et al.*, 2009). The general process can be seen in Figure 1.

The horizon review for the first part of the literature review was carried out to examine the state of the art and history of the science of SCM. It was decided to undertake a search for conceptual models published during a period of 30 years from 1989 to 2019 (Section 3.1). In Section 3.2 the second part of the literature review is presented, the focus being on the state of the art of the emerging Industry 4.0's concepts and elements within the Supply Chain Management Components (SCMCs). The review focuses on the papers of the last 12 years, referring to the concepts and enablers of Industry 4.0. The paper identification procedure involved finding the earliest authoritative state-of-the-art sources presenting SCM models (as in the case of Stevens, 1989) and then also more recent models that link SCM and Industry 4.0, and their technological trends and concepts.

The database selection was focused on obtaining a significant sample, comprising the majority of journals specializing in SCM and Information and Communication

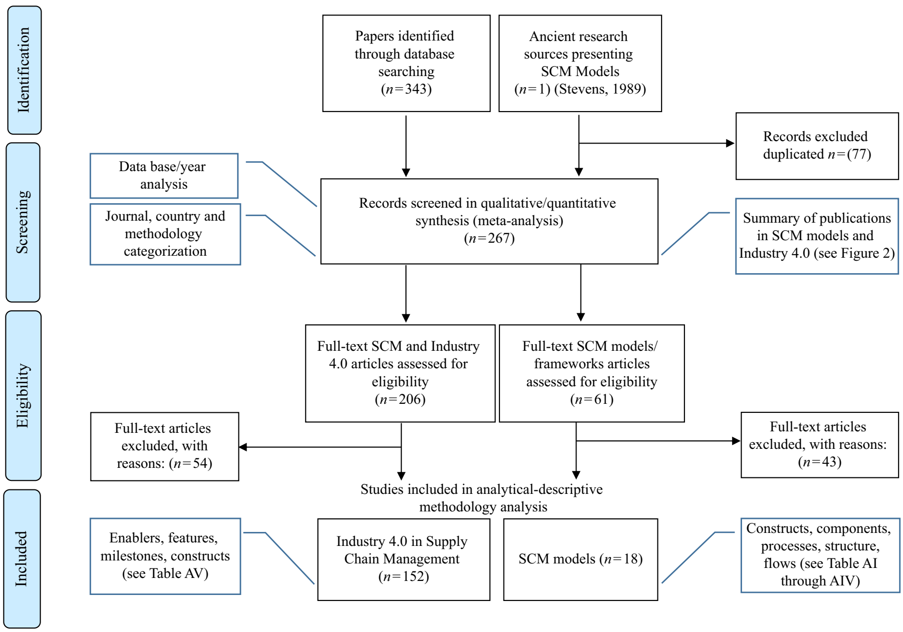

Figure 1.
Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol

Technology Management. This focus facilitated finding published works containing conceptual models, diagrams and constructs pertaining to SCs, as well as the elements of Industry 4.0, throughout our search. The following databases were identified that contain the literature on management science: EBSCO Academic Research Complete and EBSCO Business Source Complete, Web of Science, Science Direct, Emerald e-Journal Premiere Collection and Wiley Journals.

For the first part of the literature review, a search was performed on those databases with key words in the title or (and) in the text (anywhere): "supply chain*" and "conceptual model" or "framework" or "construct"; in the second part, the key words in the title or (and) in the text (anywhere) were: "digital* supply chain*" and "Industry 4.0"; "supply chain* and "Industry 4.0";"supply chain* and "smart industry"; "digitalization of the industry"; "digitalization of the supply chain"; "supply chain*" and "Internet of Things," or "IoT"; "supply chain" and "3D printing" or "advanced manufacturing" or "additive manufacturing"; "Industry 4.0" and "robotics" and "supply chain*"; "Industry 4.0" and "augmented reality" and "supply chain*"; "Industry 4.0" and "digital platforms" and "supply chain*"; "Industry 4.0" and "cloud computing" (CC) and "supply chain*."

Then, the two exclusion criteria for both searches were: any paper not written entirely in English and any non-academic or non peer-reviewed papers. It´s needed to say that 344 papers were found and then subjected to an analytical selection process. In all, 77 papers were discarded because they were duplicated in the entire set of works found. The application of the protocol was continued by reading and elaborating a descriptive analysis of the field of 267 outstanding papers, of which 61 referred exclusively to SCM models, frameworks and constructs, and the other 206 address SCM and Industry 4.0 technology enablers (see Figure 1).

As can be seen in Figure 2, during the years 1990–1993, 1996 and 1999, no evidence of any conceptual/construct-based model of SCM significant for this study was found. Since 2001, there has been a significant increase in studies on this subject; which could be due to the development of the internet, which has created a need to build new SCs to face emerging challenges (Graham and Hardaker, 2000). Another factor may be, as mentioned by Soni and Kodali (2012): "the growth of the SCM literature and empirical research in SCM since the last 15 years." From 2014 to 2018, there was an important peak in research papers related to SCM models and Industry 4.0, with a total of 57 publications comprising 60 percent of the results of the total search. Figure 2 also shows when the literature starts to include Industry 4.0 enablers related to SCM, which is the case for the works of Attaran (2007), Atzori *et al.* (2010), Graham and Hardaker (2000), Lee and Ozalp (2007), Sarac *et al.* (2010), Thiesse *et al.* (2009), White *et al.* (2008), and it can

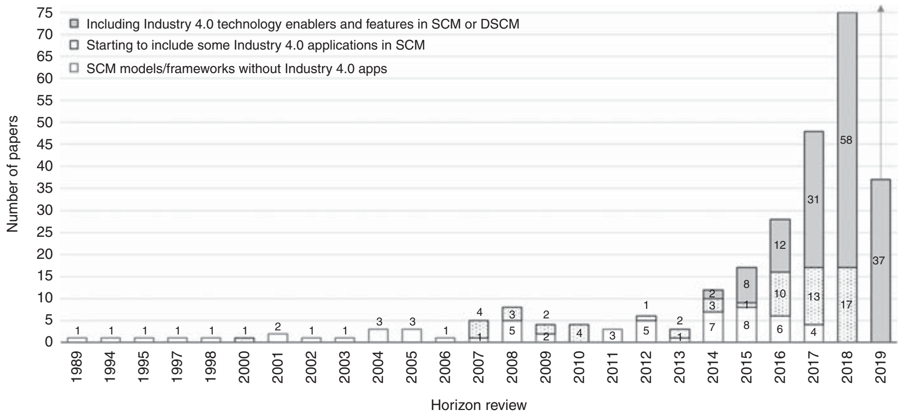

Figure 2.
Research publications in SCM models and Industry 4.0

be noted how the scientific papers referring to the elements and applications of Industry 4.0 in SCM have increased significantly since 2014. The data for 2019 are for a partial year at the time of the preparation of this manuscript.

Subsequently, an in-depth screening of the papers was performed, using the following analytical procedure: "Rough cut," excluding those papers with no significant focus on SCM, or technology applications on SCs or logistics processes, either throughout the paper or in a specific section. "Reading cut," removing any papers that do not present any model/conceptual model/framework/construct(s), actors and/or components on the functioning/behaviors of SCs and/or concepts/elements/applications of Industry 4.0 in SCM. During this step of the procedure, 18 research papers with frameworks and models with the basic constructs and concepts found in SCM were detected, and an in-depth analytical-descriptive methodology analysis was conducted for each one. Likewise, data extraction and synthesis for the 139 research papers related to Industry 4.0 in SCM applications were carried out.

The findings of the two-part literature review are presented in Sections 3.1 and 3.2, contributing to answering the initial question and connecting the key concepts that are central to this research paper. The preponderant constructs and key emerging themes were identified. The aspects identified are systematically presented through an aggregating, interpretive and inductive approach, extracting the central contributions of each one.

3. Literature review

3.1 Findings on traditional supply chain models

Several SCM models have historically been defined by the most important scholars in this field. As an early work, we can mention the paper by Stevens (1989), who introduced one of the first schemes that allows an understanding of the materials and information that flow through the main components of the physical distribution channel such as suppliers, warehouses, factories, distribution warehouses and down to the final customers.

Other models that have studied and proposed essential SCM elements are the research works by Cooper *et al.* (1997) and those currently studied by Oettmeier and Hofmann (2016), who have proposed three general constructs (see Figure 3): the SCMCs known as the managerial methods by which business processes are integrated and managed across the SC, e.g., work and organizational structures, information and communication structures; the Supply Chain Management Processes (SCMPs), referring to the activities that produce a specific value output to the customer, e.g., the customer and supplier relationship, demand and manufacturing flow management; and the Supply Chain Network Structures (SCNS), described as the member firms and the links between those firms, e.g., upstream suppliers (tiers), services-party logistics and customers.

Based on these three generic constructs, a qualitative meta-analysis was developed for the 18 selected models, by means of the previously defined search protocol. The main methodology of this literature review is an exhaustive reading of each work, in order to identify the postulated constructs, relying on the three essential elements within the SC framework: SCMCs, SCMPs and SCNS. Subsequently, the accuracy and contributions of each of the analyzed research papers and the similarities between them were identified.

It is worth to mention that Supply Chain Flows (SCFs) are considered an important construct among the SCM elements in this research paper, due to the relevant interconnection and systematic interaction provided through them and between each actor in the SCNS, e.g., products (goods) and services, information, knowledge and financial and return flows. Tables AI through AIV summarize the analyses, findings, features and components of these four SCM constructs (see Figure 3), and show the concordance of the works and models studied in this literature review.

The research works developed by Lambert *et al.* (1998), Croxton *et al.* (2001), Lambert and Schwieterman (2012) and Lambert (2014) contain very similar SCM models. The SCMPs

Figure 3.
Essential constructs of Supply Chain Management. Based on the literature review

"return management" is mentioned by few authors. This might be due to the fact that issues regarding sustainability, reverse logistics, reverse flows and reverse SC have only become of greater concern in the last 10 years as a result of stricter environmental regulations by local governments and increasing consumer awareness of environmental issues (Ilgin and Gupta, 2011; Seuring and Gold, 2012).

Another important contribution is the exploration of the actors or SCNS in the different conceptual models included in this study. One aspect that stood out is the fact that the conceptual models defined from 2000 to 2014 agreed on the definition of the following components: tiers or suppliers of suppliers, focal companies (manufacturing or services), wholesalers or distributors, retailers and final customers (Harryson and van Hoek, 2008; Jacobs *et al.*, 2008; Krajewski *et al.*, 2013). Some other elements and constructs for the SCNS, defined by the authors of the reviewed papers, are documented in Table AII.

The incorporation of these new concepts has enriched the adoption of the newly proposed structures currently functioning in the emerging SCs. Some examples are networks where multiple chains are intertwined and more widely practiced in the industry, and which are now evolving and represent great challenges, such as those mentioned by Lim *et al.* (2018): operational challenges in executing last-mile operations; the intersection between last-mile operations and sharing economy models; data harmonization and analytics; and moving from prescriptive to predictive last-mile distribution designs (Ivanov *et al.*, 2018).

It is worth emphasizing the evident changes in communication and movement along the physical channels of supply and the distribution chain in the SCNS; currently, they have been evolving into complex digital channels, transforming goods, adding processes and services, and generating great synergy between different SCs, thus obtaining fast responses and constant flows. This has previously been pictured as a pipeline, showing directional SCFs, services, financial resources, the information associated with these flows and the informational flows of demands and forecasts (Mentzer *et al.*, 2001). Therefore, a scenario has been reached where, as mentioned by Chopra *et al.* (2016), "most supply chains are, in fact, networks."

Consequently, the coordination of the flows, moving within and through the interested companies in the networks into the SCNS has been relevant in achieving a competitive advantage and productivity, both for individual companies in the SC, as well as for the members of the SC collectively (Ballou, 2004).

The findings on the different types of flows that have been proposed and developed in the reviewed SC models are shown in Table AIII. We can highlight the construct called "virtual supply chain" and "virtual value creation," proposed by Graham and Hardaker (2000). The first construct is a starting point for the present research, because surrounding this construct it is possible to observe all those key components of the emerging and current digital SC; the second explains the concept of meaning which, thanks to the flow of information and the activities generated such as: information collection, systematization, selection, processing, distribution, exchange, analysis and offering, a virtual SC has emerged, developing different activities in the marketplace and operating completely independently of the physical value chain.

Another finding, regarding the SCFs observed within the examined models, is the great impact that the development of information and communication technology has generated in the management and integrated control of information, finances, risks and merchandise flows, thus making possible a new range of production systems and distributions. The growth in information technology and the increase in global business competition have also forced organizations to find new ways of doing business (Almajali *et al.*, 2016). These new ways of doing business can only be carried out by using an elementary factor in organizations: the SCMs. Therefore, the analysis shown in Table AIV refers to the management methods by which all SCMPs are integrated and managed throughout the SC.

Through validation with management experts, Lambert (2014) mentioned two types of SCMCs: structural management components and behavioral management components. Based on the research work developed by this author, these components have been a primary reference for the validation and comparison of the conceptual models of SCs in the literature review explored in this paper.

The authors of the 18 examined papers have coincided in more than five of the ten general SCMCs. This in itself represents and validates these elements as a fundamental part of the management of activities that add value throughout the SCs and SC networks. Furthermore, within the research papers analyzed, other valuable concepts have been detected; outstanding examples include: approaches in SC flexibility (Duclos *et al.*, 2003; Martínez Sánchez and Pérez Pérez, 2005); in SC integration (Stevens, 1989; Cooper *et al.*, 1997; Mentzer *et al.*, 2001; Zhang *et al.*, 2015); in definition and validation of SC constructs (Cooper *et al.*, 1997; Lambert *et al.*, 1998; Lambert and Stock, 2000; Chen and Paulraj, 2004; Lambert and Schwieterman, 2012; Lambert, 2014); in SC evolution (Oettmeier and Hofmann, 2016) and in SC life cycles (MacCarthy *et al.*, 2016; Stevens and Johnson, 2016).

This exploration has also allowed us to recognize that only Graham and Hardaker (2000), Stevens and Johnson (2016) and Hofmann and Rüsch (2017) presented, through their models, the most significant approach in the construction of components and in the definition of the elements that are currently key in the operation of Global Integrated SCs, SC clusters and goal-directed networked SCs, during the era of the Fourth Industrial Revolution.

The literature review also showed that there are four works that link a conceptual model approach to the internet and digitalization (Alcácer and Cruz-Machado, 2019; Ardito, Petruzzelli, Panniello and Garavelli, 2018; Bag *et al.*, 2018; Büyüközkan and Göçer, 2018; Graham and Hardaker, 2000; Hofmann and Rüsch, 2017; Muhuri *et al.*, 2019; Tu, 2018), thus presenting an initial and incipient incorporation of constructs and elements for Industry 4.0 within the essential components of SCM. The research work developed by Büyüközkan and Göçer (2018), showed a literature review for DSCs and their enablers and proposed a framework, but the suggested components of SCM are not supported by the basic literature review and constructs of the discipline. Otherwise, the further decomposition of a digital SC model is not included and it is not possible to observe the consolidation of each element as a construct or as an integrated part of the main elements of a SC, such as a digital and physical: SCNS, SCMCs, SCMPs and SCFs, nor a precise identification of the main concept enablers and features of Industry 4.0 integrating the core management of the digitalized SCs.

According to the literature review research carried out on traditional SC models, we identified the main characteristics detected within different frameworks presented over the years, which undoubtedly reflect the interaction between their components, processes, structures and flows (see Table I in Section 3.2). Therefore, it is pertinent to present the findings and discussions for the *RQ1*.

The evolution of the 18 presented models shows the remarkable progress and development of the components and constructs that have been incorporated into the SCM over the years. However, this literature review has revealed the absence of a strong model that contains: the basic theoretical concepts and also addresses the incorporation of digital components in the functioning of the new SCs, including all of these Industry 4.0 elements and constructs within the SCNSs (flows, processes and management components).

That is to say, sufficient evidence has not been found of any conceptual model or construct that exhibits the incorporation of all the emerging elements and constructs inherent in the new and current functioning of the "Global Supply Chains" or "Digital Supply Chain Networks," as named by some authors and as Straub *et al.* (2004), Jayaram (2016), Kim and Chai (2017) and Klötzer and Pflaum (2017). This finding can be supported by the work done by Barata *et al.* (2018), Ben-Daya *et al.* (2017) and (Bibby and Dehe, 2018), who, through a review of the current literature on Industry 4.0 applications in SCM, identify: a lack of solid frameworks, models or roadmaps that address SC in an Industry 4.0 environment with the implementation of new concepts, and Industry 4.0 features and technologies in SCM.

Stemming from this detected opportunity, this research study proposes the construction of a new conceptual model that allows the new and digital SCs to be represented, depicting them as agile, flexible, integral, inter-coordinated, interconnected and interacting synergistically for the creation of value in real time by means of characterizing and stratifying the different actors, elements and technology application trends that support digitization and Industry 4.0 within the main SCM constructs.

Having thus summarized the evidence in order to answer the above question for this research project, the following section describes a summary of the literature review of the technology trends and concepts related to the emerging terms of Industry 4.0 in the SCM. Later, the outstanding components of SCs are identified and described for the proposed DSC model for Industry 4.0.

Table I. Literature review synthesis: Industry 4.0 technologies trends and concepts related to SC components

Industry 4.0 technologies trends concepts	Physical and digital SCM components	Physical and digital SCM processes	Physical and digital SC network structure	Physical and digital SC flows	Industry 4.0 enablers	Industry 4.0 features	Research works
3D printing/additive manufacturing	X	X			X		Brinch (2018), Buonafede *et al.* (2018), Chan *et al.* (2018), Durach *et al.* (2017), Durão *et al.* (2017), Lopes de Sousa Jabbour *et al.* (2018), Luiz *et al.* (2019), Murmura and Bravi (2017), Oettmeier and Hofmann (2016), Pärn and Edwards (2017), Rogers *et al.* (2016), Ryan *et al.* (2017), Santos *et al.* (2018), Sasson and Johnson (2016)
Augmented reality/virtual reality/mixed reality robotics	X	X	X		X	X	Aydin (2018), Brettel *et al.* (2014), Cirulis and Ginters (2013), Dallasega *et al.* (2018), Ginters *et al.* (2013), Kerin and Pham (2019), Liao *et al.* (2017), Lu (2017), Merlino and Sproge (2017)
Automation manufacturing/ automation/distribution robots/self-driving vehicles/automation warehousing		X	X	X	X	X	Albers *et al.* (2016), Alcácer and Cruz-Machado (2019), Baruffaldi *et al.* (2019), Ben-Daya *et al.* (2017), Büyüközkan and Göçer (2018), Chang and Lai (2017), Chiarvesio and Romanello (2018), Jayaram (2016), Oesterreich and Teuteberg (2016), Tang and Veelenturf (2019), Sarc *et al.* (2019), Vanderroost *et al.* (2017)
Big Data/Big Data analytics/data mining/data trends	X	X		X	X	X	Ardito, Petruzzelli, Panniello and Garavelli (2018), Ardito, Scuotto, Del Giudice and Messeni (2018), Kache and Seuring (2017), Nguyen *et al.* (2018), Oesterreich and Teuteberg (2016), Rajput and Singh (2018), Richey *et al.* (2016), Strange and Zucchella (2017), Tiwari *et al.* (2018)
Block chain	X	X		X	X		Andoni *et al.* (2019), Florea (2018), Ghobakhloo (2018), Korpela *et al.* (2017), Preuveneers *et al.* (2017), Queiroz *et al.* (2019), Skwarek (2017), van Tulder *et al.* (2018), Wang *et al.* (2019)
Cloud computing/mobile computing/artificial intelligence/machine-learning technology	X	X	X	X	X	X	Akbaripour *et al.* (2015), Ardito, Petruzzelli, Panniello and Garavelli (2018), Bruque Cámara *et al.* (2015), Calatayud *et al.* (2019), Faheem *et al.* (2018), Hofmann and Rüsch (2017), Mourtzis and Vlachou (2016), Ren *et al.* (2016), Sundarakani *et al.* (2019), Qu *et al.* (2016)

(*continued*)

Table I.

Industry 4.0 technologies trends concepts	Physical and digital SCM components	Physical and digital SCM processes	Physical and digital SC network structure	Physical and digital SC flows	Industry 4.0 enablers	Industry 4.0 features	Research works
Cyber-physical systems/embedded systems	X	X	X	X	X	X	Jiang *et al.* (2018), Klötzer and Pflaum (2017), Lee *et al.* (2015), Lu (2017), Oesterreich and Teuteberg (2016), Panetto *et al.* (2019), Singh *et al.* (2019), Sony and Naik (2019), Thiede *et al.* (2018)
Cybersecurity	X	X	X	X	X	X	Ardito, Petruzzelli, Panniello and Garavelli (2018), Bienhaus and Haddud (2018), Oesterreich and Teuteberg (2016), Singh *et al.* (2019), Strange and Zucchella (2017)
Digitalization/digital lean/digital reality/social media	X	X	X	X		X	Bolwijn *et al.* (2018), Chiarvesio and Romanello (2018), Eden (2018), Götz and Jankowska (2018), Jayaram (2016), Klötzer and Pflaum (2017), Lee *et al.* (2018), Lu (2017), Lugert *et al.* (2018), Martinez (2019), Müller *et al.* (2019), Sanders *et al.* (2016), Oesterreich and Teuteberg (2016), Rachinger *et al.* (2018), Schniederjans *et al.* (2019), Srai and Lorentz (2019), Ustundag and Cevikcan (2018), Wilkesmann and Wilkesmann (2018)
E-commerce/E-business	X	X	X	X	X		Dallasega *et al.* (2018), Fosso Wamba (2012), Lim *et al.* (2018), Sharma *et al.* (2016), van Tulder *et al.* (2018), Yu *et al.* (2017)
ERP intelligent demand assessment/pull replenishment – real-time SCM	X	X	X	X	X	X	Asdecker and Felch (2018), Bienhaus and Haddud (2018), Dallasega *et al.* (2018), Lu (2017), Oesterreich and Teuteberg (2016), Panetto *et al.* (2019)
Flexibility/horizontal and vertical integration	X	X	X	X	X	X	Bag *et al.* (2018), Brettel *et al.* (2014), Chiarvesio and Romanello (2018), Liao *et al.* (2017), Majeed and Rupasinghe (2017), Oesterreich and Teuteberg (2016), Ranjan *et al.* (2017)
Human–computer interaction.	X	X	X		X		Oesterreich and Teuteberg (2016), Barata *et al.* (2018), Dallasega *et al.* (2018)
Information integration and sharing	X		X	X		X	Ardito, Petruzzelli, Panniello and Garavelli (2018), Bartnik and Park (2018), Calatayud *et al.* (2019), Choi (2018),

(continued)

Industry 4.0 technologies trends concepts	Physical and digital SCM components	Physical and digital SCM processes	Physical and digital SC network structure	Physical and digital SC flows	Industry 4.0 enablers	Industry 4.0 features	Research works
							Colicchia *et al.* (2019), Dallasega *et al.* (2018), Friday *et al.* (2018), Lin *et al.* (2018), Thiede *et al.* (2018), Yang *et al.* (2018)
Internet of Things/Internet of Services	X	X	X	X	X	X	Ammirato *et al.* (2019), Birkel and Hartmann (2019), Borgia (2014), Čolaković and Hadžialić (2018), Del Giudice (2016), Haddud *et al.* (2017), Li *et al.* (2017), Leminen *et al.* (2018), Montori *et al.* (2018), Ray (2018), Rajput and Singh (2018), Skwarek (2017), Tu (2018), Tu *et al.* (2018b), Zhou *et al.* (2015)
Omni-chain/omni-channel/market place/market space. click and collect delivery/pick-up points/home collect/in-car delivery	X	X	X	X	X	X	Adivar *et al.* (2019), Graham and Hardaker (2000), Hübner *et al.* (2016), Murfield *et al.* (2017), Lim *et al.* (2018)
Product-lifecycle management	X	X	X	X	X		Ang *et al.* (2017), Ben-Daya *et al.* (2017), Hendler (2019), Li *et al.* (2015), Lopes de Sousa Jabbour (2018), Rizzi *et al.* (2017)
Radio-frequency identification/sensor technology/signalization/beacons	X	X	X	X	X	X	Attaran (2007), Atzori *et al.* (2010), Büyüközkan and Göçer (2018), Lee and Ozalp (2007), Liukkonen and Tsai (2016), Lv and Lin (2017), Ngai *et al.* (2008), Pei *et al.* (2017), Ramadan *et al.* (2017), Sarac *et al.* (2010), Thiesse *et al.* (2009), White *et al.* (2008), Xu *et al.* (2014)
Simulation tools/simulation models	X	X			X	X	Atzori *et al.* (2010), Chong and Zhu (2018), Ghobakhloo (2018), Liao *et al.* (2017), Oesterreich and Teuteberg (2016)
Smart factory or firm/smart logistics/smart manufacturing.	X	X	X	X	X	X	Agostini and Filippini (2019), Alcácer and Cruz-Machado (2019), Bortolini *et al.* (2018), Frank *et al.* (2019), Habraken and Bondarouk (2017), Hofmann and Rüsch (2017), Kang *et al.* (2018), Kazancoglu and Ozkan-Ozen (2018), Kusiak (2019), Liboni *et al.* (2019), Lin *et al.* (2018), Lu (2017), Müller (2019), Oesterreich and Teuteberg (2016), Oh and Jeong (2019), Park *et al.* (2018), Sharma *et al.* (2016)
Wearables			X	X		X	Srai (2018), Srai and Lorentz (2019), Wilkesmann and Wilkesmann (2018)

Table I.

3.2 Findings on Industry 4.0 technology applications in digitalized supply chains
The second part of the systematic literature review focuses on the state of the art of the emerging Industry 4.0 concepts and elements within the SCMCs, SCMPs, SCFs, and structures. A meta-synthesis of the 139 research works selected as part of the systematic eligibility methodology was carried out, proposing a categorization and stratification of each one of the elements, concepts, enablers and technological applications concerning the three principal SCM issues: the SCNS, and the SCMPs and SCMCs.

The objective of Section 3.2.1 is to identify and include the emerging technology enablers and features of Industry 4.0 that are transforming the old SCs into the new digitalized SCs, through the implementation of technology. Furthermore, this fourth revolution has been changing the traditional SCMCs, SCFs, SCMPs and even the network structure, leading to new ways of management, processing and interaction between the actors in the SCM structure, evolving into a physical and digital operational approach within a virtual and physical world, described in Section 3.2.2.

3.2.1 Industry 4.0 enablers and features. Economic civilization development globally has had three important stages, called revolutions or disruptions of the industrial process. The first was related to the mechanization of production using steam engines, the second was the introduction of mass production due to electricity (Witkowski, 2017), and the third was based on process computerization using information technology, informatics controllers for accelerated automation (Dujin *et al.*, 2014). The fourth era, namely, Industry 4.0, referred to as the "Fourth Industrial Revolution," also known as "smart manufacturing," "industrial internet," or "integrated industry," is on-going, with the characteristics of CPS production based on heterogeneous data and knowledge integration, which has begun to be dominated by intelligent (smart) products, 3D printers and autonomous vehicles (Hendler, 2019; Hofmann and Rüsch, 2017; Mehami *et al.*, 2018).

Furthermore, Industry 4.0 encompasses numerous technologies and associated paradigms (Lu, 2017). Due to this, it is necessary to identify and understand all of the constructs that have been incorporated as important elements of the nascent digital and physical SCM, as identified in this state of the art (da Silva *et al.*, 2019). To understand the current digital technologies and enablers of Industry 4.0, it is important to recognize that CPS conception has as a starting point to develop the IoT, Big Data (De Mauro *et al.*, 2016; Witkowski, 2017), and other essential enablers and applications, interacting within the SCNS.

Table I shows a summary of the literature review findings with regard to Industry 4.0 technology trends and concepts as enablers for the acceleration, technology implementation and digitalization of the SCs. Those suggested pillars of technological advancements are based on the research work of Chiarvesio and Romanello (2018). A categorization for each of the SCM main components was carried out. It is worth mentioning that the main research studies that helped the systematic analysis of these constructs are by: Ardito, Petruzzelli, Panniello and Garavelli (2018), Ardito, Scuotto, Del Giudice and Messeni (2018), Ben-Daya *et al.* (2017), Büyüközkan and Göçer (2018), Dallasega *et al.* (2018), Ghobakhloo (2018), Liao *et al.* (2017), Lu (2017) and Oesterreich and Teuteberg (2016) and Sony and Naik (2019).

The Industry 4.0 enablers and features in digitalized SCs could be described as the key elements that provide the typical quality for the digital connectivity and communication of the physical and digital elements in the SCs, thus allowing real-time data storage, analysis and sharing (Ben-Daya *et al.*, 2017). Moreover, these components grant and facilitate planning, control and coordination of the activities and processes of the SCMCs, SCFs and SCNS. Table AV shows the main definitions of the theoretical concepts developed by scholars in the field of study in Industry 4.0.

Therefore, the main objectives of Industry 4.0 is expected to enable factories to: organize and control themselves autonomously, in a decentralized fashion and in real time (Brettel *et al.*, 2014), reaching a state of multiple intelligent factories and smart manufacturing

(Liboni *et al.*, 2019; Lu, 2017). This system was previously envisioned by academics in Operations Management, that is a real global practice of a SCs integration, interconnected in real time, achieving optimal flexibility and responsiveness (Dallasega *et al.*, 2018; Ryan *et al.*, 2017; Stevens and Johnson, 2016; Tu *et al.*, 2018a; Zhou *et al.*, 2015). Thus, these three targets of Industry 4.0 are the basis for the proposal of this research study, as a visionary construct which we are already living with.

Once these components of Industry 4.0 have been analyzed in Table I, the way in which they are modifying the current SCs managerial process and components, flows and structures, through technological trends is validated. Thus, based on the research studies found in the extensive literature review presented in this section, it is possible to affirm that the integration of these concept trends and enablers of the Fourth Industrial Revolution is generating an essential dimension in the transition of traditional SCs into DSCs.

3.2.2 Digitalized supply chains. Current SCs have an accelerated life cycle and are in constant evolution; this evolution is driven by changes in the markets and emerging needs of the Fourth Industrial Revolution era. For this reason, new terms for digitalized SCs have been flourishing. This is the case for the "Digital Supply Chain" construct, referring to the evolution of how the current SCs are driven in Industry 4.0.

The state of the art and definitions of the DSC have been proposed by some authors in recent years (Calatayud *et al.*, 2019; Klötzer and Pflaum, 2017; Oswald and Kleinemeier, 2017; Park *et al.*, 2018; Wu *et al.*, 2016; Xu, 2014). The literature review by Büyüközkan and Göçer (2018) brings us a step closer to the most appropriate constructs for this research paper.

The most relevant definitions of DSC include:

> […] an intelligent, value driven network that leverages new approaches with technology and analytics to create new forms of revenue and business value, through a centric platform that captures and maximizes the utilization of real-time information emerging from a variety of sources. (Kinnett, 2015)

And:

> […] an intelligent best-fit technological system that is based on the capability of massive data disposal and excellent cooperation and communication for digital hardware, software, and networks to support and synchronize interaction between organizations by making services more valuable, accessible and affordable with consistent, agile and effective outcomes. (Büyüközkan and Göçer, 2018)

As presented in the previous section, the key Industry 4.0 enablers and features are changing the core of SCs, but it is important to emphasize how dealing with the digitalization of the SC is more than maintaining the same way of managing traditional SCs and simply digitizing all knowledge and information flows. Therefore, it is significant to highlight that the whole structure, as well as all of the processes, managerial components and flows in the chain are changing because of the emergent and customized markets that need rapid responses. In this regard, the technology trends and applications of the Fourth Industrial Revolution are now helping to transform the value chain, as we know, into a virtual value chain enabled by digitalization (Lee *et al.*, 2018; Müller, 2019; Müllner and Filatotchev, 2018; Sony and Naik, 2019; Srai and Lorentz, 2019; Ye and Ma, 2018).

On the other hand, the main features of the DSCs that make up the difference between the traditional SCs, referring to the operational management of the basic components, as shown in Figure 3, and the proposal dimensions in Figures 4 and 5, are: accelerated, adaptable, smart, real-time data gathering, transparent, globally connected, scalable and clustered, breakthrough, inventive and sustainable. Thus, compared with traditional SCs, DSCs outstanding by the main characteristics described in Table II.

On comparing the different literature review SC frameworks, a clear gap is evident. What is lacking is a novel and multi-dimensional model that permits a graphical visualization of

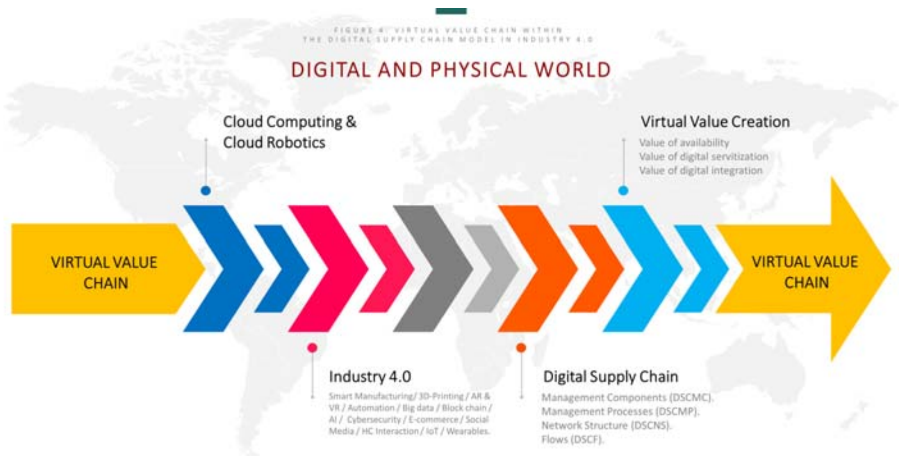

Figure 4.
Virtual Value Chain within the Digital Supply Chain Model in Industry 4.0

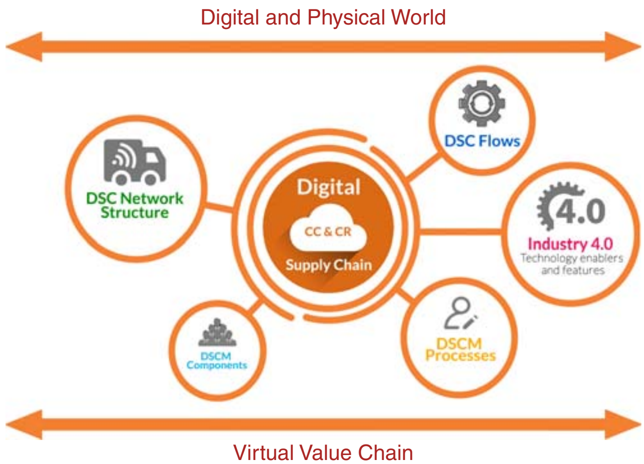

Figure 5.
General Construct of the Digital Supply Chain Dimensions in Industry 4.0

the interconnectivity and rapid response between the actors along the entire chain (Barata *et al.*, 2018; Ganji *et al.*, 2018). The classical models and their graphical structural description fall short of visualizing the interconnectivity and speed in the communication and technology integration; they do not show the rapid changes and responses by the whole digital and physical SC structure. On the other hand, current and emerging flows, as well as new approaches to creating value along the chain are missing.

Moreover, it is significant that a baseline is lacking to include those new actors and stakeholders who are appearing and evolving on the grounds of digitalization. Similar issues have been noticed regarding a lack of scope for new managerial methods to re-shape and adapt to the physical and digital processes, of brand-new behaviors and ways to do business, of a work structure and so on. In order to bridge this gap between the construction of different SC blueprints, after and during the evolution of digitalization, the following section describes a proposal for a framework for a DSC that includes traditional SC actors and constructs, as well as new and emergent elements inherent to the Industry 4.0 era.

Traditional supply chain characteristics	Digitalized supply chain characteristics
Show a lineal and hierarchic interaction between the SC structure without a real-time connectivity vision	Show a multi-dimensional, non-linear interaction among all of the elements within the DSC model: management components, processes, network structure, and flows
Is designed to manage logistics activities and manufacturing operations	Are designed with a more acute knowledge of customer needs to response speed and the quality needed to satisfy real demands via digitalization, supporting the quick and easy return of these products at end of life
Lack of real knowledge of the return, risk, and value flows, or absence, of an optimal stream of them, among the SC components	Present new emerging flows sharing within the network structure, such as: risk flows, virtual value and real-time information, knowledge, money, virtual goods/services and returns flows
Its structural management components and processes, and administration methods, are spread between individualistic behaviors, thus forgetting the entire system they are part of	Come up with new actors who have an important role in the network structure, such as 4th/5th Party Logistics, information technology, and data trend service specialists
Some management components such as Planning and Control Methods continue to perform archaic practices, or they are done due to an autocratic leadership; this generates a slow response capacity to external changes	Research, experiment, and apply new managerial methods in the traditional SC components and processes to evolve and obtain better integration, automation and reconfiguration
Low or medium-level integration in the workflow activity structure and organizational structure	Have the ability to integrate other supply chains via clusters, reaching interconnection in real time via global connectivity, thus achieving optimal flexibility and responsiveness
Lack of agility and flexibility	Offer physical and/or digital goods and services
Focuses on mass production with low customization	Provide for their customers a centric platform that captures and maximizes virtual and physical value creation through a virtual and physical global value chain
Rapid response in well-defined target markets and when slow changes occur	Deliver mass, customized products and services ecosystem (digital and physical), through data mining and data trends, even predicting customer requirement lifecycles, adapting their operations to rapid and optimal responses
Has several or different communication and information systems that tend not to converge in one, or has problems updating information or achieving real-time communication	Use computational intelligence to develop machine-learning bots based on defined algorithms for self-learning, self-regulation and the autonomous generation of decision-making patterns
Knowledge management is not usually available to all, which in some cases even generates low-quality costs or activities that could become non-ethical	Enable demand stimulation, matching, sensing and management to optimize performance and minimize risk among the DSC network structure
Great efforts to attain horizontal and vertical integration, but without reaching long-term agreements of real interdependence between the network structure	Keep open channels of communication, thus enhancing ethics, transparency and accountability
	Commit to continuous innovation to improve the performance of its key components, mainly pursuing the endless invention of Industry 4.0 technology enablers and features
	Seek a circular economy strategy through the technology enablers of Industry 4.0 to reach sustainable operations management in the DSCs in products, production/processes, and logistics decisions

Table II.
Traditional vs digitalized supply chain main attributes

4. Digital supply chain model in Industry 4.0

The proposal DSC model in Industry 4.0 consists of six continuously interconnected dimensions of the SCMPs and SCMCs; the SCNS; the Industry 4.0 technology enablers and features; the flows; the virtual value creation (which generates the virtual value chain); and the digital and physical world (as shown in Figures 5 and 6). These dimensions interact constantly within the physical SC and a virtual SC (Graham and Hardaker, 2000), or also named by Hofmann and Rüsch (2017) as a physical SC scope and a digital data value chain scope.

The main intention of the DSC model is to present a framework with possible interconnections and configurations to the new digitalized SCs in Industry 4.0 and which are spreading out as part of the evolution of its daily activities.

According to Graham and Hardaker (2000), the virtual value chain shown in Figure 4 identifies the changing nature of value creation, but, just as importantly, indicates how new products and services are emerging through the information-driven economy. Taking as a starting point this proposal, the most important output in any DSC is to achieve virtual value creation through the new construct, now embodied in this proposed model, called CC and Cloud Robotics (CR), shown in Figure 5.

Only with this powerful intelligence, is it possible to reach the value of availability (making products and services available to the customer via autonomous delivering), plus the value of digital servitization (several IT-based service options going beyond the simple distribution of products or physical services), and the value of digital integration (that arises through a permeable transparency and traceability along the DSC) (Hofmann and Rüsch, 2017).

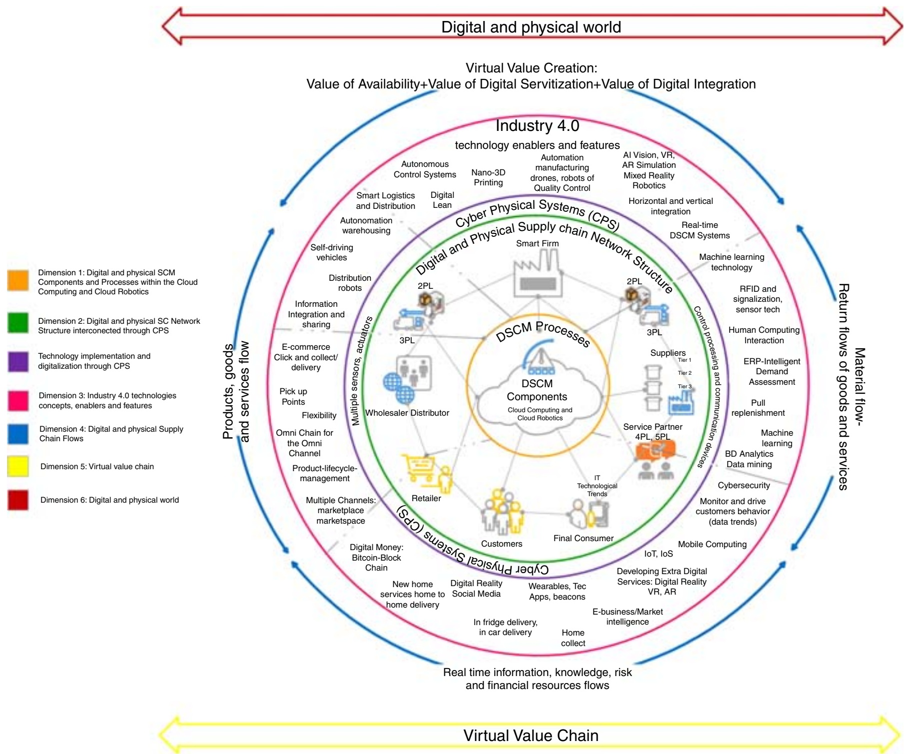

Figure 6.
Digital Supply Chain Model in Industry 4.0

Furthermore, it is worth taking into account how global connectivity and performing different types of flows are transforming the value chain in the digital era, toward the construction of a virtual value chain; the conceptualization described previously can be observed in Dimension 4 of the DSC model, as shown in Figure 6.

The model shown in Figure 6 is described in the following subsections. Each description of the main components and constructs are presented below the figure. The model will be explained by starting with the description of the most internal concept (dimension) located at its center and then moving toward the external portions.

4.1 Dimension 1

The first dimension at the center of the model (as shown in Figure 6), makes an explicit visualization of the intelligent technological system known as CC, CR and cognitive computing, acting as the core that allows the effective handling of the digital and physical DSC management components, including all those managerial methods by which a business can process throughout real-time integration (Calatayud *et al.*, 2019).

To better describe this conception, it is important to think about the cloud robot's "brain" (which interacts with one or more computer systems, accessed via the internet), with provision to Big Data, global maps and descriptions of objects (Bogue, 2017). This "robot" with machine learning or artificial intelligence allows the digitalized SCs to be more flexible and capable of responding rapidly, as conditions change.

Nowadays, the capacity of the deployment and integration of systems through CC, CR, CC and artificial intelligence/machine learning, is possible to establish a macro-interconnectivity between every component, process, actor, flow, technology and so on within the DSC model (see Figure 6 and Table I). This means that multiple DSCs can be interconnected in real time while executing their main processes, and empowering the generation of clusters (Stevens and Johnson, 2016) or groupings according to their needs and life cycles (MacCarthy *et al.*, 2016).

Presenting CC as the central baseline in the DSC components is intended to recognize the current and significant standing of this technology in different business models, because of its rapid and crescent evolution into machine learning or artificial intelligence, to be able to analyze data, to learn from these data, to understand the context, and, from all that, make decisions in order to subsequently execute actions (Bogue, 2014).

This dimension has its focus in the evolution of new processes, flows and structural and behavioral management methods in DSC, driven by CC and CR. This scenario can be supported by the literature findings that show how both technology enablers grant to the SCNS the knowledge to be aware that rapid changes occur not just on the demand side, but also on the supply side. Indeed, on-going applications and cases of study have been experimented adopting integrated manufacturing and supplying processes, and controlling and managing customer interactions, cloud applications, resource providers and suppliers (Akbaripour *et al.*, 2015; Ardito, Petruzzelli, Panniello and Garavelli, 2018; Mourtzis and Vlachou, 2016; Sundarakani *et al.*, 2019).

4.2 Dimension 2

The second dimension, as shown in Figure 6, is describing the physical and digital SCNS linked to the physical and digital SCMPs and three Components. The enabler who permits this connection is the CC, considering as a value matrix (Graham and Hardaker, 2000; Stevens and Johnson, 2016), or as the intelligence to create new forms of virtual value chain through the complete DSC structure and all its components.

The model suggests the following elements of the network structure as: upstream suppliers or Tier 0.5, 1, 2, 3 suppliers; the second and third part logistics; the main company, a focal firm or smart firm; the fourth and fifth part logistics; the customer, wholesaler or distributor; the retailer; and finally, the last consumer, end-consumer or end-user (see Figure 3 and Table AII).

Triggered by CC, the entire physical and digital network SC structure can interact and be interconnected with Industry 4.0 technology enablers and features through the CPS (Lee *et al.*, 2015). This sight is represented within this framework as Dimension 3: technology implementation and Industry 4.0 digitalization through CPS, which allows and gives rise to the functionality and integration of all the traditional SC constructs previously found by the literature review.

4.3 Dimension 3

The convergence point of all the dimensions in the DSC proposal model is the technology implementation and digitalization of Industry 4.0 concepts, enablers and features (Schniederjans *et al.*, 2019). This context anticipates the development and application of best practices in product research and product development, better types of marketing, and new manufacturing strategies in smart factories, as well as innovative forms of distribution and delivery.

Table I shows all the features of Industry 4.0 included within this dimension framework, which were obtained by the extensive literature review presented in Section 2. In the following paragraphs, each one of these technology enablers are described, based on a pull system and mass customization interaction approach.

The first step to trigger a DSC is the customer order, now developed through new ways to the commercialization process, such as multi-channel distribution, born from the need to satisfy customer demands via multiple but distinct distribution channels (Murfield *et al.*, 2017). This has been named the Omni-chain for the Omni-channel, a concept created to define the interconnectivity of different companies toward the user (Adivar *et al.*, 2019; Murfield *et al.*, 2017; Lim *et al.*, 2018), either through the marketplace (physical) or market space (virtual).

In this way, customers can be in contact with any company via multiple avenues, “multi-channel,” “cross-channel,” “everywhere commerce,” or “on-line commerce.” This has allowed for different interfaces with the retailer for shopping or information gathering, e.g., in-store, online store, social media, mobile commerce, catalogue or phone, which are commonly used to distinguish retailer channel activities from a customer point of view (Barata *et al.*, 2018; Hübner *et al.*, 2016).

Afterwards, transactions via E-commerce have triggered new ways of acquiring goods and services by digital currency (bitcoin or cryptocurrency) (Preuveneers *et al.*, 2017; Yu *et al.*, 2017). The meaning of using this type of purchase implies a need to record transactions in such a way that the new units of currency are generated by a computational solution of mathematical problem, and which operates independently of a central bank, now-named Block Chain (Florea, 2018; Korpela *et al.*, 2017; van Tulder *et al.*, 2018). At this point, the Industry 4.0 enabler called cybersecurity, has been looking for a state that means being protected against the criminal or unauthorized use of electronic data, or the measures taken to achieve it (Bienhaus and Haddud, 2018; Lezzi *et al.*, 2018).

Therefore, by means of the DSC proposal model, real pull system scenarios are able to design and implement with a focus on mass customization, due to the interconnectivity of the two DSC dimensions explained previously, given by Industry 4.0 enablers (Sanders *et al.*, 2016). Indeed, all elements of the virtual value chain are being empowered thanks to links with the real-time information from the wholesaler, distributor, retailer, customer or final consumer, at the moment he sends a request via new intelligence models for E-business in the marketspace/marketplace (Dallasega *et al.*, 2018).

In this pull system, when all the information has been received by the CC (Dimensions 1 and 2), all the processes, business management methods and physical/digital structures of the DSC should be activated and should make it possible to provide the client with a series of experiences through the deployment of extra digital services by means of IoT, Internet of Services (Hermann *et al.*, 2015), artificial intelligence, virtual reality, and augmented reality via stationary devices in sales and consumption (Borgia, 2014) or apps (Dallasega *et al.*, 2018; Lu, 2017), thus integrating them into the dimensions shown in the DSC model, to accomplish virtual value creation. Continuing with the presented scenario, once the customer order is placed, it is possible to achieve an efficient and effective manufacturing flow process thanks to the information collected in real time in CC, analyzed with the support of industrial information current methods and techniques, employing architectural integration computer systems such as: business process management, workflow management, enterprise application integration, service-oriented architecture, grid computing, and enterprise resource planning (ERP) and now the emergent real-time DSC management (Lu, 2017; Panetto *et al.*, 2019).

The generation and effective management of knowledge obtained along the entire chain is feasible, through the cognitive analysis and monitoring of the Big Data analytics, data mining and data trends gathered by mobile computing devices such as mobile phones, tablets, laptops, PCs, wearables, beacons and other emerging new technologies. This continuous connectivity has been reached by specially designed systems to collect real-time and sizeable information, such as: apps, Global Positioning Systems (GPS) and social media. These enablers and features are key elements in DSC operations, whose main characteristic is a focus on the customer, who is at the forefront of any business. As a consequence, DSCs have a more in-depth relationship with their customers, hence achieving better efficiency for the real-time inventory operations, production flow monitoring, equipment management and customer integration (Ghobakhloo, 2018).

Consequently, integrated knowledge has allowed the achievement of superior performance in demand management and the procurement process (Dimension 1, Figure 6), through an ERP intelligent demand assessment; as well as monitoring and driving the customers' real-time behavior, thereby reaching a real just-in-time pull replenishment (Ranjan *et al.*, 2017). Even though the demand information willing is real, the developed machine-learning technology in CC could forecast new customers' needs, attitudes, purchase conducts, and trends in order to move forward the entire chain to maximum flexibility and response capability.

On the other hand, the production, manufacturing and creation of tangible and virtual value has to be developed through manufacturing processes in conjunction with the administration of the flow in the logistics operations (inbound/outbound); all this development is fully integrated in the now-named "smart factory," "digital factory," "smart manufacturing," "smart firm," "industrial internet" or "integrated industry." The way in which this digital factory is connected, is through a dynamic and integrated cyber-physical-human manufacturing system, in which the physical resources are implemented as smart things that communicate with each other and with human resources via the Industrial IoT, the internet of People and the Web of Things infrastructure, as enabled by CC and CR (Ghobakhloo, 2018; Hofmann and Rüsch, 2017; Kazancoglu and Ozkan-Ozen, 2018; Liboni *et al.*, 2019; Mourtzis and Vlachou, 2018; Whysall *et al.*, 2019).

It is relevant to highlight that the CR target in smart firms along their DSC dimensions, is to provide a technology that seeks to build on the cloud concept by exploiting this computing power and the massive data storage capacity of CC systems, combined with the ubiquitous available net connectivity, currently centered on the benefits of a converged infrastructure and shared services for robotics (Bogue, 2017).

In addition, smart factories incorporate a variety of strategies and technologies that optimize any type of DSC management operation tasks. Such is the case for new concepts and applications currently being developed and with a large field of research such as: digital manufacturing; digital lean (Lu, 2017; Sanders *et al.*, 2016; Jayaram, 2016); additive manufacturing; *in situ* nano-3D printing (Büyüközkan and Göçer, 2018; Rogers *et al.*, 2016;

Ryan *et al.*, 2017; Sasson and Johnson, 2016; Oettmeier and Hofmann, 2016); automation manufacturing: with drones and intelligent robots for quality control systems (Albers *et al.*, 2016; Alcácer and Cruz-Machado, 2019); digital transportation management systems and warehouse management systems (Baruffaldi *et al.*, 2019; Vanderroost *et al.*, 2017); quality controlled logistics; autonomous control systems; smart logistics and distribution; autonomous and self-driven vehicles; distribution robots; automation of warehousing (Ben-Daya *et al.*, 2017); radio-frequency identification and signaling and sensor technology (Attaran, 2007; Ngai *et al.*, 2008; White *et al.*, 2008; Thiesse *et al.*, 2009; Sarac *et al.*, 2010); simulation tools and models; augmented reality simulation; mixed reality robotics; human–computer interaction and human–machine interfaces as virtual reality; augmented reality simulation; and artificial intelligence vision (Atzori *et al.*, 2010; Fleisch, 2010; Liao *et al.*, 2017; Lu, 2017), among other incipient research applications.

The Industry 4.0 enablers and features are party to the latest outbound logistics processes in order to deliver goods and services to wholesalers, retailers and the final customers, but which mainly have a presence in the DSC flows, and are described in the next fourth dimension.

4.4 Dimension 4

The four significant flows that are presented and described in the DSC model (see Dimension 4 in Figure 6) are: material flow (inbound), finished products/goods flow (outbound), services flow, information flow, knowledge flow, financial resources flow (money/profit), risk and return flows of goods/services.

To create proximity and a long-lasting flows connection within the network structure, primarily with suppliers and customers, it requires providing new digital products and services that offer a virtual value creation. It is here the union with the fifth dimension within the proposal framework, named the virtual value chain, is shaped according to three benefits: the value of availability, the value of digital servitization, and the value of digital integration (Hofmann and Rüsch, 2017).

The value of availability is the capacity to make materials, finished products and services available to the customer via autonomous delivery, an example of which is the flow of goods and services by means of emerging techniques such as smart logistics and distribution, including distribution robots such as drones or autonomous vehicles, as well as the value of digital servitization when several IT-based service options go beyond the simple distribution of products or physical services, e.g., new home services including home delivery, in-fridge delivery, or in-car delivery, and pick-up points and click and collect.

Third, the value of digital integration allowing transparency and traceability of the information and communication along the DSC, through human–computer interaction with customers, as with human–machine interfaces such as augmented reality or machine learning via stationary devices, continuous tracing and tracking GPS systems in conjunction with customers' apps and wearables (Atzori *et al.*, 2010; Fleisch, 2010; Hübner *et al.*, 2016; Li *et al.*, 2017; Liao *et al.*, 2017; Lim *et al.*, 2018; Lu, 2017; Sharma *et al.*, 2016; Zhang *et al.*, 2018).

Furthermore, the information, knowledge, financial resources and risk flows are cooperative, coordinated and communicated. These conditions give to the network structure transparency, responsiveness and collaboration among the participants, thanks to the Industry 4.0 enablers. The integration of the flows in the DSC is through the assimilation of powerful information and communication technology: CC (Bruque Cámara *et al.*, 2015; Haddud *et al.*, 2017; Lu, 2017).

The last flow in the network structure, the return flows of goods/services, has been an urgent and relevant issue in the practice of sustainable development (Bag *et al.*, 2018; de Sousa Jabbour *et al.*, 2018). Indeed, it impacts directly on a key implication of the nascent DSCs, as the capacity of any SC to create and maintain the conditions in which humans and nature can exist in productive harmony to support present and future generations (EPA/US Environmental Protection Agency, 2017).

Even so, the research processes have standardized and real awareness of the return flows' implementation has been scarce. An increase in the development of these issues through a circular economy and Inverse Logistics Sustainability via Industry 4.0 enablers as closed-loop reuse or open-loop reuse, and reverse logistics management systems are needed (Farooque *et al.*, 2019; Lopes de Sousa Jabbour, 2018; Rizzi *et al.*, 2017; Sarc *et al.*, 2019).

4.5 Dimension 5

The digital age has seen information functioning as a unique source of competitive advantage. Now, virtual supply-chain activities in the marketspace can operate completely independently of the physical value chain, leading to a blurring of the boundaries between virtual and physical markets (Graham and Hardaker, 2000).

As mentioned in the previous section, information flows affect a firm's ability to integrate value-adding operations and improve innovation, considering the new and changing role of information. Consequently, the virtual value chain is a key integration mechanism via dynamic information.

The virtual value chain offers a view that encompasses the entire chain, along with its usage of the Industry 4.0 technology facilitators. The virtual value chain dimension has a correlated and close relationship with each component in the DSC; the goal of this relationship is to maintain the transparency, communication, collaboration, flexibility, responsiveness and accuracy throughout the entire structure.

The optimal development of each component and actor in the DSC physical and virtual network structure, as shown in the framework in Figure 6, will create a union of different companies clustering and working together based on shared values and the common goal of doing business; this is the approach used to reach a complete virtual and physical value chain.

4.6 Dimension 6

Nowadays, the digital age is causing rapid changes in every area, giving us a new digital living society and economy. With regard to science and technology, continuous research and innovations in every construct presented previously about Industry 4.0 are being merged together, to bring about a new system where the real and digital worlds meet and are abiding in symbiotic interaction.

In order to describe the sixth dimension presented in the proposed model, the main characteristics detected in the physical and digital contemporary world are: an agile and collaborative approach which is globally connected 24/7; interactive with virtual collaboration via diverse communication channels; simultaneously messaging and exchanging ideas and experiences, but with a decline in face-to-face interactions; rapidly and constantly evolving; with a direct approach, eliminating any unnecessary intermediaries or channels, thus creating immediate relationships; open to sharing; signaling, tracing, tracking and recording identity theft and cyber hacking (Calatayud *et al.*, 2019); developing digital and cross-cultural emotionality; robust, eager to share and gather data and to obtain statistical analysis; changing job markets; designing and producing in separated locations; highly expectant of customization; creating a disparity between opportunity and wealth; digitally accessing increased success; removing any superficial, frivolous and consumer pressure in order to be improved and updated constantly.

In the next section, there will be a discussion of the implications of the DSC model and its components.

5. Discussion and practical implications for the digital supply chain model

From this research study analysis, it will be important to recognize that the evolution of the SCs is not only due to the implementation of physical and virtual digitalization in network structures or in the information and communication technology systems of traditional SCs (e.g. having invested and installed a brand-new 3D printer, or implemented IoT in a work area); instead, the transformation requires special attention in the embodiment of new forms of administration to generate a culture of change with a focus on digitalization, creating a proper environment for the evolution of each one of the components already studied in traditional SCs.

The DSC model proposal provides a framework for the adoption and incorporation of the current and nascent Industry 4.0 technology enablers and features within the current SCM in order to evolve in a digitalized SCM. This approach is shown within a multi-dimensional and interconnected framework with the following technological and managerial implications.

Historical SCM studies have defined the base line of the main elements and constructs to operate the entire chain structure and activities. However, problems have been observed in the literature regarding SC integration, flexibility, communication and customer satisfaction. Therefore, it is significant to recognize that ancient studies and SCM models laid the foundations for those SCs that lived and operated in a different world, and to realize how innovation research, inventive transformation and the rapidity of the emerging Industry 4.0 technologies will lead to an imminent revolution and evolution toward the digitalization of SCMs. Failure to accept this change could put business models at risk, and they could become stuck in the adoption and implementation of technology enablers, thus leading to their decline (Castelo-Branco *et al.*, 2019).

To achieve a superior SC performance (cost, quality, flexibility and time performance) requires multi-lateral integration: internal/external integration; functional integration; geographical integration; integration in chains and networks; and integration through IT (Oh and Jeong, 2019). This integration goes even further to include the supplier's supplier and the customer's customer to leverage the power of the "network" beyond their own part.

Five essential elements are crucial for successful Industry 4.0 technology implementation into DSCs, which are: project management to digitalize and manage the culture's organizational behavior in the SCMCs; human and technology relationships in digital SCMPs; the formation of a technology infrastructure or a digital and physical SCNS; Industry 4.0 technology enablers and features deployment, all without losing sight of the ever wider-ranging digital and physical SCFs in order to provide the right digitalization.

On the other hand, interconnectivity and mass customization efforts improve the customer experience. When drawing up a near-term strategical objective for digital improvements, clients' preferences should never be far from the leaders' minds. Consumers want "convenience, choice and control," and when SCs become more digital and data-driven, they can create services that provide these benefits.

Each player involved into the value chain delivery are ready to stop thinking about the connectivity between each actor and the structure of the SC in a linear way, and start betting on development as a multi-dimensional organizational strategy for the following characteristics of the DSC: transparency, communication, collaboration, real-time responsiveness, accuracy and flexibility.

To create a real organizational vision, the digital strategic enterprise needs to recognize and bear in mind the main characteristics of the global world (Dimension 6), from which arise changes in customer behavior and a shift in the market's overall demands, challenges and risks (Birkel and Hartmann, 2019; Colicchia *et al.*, 2019; Friday *et al.*, 2018).

A reasonable number of processes will have to take on new virtual and intelligent-automated characteristics to give companies the full DSC experience. As more businesses take the plunge into this new style of operations, companies that retain too many outdated manual processes may fall behind.

The whole SC structure is changing because of digitalization. Triggered by the proposal framework, it is possible to arrive at a formulation of a new visual manifestation of the current functioning of directed networked SCs in globally integrated clusters. DSCs, enabled by the CC, have clear challenges which together drive unprecedented visibility, insights, and flexibility while operating rapidly and on a large scale. Due to losing control over data that were previously housed on internal servers and/or computer hard drives, the safety of these data on the web and service outage situations also present some challenges.

Technology development systems processed within multiple DSCs and their clusters will be the developers of the actual integration of diverse smart factories and even more of the global integration, knowledge and information in real time. The virtual world will emerge from the physical one, but beyond that will have the capacity for prediction, multiple intelligences and interconnectedness directed toward a digital world.

Each of the components of the DSC model, both in Industry 4.0 and in a digital and smart world, is already boosting a revolution of integration, interconnectivity and great added value for final consumers, as well as internal customers and suppliers.

Consequently, a pertinent stage of this historical visualization and of the present status of the state-of-the-art DSCs is realizing the developmental stages which are moving from internal integration and growth in the direction of external integration – headed toward a goal-directed network SC and DSC management to achieve evolution for collaborative DSC clusters. However, the above concept may only be achieved by changing the construct of a single, linear SC by moving to integrated DSC networks interconnected with life cycles (MacCarthy *et al.*, 2016), constantly changing through multiple smart factories in a smart world. Therefore, three steps for the adoption of the Industry 4.0 digitalization enablers are suggested below:

(1) First, perform the first digital adoption with a focus on the digital experience with the client. Offer products, services and rapid responses focused on digitalization and real time (Dalenogare *et al.*, 2018). As much as possible, be in direct contact and create virtual value (develop those Industry 4.0 enablers, as shown in the quadrants in Figure 6, of wholesaler, retailer, customer and final customer). A long-term result of success in this first strategy may be the disappearance of intermediaries such as wholesalers and retailers. Another natural result will be the evolution of digital knowledge, technologies and competitiveness, which will naturally develop 2PL, 3PL and 4PL which can be used in favor of the organization.

(2) Second, make a considerable investment in the virtual value chain, particularly in the distribution channels with the support of 5th party logistics, to make the customers aware of the new delivery services (see Section 4).

(3) Third, execute the transformation to a smart factory or, if this is the case, the development of smart services and processes. In addition, support the incorporation of this initial approach to DSC by suppliers. This can develop interesting success stories with a more effective and efficient vertical integration.

Finally, a relevant implication of this study and its contribution to scholars in the field means that new SCMCs are now evolving, both in the traditional SC, as well as in the nascent and digitalized ones. It will have a great impact to be able to carry out field research on the new constructs while referring to the reconfiguration of logistical processes and SCM, the form of administration, the flows and even new physical and digital actors who can take on relevant management roles and even implement new technological and digital structures.

6. Conclusions, limitations, and future research directions

In conclusion, this paper presents a DSC Model, which includes the traditional SC actors and constructs, as well as the new and emergent elements inherent to the Industry 4.0 era.

The model is based on and supported by the results of a two-part literature review. The first part of this review identified the most significant conceptual models in the area of SCM, published from 1989 to 2019, and revealed the lack of a comprehensive DSC model. The second part of this review systematically examined the Industry 4.0 state of the art to identify a summary of the emergent elements and technology constructs used in the nascent digitalized SC.

An extended formalization of the final dimension of the construct DSC model is presented in Figure 6, where the inter-cooperation between the components are shown in Figures 4 and 5, with the information and communication technology trends of Industry 4.0, as well as the digital and physical worlds, are disclosed. All this has been made possible thanks to real-time decision making, given the information gathered in the CC and CR analyzed by the monitor and drives customers' behavior (data trends) for an optimal intelligent demand assessment, as well as effective and efficient input/output processes in logistics.

The DSC model proposal provides a state of art guidance for the Industry 4.0 enablers and features to be adopted in a digital SC context and seeks to reduce some of the barriers against the implementation of all the elements surrounding this fourth transformation within the SCM, from both a technological and a managerial perspective. For example, Figure 6 and Table I provide guidance with respect to pointing out the essential components of Industry 4.0 interacting in real-time with all the SCMCs, SCMPs, SCFs and structure, providing an integrated structure to facilitate the understanding in the transition for the traditional linear chains to digitalized SCs. Special considerations for some of the main barriers are the difficulty of visualizing the digital and physical flows and the determination of the appropriate level of interconnectivity between the physical and digital world. Therefore, another example of the impact of this proposed model is the reduction of gaps in the actual context-relevant situation, for how software and technology are digitalizing the service and manufacturing value chains. Figure 6 enables the visualization of the SCM dimensions and physical and digital flows and Table I provides the required level of interconnectivity between the SCMCs.

The DSC model in Industry 4.0 proposes as a focal point and in an innovative way, CC and CR as core elements to achieve virtual value creation, because they enable interconnection in real time with regard to the physical and the virtual: SCMCs and SCMPs along with everyone interested in the SCNS via the SCFs. Similarly, the CPS is presented as the principal elements of the link between the physical SC (physical world/physical things) and the virtual SC (a digital data global value chain) and Industry 4.0 (Strange and Zucchella, 2017). From this analysis, it is possible to arrive at a formulation of a new and visual manifestation of the current functioning of digital globally integrated SCs, SC clusters and goal-directed networked SCs (Götz and Jankowska, 2018).

The integration and inter-cooperation of different DSC clusters will have to be based on strategies to help industry and governments create sustainable economic growth, thus creating a transition toward a sustainable digital world, the basis of which must be the three pillars of sustainable development: environmental, social and economic. This can only take place by working hard on the application of tactics such as green and reverse logistics, an access economy, a circular economy, a collaborative consumption/economy and a sharing economy, among others (Hasan *et al.*, 2019; Kim and Chai, 2017; Rosa *et al.*, 2019; Sharma and Foropon, 2019). It is expected that green behavior will become the standard for doing business and that no external pressure will be necessary to further promote this conduct (Müller *et al.*, 2019; Schoenherr, 2009).

The presented research study has taken place in the context of a literature review of existing studies and empirical evidence with regard to SCM and the elements of Industry 4.0. However, this allows for future work to be focused on the validation of the preliminary DSC model by experts and by considering real case studies from contemporary manufacturers or service providers. This could provide the validation of its components and even make headway toward new and emerging constructs.

In this way, new findings could be incorporated regarding key elements for the development and current operation of DSCs, as well as the incipient activities directed toward the construction and implementation of collaborative SC clusters. For example, future research could evolve theme answers to some questions as follows: do companies identify and validate the components presented? Are there different components for different business models or could they be universal? what kind of indicators should be used to evaluate each link and stage of the DSCs? On what level should processes and management components be integrated between firms and throughout the DSCs and clusters? Are the different DSCs that have been evolving? How do they interact? What are their best practices? These are just a few of the many questions.

This work also allows increasing interest among academics with regard to the development of more and better roadmaps for DSC models for diverse manufacturing and specialized service industries, as well as for multiple contexts such as for small and micro-enterprises (Agostini and Filippini, 2019; Bär *et al.*, 2018; Mittal *et al.*, 2018; Müller *et al.*, 2018, 2019; Scuotto *et al.*, 2017). Hence, maturity models for each of the DSC scenarios, as named by Srai *et al.* (2017) for the Srai (2018) may be created for each of the DSC contexts in order to help companies think about what areas they want to focus on, assess their levels of achievement to date and prioritize their efforts.

These future studies could focus on the integration of these emerging components and stages in the on-going implementation of Industry 4.0 in diverse DSCs. More research could be undertaken regarding the digital evolution of each basic construct (digital SCMPs, SCMCs, SCNS and SCFs) in order to discover processes, methods, structures and new management flows that are emerging due to digitalization and progress in key technologies. Some examples are: the development of new organizational cultures, norms, policies and techniques to more effectively manage challenges in regulations, intercommunication, interoperability and transparency, among others.

The limitations of this study refer to the exclusion criteria that were used to perform the literature review, which eliminated papers not written in English and which may also have ignored research in other languages, as well as terms other than those defined in the search protocol.

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Appendix. Tables AI through AIV summarize the analysis, findings, features and components of the four Supply Chain Management constructs: Supply Chain Management Components (SCMC), Supply Chain Management Processes (SCMP), Supply Chain Network Structures (SCNS), Supply Chain Flows (SCF), and shows the concordance of the works and models studied in the literature review presented in Section 3.1.

Table AI. Coverage of supply chain management processes in the literature

Author	Customer relationship management	Supplier relationship management	Customer service management	Demand management	Order fulfilment	Manufacturing flow management	Product development and commercialization	Returns management
Stevens (1989)	X	X	X		X	X	X	X
Cooper *et al.* (1997)	X		X	X	X	X	X	
Lambert *et al.* (1998)	X	X	X	X	X	X	X	X
Graham and Hardaker (2000)	X	X	X	X	X	X	X	
Croxton *et al.* (2001)	X	X	X	X	X	X	X	X
Mentzer *et al.* (2001)	X		X	X	X	X	X	
Duclos *et al.* (2003)	X	X	X	X	X	X	X	
Chen and Paulraj (2004)	X	X	X	X	X	X	X	
Martínez Sánchez and Pérez Pérez (2005)	X	X	X	X	X	X	X	
Lambert and Schwieterman (2012)	X	X	X	X	X	X	X	X
Lambert (2014)	X	X	X	X	X	X	X	X
Zhang *et al.* (2015)	X	X	X	X	X	X	X	X
MacCarthy *et al.* (2016)	X	X	X		X	X	X	X
Stevens and Johnson (2016)	X	X	X	X	X	X	X	
Oettmeier and Hofmann (2016)	X	X	X		X	X	X	X
Hofmann and Rüsch (2017)	X	X	X	X	X	X		
Ardito, Petruzzelli, Panniello and Garavelli (2018) and Ardito, Scuotto, Del Giudice and Messeni (2018)	X	X	X	X			X	
Büyüközkan and Göçer (2018)	X		X			X	X	

Table AII. Analysis of supply chain network structures, based on the literature review

Author	Upstream suppliers (Tier 0.5, 1, 2, 3 supplier)	Second and third part logistics	Company/focal firm/smart firm (departments and infrastructure facilities)	Fourth and fifth part logistics	Customer/wholesaler or distributor	Retailer	Final consumer/end-consumer/end-user	Others supply chain network structure constructs
Stevens (1989)	X		X		X		X	Producer factory, internal supply chain
Cooper *et al.* (1997)	X	X	X		X		X	
Lambert *et al.* (1998)	X	X	X		X	X	X	
Graham and Hardaker (2000)	X		X		X	X	X	Marketplace/marketspace, physical supply chain, virtual–actual supply chain, value matrix, new and existing markets
Mentzer *et al.* (2001)	X	X	X		X	X	X	The global environment, market research firm, financial provider
Croxton *et al.* (2001)	X	X	X		X	X	X	
Duclos *et al.* (2003)	X	X	X	X	X		X	Node/unit flexibility
Chen and Paulraj (2004)	X		X		X		X	Internal supply chain, environmental uncertainty
Martínez Sánchez and Pérez Pérez (2005)	X		X				X	Environmental uncertainty, technological complexity
Lambert and Schwieterman (2012)	X	X	X		X	X	X	
Lambert (2014)	X	X	X		X	X	X	Market, environmental uncertainty, technological complexity
Zhang *et al.* (2015)	X	X	X		X	X	X	
MacCarthy *et al.* (2016)	X		X		X	X	X	Technology and innovation, economics, markets and competition, policy and regulation

(*continued*)

Author	Upstream suppliers (Tier 0.5, 1, 2, 3 supplier)	Second and third part logistics	Company/focal firm/smart firm (departments and infrastructure facilities)	Fourth and fifth part logistics	Customer/wholesaler or distributor	Retailer	Final consumer/end-consumer/end-user	Others supply chain network structure constructs
Stevens and Johnson (2016)	X	X	X	X			X	Technology and systems infrastructure, internal supply chain, external supply chain integration, goal-directed network SC, devolved, collaborative supply chain clusters
Oettmeier and Hofmann (2016)	X		X			X	X	
Hofmann and Rüsch (2017)	X		X				X	Physical supply chain dimensions: physical world, physical thing; and digital data value chain dimensions: machine and sensor data (cyber-physical systems), digital world, cloud. Internet of Things, Internet of services, smart things, smart factory, smart shop floor, smart warehouse, wearables, block chain
Ardito, Petruzzelli, Panniello and Garavelli (2018) and Ardito, Scuotto, Del Giudice and Messeni (2018)	X		X		X	X	X	Information and knowledge structure form the cloud and data analytics solutions, cybersecurity protection actors
Büyüközkan and Göçer (2018)	X		X			X	X	Global and digital retailers

Table AII.

Author	Material flow (inbound)	Finished products/goods flow (outbound)	Services flow	Information flow	Knowledge flow	Financial resources flow (money/profit)	Return flows of goods/services	Outputs defined in the different supply chain management models
Stevens (1989)	X	X	X	X				Products, customer service
Cooper *et al.* (1997)	X	X		X				Products, services and information that add value for customers
Lambert *et al.* (1998)	X	X		X				
Graham and Hardaker (2000)	X	X	X	X		X	X	Virtual value creation, profit margin
Mentzer *et al.* (2001)	X	X	X	X		X		Customer satisfaction, value, profitability, competitive advantage
Croxton *et al.* (2001)	X	X		X				
Duclos *et al.* (2003)	X	X	X	X		X		Customized products, services, flexibility
Chen and Paulraj (2004)		X	X	X		X		Supplier performance, buyer performance, products that satisfy and/or exceed customer expectations
Martínez Sánchez and Pérez Pérez (2005)	X	X	X	X	X	X		Supply chain flexibility
Lambert and Schwieterman (2012)	X	X		X				
Lambert (2014)	X	X		X				Value chain
Zhang *et al.* (2015)		X		X				Customer satisfaction, value-added products, information feedback, knowledge accumulation, and financial revenues
MacCarthy *et al.* (2016)	X	X		X	X	X		High-value customized products combined with services

(*continued*)

Table AIII. Analysis of the supply chain flows, based on literature review

Table AIII.

Author	Material flow (inbound)	Finished products/goods flow (outbound)	Services flow	Information flow	Knowledge flow	Financial resources flow (money/profit)	Return flows of goods/services	Outputs defined in the different supply chain management models
Stevens and Johnson (2016)	X	X		X			X	Products and services, SC Configuration, SC Performance
Oettmeier and Hofmann (2016)	X	X		X	X	X	X	3D objects, customized parts/products
Hofmann and Rüsch (2017)	X	X		X				Physical SC with logistics activities. Value of digital integration, customer value: value of digital servitization, value of availability. Value-added business services, digital services, physical services, individualized products, smart contracts
Ardito, Petruzzelli, Panniello and Garavelli (2018) and Ardito, Scuotto, Del Giudice and Messeni (2018)	X	X	X	X	X			Raw data from industrial Internet of Things, cybersecurity protection, cloud services
Büyüközkan and Göçer (2018)	X		X	X			X	Digital products and services

Table AIV. Analyzing the supply chain management components, based on the literature review

Author	Structural management components: Planning and control methods	Workflow activity structure	Organizational structure	Information and communication flow facility structure (ICT)	Behavioral management components: Knowledge management	Management methods	Power and leadership	Risk and reward	Culture and attitude	Trust and commitment	Others supply chain management components
Stevens (1989)	X	X	X	X		X					
Cooper *et al.* (1997)	X	X	X	X		X	X	X	X		
Lambert *et al.* (1998)	X	X	X	X	X	X	X	X	X	X	
Graham and Hardaker (2000)	X	X	X	X	X		X		X		Multiple interactions: business to business, business-to-customer, marketspace. Knowledge management through information: collection, systemization, selection, processing, distribution, exchange, analysis, offering
Croxton *et al.* (2001)	X	X	X	X	X	X	X	X	X	X	
Mentzer *et al.* (2001)	X	X	X	X	X	X	X	X	X	X	
Duclos *et al.* (2003)	X	X	X	X	X	X			X		SC flexibility components (6): operations systems flexibility, market flexibility, logistics flexibility, supply flexibility, organizational

(*continued*)

Table AIV.

Author	Structural management components				Behavioral management components						Others supply chain management components
	Planning and control methods	Workflow activity structure	Organizational structure	Information and communication flow facility structure (ICT)	Knowledge management	Management methods	Power and leadership	Risk and reward	Culture and attitude	Trust and commitment	
											flexibility, information systems flexibility
Chen and Paulraj (2004)	X	X	X	X	X	X	X	X			Customer focus, top management support, competitive priorities, strategic purchasing, information technology
Martínez Sánchez and Pérez Pérez (2005)	X		X	X	X	X		X		X	Flexibility dimensions (10): product, volume, routing, delivery, trans-shipment, postponement, sourcing, launch, access
Lambert and Schwieterman (2012)	X	X	X	X	X	X	X	X	X	X	
Lambert (2014)	X	X	X	X	X	X	X	X	X	X	Information technology, technological complexity
Zhang *et al.* (2015)	X	X	X	X	X	X		X	X	X	Elements of integration: benefit alignment, material, information, knowledge, finance, process, organization, planning and control, and strategic integration

(*continued*)

Table AIV.

Author	Structural management components				Behavioral management components						Others supply chain management components
	Planning and control methods	Workflow activity structure	Organizational structure	Information and communication flow facility structure (ICT)	Knowledge management	Management methods	Power and leadership	Risk and reward	Culture and attitude	Trust and commitment	
MacCarthy *et al.* (2016)	X	X	X	X				X			Dimensions to differentiate SC: supply network configuration, product delivery strategy, customer-order decoupling point positioning, strategic inventory positioning, strategic capacity positioning, transportation mode, process choice, SC relationships. influencing the evolution: SC strategy and re-engineering
Stevens and Johnson (2016)	X	X	X	X	X	X	X	X	X	X	Technology and systems infrastructure
Oettmeier and Hofmann (2016)	X	X	X	X	X	X	X	X	X	X	Additive manufacturing technology
Hofmann and Rüsch (2017)	X	X	X	X	X			X		X	Digital connectivity, Internet of Things, Internet of Services, real-time consumption data and demand patterns. End-to-end route optimization,

(*continued*)

Author	Structural management components: Planning and control methods	Workflow activity structure	Organizational structure	Information and communication flow facility structure (ICT)	Behavioral management components: Knowledge management	Management methods	Power and leadership	Risk and reward	Culture and attitude	Trust and commitment	Others supply chain management components
											integrated ERP systems for the whole supply chain (cloud). Decentralized value networks. Smart planning, smart technology, smart sales, smart distribution
Ardito, Petruzzelli, Panniello and Garavelli (2018) and Ardito, Scuotto, Del Giudice and Messeni (2018)	X	X	X	X	X	X					Management methods with a systematic view, using digital technologies. marketing and supply chain management customer relationship
Büyüközkan and Göçer (2018)	X		X	X				X	X		Management process, human and technology relationship, the formation of technology infrastructure, and technology enablers. Digital operations. Digital organization structure

Table AIV.

Industry 4.0	A fourth industrial revolution which is the computerization of manufacturing systems. It has cyber-physical systems which are the combination of software and production assets. It includes automation, the industrial Internet of Things, data sharing and cloud computing. It has mainly the following characteristics: interoperability, transparency, technical guidance and independent choices (Jayaram, 2016)
Internet of Things (IoT)	A system (objects, processes, data, people, animals or atmospheric phenomena – everything that can be treated as a variable) in which the material world communicates with computers (exchanges data) with ubiquitous sensors (Witkowski, 2017)
Big Data	The information asset characterized by such a high volume, velocity and variety to require specific technology and analytical methods for its transformation into value (De Mauro *et al.*, 2016)
Internet of Services (IoS)	Service vendors to offer their services via the internet. [. . .] consists of participants, an infrastructure for services, business models, and the services themselves. Services are offered and combined into value-added services by various suppliers; they are communicated to users as well as consumers and are accessed by them via various channels (Hermann *et al.*, 2015)
Additive manufacturing /digital manufacturing	When products are built layer-by-layer based on a digital representation of the object, stemming, e.g., from CAD-files or three-dimensional scans (Oettmeier and Hofmann, 2016). In such circumstances, additive manufacturing can support the "smart factory" idea through improved speed to production, manufacturing design freedom, SC reductions, rapid prototyping, and small-scale production experiments (Ghobakhloo, 2018)
Digital factory/smart factory/smart firm	A dynamic integrated cyber-physical-human manufacturing system in which the physical resources are implemented as smart things that communicate with each other and with human resources via the Industrial IoT, the Internet of People, and the Web of Things infrastructure (Ghobakhloo, 2018)
Cyber-physical systems (CPS)	Integrations of computation and physical processes. Embedded computers and networks monitor and control the physical processes, usually with feedback loops where physical processes affect computations and vice versa (Hermann *et al.*, 2015). CPS are introduced to bridge the gap between the physical and digital divide in IoT systems (Tu *et al.*, 2018a, b)
Cloud computing (CC)	A model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources that can be rapidly provisioned and released with minimal management effort or service provider interaction (Mourtzis and Vlachou, 2016)
Cloud manufacturing (CM)	A smart networked manufacturing model that embraces cloud computing, aiming at meeting growing demands for higher product individualization, broader global cooperation, knowledge-intensive innovation, and increased market- response agility (Mourtzis and Vlachou, 2016). CC has brought virtualized technologies into large-scale use, it is not only a technical process, as it has made possible to also virtualize and, therefore, internationalize business applications, processes, locations and services (Bruque Cámara *et al.*, 2015)
Cloud robotics (CR)	A technology that seeks to build on the cloud concept by exploiting the inexpensive computing power and massive data storage capacity of cloud computing systems, combined with the ubiquitous net connectivity available, currently centered on the benefits of converged infrastructure and shared services for robotics (Bogue, 2017)
Virtual value chain (VVC)	A key integration mechanism via dynamic information. Information flows affect a firm's ability to integrate value-adding operations and improve innovativeness, considering the new and changing role of information. The digital age has seen information functioning as a unique source of competitive advantage. Now virtual supply-chain activities in marketspace can operate completely independent of the physical value chain, emerging blurring of boundaries between virtual and physical markets (Graham and Hardaker, 2000)

Note: It shows the main definitions of the theoretical concepts developed by scholars in the field of study in Industry 4.0, all of these are used to describe the Digital Supply Chain Model in Section 4

Table AV. Essential theoretical concepts in Industry 4.0 research

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