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A review of Industry 4.0 in supply chain management studies

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Abstract

Purpose – The purpose of this paper is to assess how the emergent theme of Industry 4.0 is considered in the context of supply chain management (SCM) and to identify important areas for future research.
Design/methodology/approach – A systematic literature review of 334 studies is carried out. The papers have been analyzed by having a focus on the unit of analysis, research methods used, the key themes covered and how the debate has evolved over a period of time.
Findings – Findings of the study reveal that scholars have so far focused on principles and practices for digitized SCM, identified enablers and barriers, and considered the Industry 4.0 at various levels, particularly at the firm level. Majority of studies focus on manufacturing from the perspective of the focal firm.
Research limitations/implications – Limitation of this study is its unit of analysis where only peer-reviewed journal and conference articles published in the English language have been considered.
Practical implications – This review identifies the important themes and areas for practitioners to consider *vis-à-vis* the implementation of Industry 4.0 standards in supply chains. The review provides insights into under-researched areas and highlights the need for future researchers to develop more practical models for guiding the implementation of Industry 4.0.
Originality/value – This paper is one among the few studies that assess the Industry 4.0 implementation in the context of SCM and provides insights and implications for further research.

Keywords Digitalization, Supply chain management, Industry 4.0

Paper type Literature review

1. Introduction

Industry 4.0 has recently become a prominent topic not only in the management domain but across the global community. In light of the changing business trends, organizations are required to embrace this upcoming change in their operations as well as in the wider supply chain networks (Geerts and O'Leary, 2014; Ivanov *et al.*, 2016; Lin *et al.*, 2017). Industry 4.0 involves a combination of smart manufacturing, smart products and the Internet of Things (IoT) and aims to provide real-time information on production, machines and flow of components. This information is integrated to assist managers in making decisions, monitoring performance and real-time tracking of materials (Lasi *et al.*, 2014; Stock and Seliger, 2016). Despite the advantages as outlined above, Industry 4.0 is in its nascent stage regarding application in SCM.

According to Rivera and van der Meulen (2014), a 30-fold increase in the number of smart devices by the year 2020 will drastically change the way supply chains operate. It is important for the businesses to have visibility of products in every stage of the supply chain, such as the identity, location and other tracking information (Ganesan *et al.*, 2016). As a result, Industry 4.0 implementation has emerged as an important potential lens to consider how SCM can be altered to achieve business goals. Although the topic of Industry 4.0 emerged in 2011 in Germany when the development of a new strategy for the German economic policy was proposed (Mosconi, 2015), SCM scholars have only recently started to show an interest in addressing Industry 4.0.

Literature reviews in the related field previously had a narrower scope. For example, Ben-Daya *et al.* (2019) examine the role of the IoT and its impact on supply chain management (SCM). These authors recognize the importance of Industry 4.0 in SCM but they focus mainly on the process-centric view of SCM that is being affected by IoT applications. Büyüközkan and Göçer (2018) present an overview of the digital supply chains

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along with definitions, features and challenges but they emphasize how different aspects of Industry 4.0 are evolving in SCM. Ghobakhloo (2018), in their review of literature, identify, cluster and describe design principles and technology trends associated with Industry 4.0. However, in the current study, we intend to take account of the interest of SCM researchers in Industry 4.0 to examine how the principles of Industry 4.0 have been considered in the study of SCM. We use the term "digitalization" in the context of Industry 4.0 implementation. This following research questions guide our literature review:

RQ1. How is the concept of Industry 4.0 defined and operationalized in the literature?

RQ2. What are the main topics, trends and theories in the debate on Industry 4.0 in SCM?

RQ3. What are the potential avenues for future research and practice in this area?

The paper is organized into six sections. Section 2 presents the methodology adopted for carrying out a systematic literature review. Analysis of the literature is presented in Section 3. Section 4 presents the discussion and avenues for future research. The academic and managerial implications are presented in Section 5. Finally, in Section 6 we discuss limitations and future research directions.

2. Methodology

We reviewed and synthesized the literature on Industry 4.0 in SCM to answer our research questions using a systematic literature review. Systematic reviews differ from narrative reviews as the process involved is replicable, scientific and transparent. Systematic reviews allow researchers to examine the strength of the published evidence while remaining as unbiased as possible (Tranfield *et al.*, 2003). This way, the systematic literature reviews contribute to the development of existing knowledge bases (Denyer and Tranfield, 2009; Tranfield *et al.*, 2003).

2.1 Systematic literature review approach

We followed the steps for the systematic literature review process, which are outlined as the following:

(1) identification of research;

(2) selection of studies;

(3) quality assessment of studies;

(4) data extraction and examining progress; and

(5) synthesis of data.

Figure 1 gives a summary of the steps of a systematic literature review.

The first step in the systematic literature review is the identification of the literature. To identify the literature, we limited our search to articles published in the English language across peer-reviewed journals and conferences. We searched the following combination of search string across the academic databases: "Industry 4.0" OR "Internet of things" Or "Smart Supply Chain" OR "manufacturing digitalization" OR "digital supply chains" OR "smart manufacturing" OR "Industry du Futur" OR "Smart Industry." We applied the search string to the titles, keywords and abstracts of publications in google scholar and

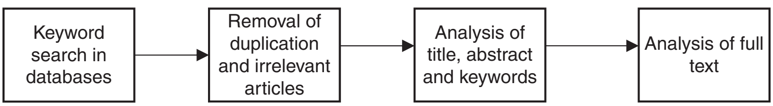

Figure 1.
Systematic literature review process

other academic databases that include Scopus, EBSCOhost, ProQuest and Emerald databases. These databases are widely used sources of literature for review studies.

Upon searching the databases, 3,890 results appeared from an initial search that contained at least one instance of our search strings. Results from the books, book chapters, surveys, working papers and reports were removed from the search results. We analyzed the search results and deleted the duplicate ones. The literature search was done in October 2018, and articles appeared in these databases along with google scholar till October 2018 were considered for the study. A total of 895 articles were gathered in the first step. The time duration for the studies was taken from all time to till date.

In the second step, articles were analyzed to decide whether the selected papers address the topic under study. We carefully scrutinized the titles, keywords and abstracts of the 895 articles. The entire text was analyzed if the title, keywords and abstract did not provide a clear focus of a study. The articles with a title and abstract that did not fit our inclusion criteria were removed, with 568 articles remaining. The inclusion criteria that guided for filtering the articles are as follows: articles published in peer-reviewed academic journals, conference articles and articles in press available up to and including October 2018 were considered for the review. The articles that have a clear focus on Industry 4.0 technologies and one or more aspects of SCM were selected for the review. After full texts were checked, finally 334 articles were selected for the systematic review. Papers were excluded if the focus was not on Industry 4.0 from an SCM standpoint. Specifically, articles focusing on the technical perspective of Industry 4.0 that include data mining, system architecture and related fields were considered outside the scope of this review. Recognizing the multidisciplinary nature of Industry 4.0 research, we included all journals and conferences that addressed the topic of Industry 4.0 within the context of the supply chain.

In the third stage of the systematic literature review, we assess the quality of the articles. Our review only included articles that underwent a peer-review. We included only the peer-reviewed journals and conference articles as the review process acts as quality control (McCartney *et al.*, 1986). In the fourth step, an analysis of the literature and in the fifth step emerging categories were identified from the literature during the synthesis. A full analysis of the paper was carried out in line with the recommendations of Denyer and Tranfield (2009). Figure 2 shows the criteria for analysis of papers. After that frequency analysis was carried out to analyze the allocation of papers across journals and conferences, year of publication and the research methods. In line with our research questions, a qualitative analysis of the papers was carried out while keeping a focus on the following areas:

- definitions of Industry 4.0;
- main topics/themes; and
- major findings.

By analyzing the topics and themes addressed in the papers, we created codes for the identification of key themes covered in the reviewed studies. The codes covered all the themes evident in the literature related to Industry 4.0 in SCM. After coding individually, the codes and categories were discussed and matched by the authors. The differences in coding were reconciled by re-reading and re-coding the papers. In case of overlap in the themes, the paper was reviewed under both the themes. The following categories and subcategories of themes emerged after coding the studies:

- conceptualization of Industry 4.0 in SCM;
- principles for implementing Industry 4.0;
- managing digitized supply chains;
- digitalization outcomes;

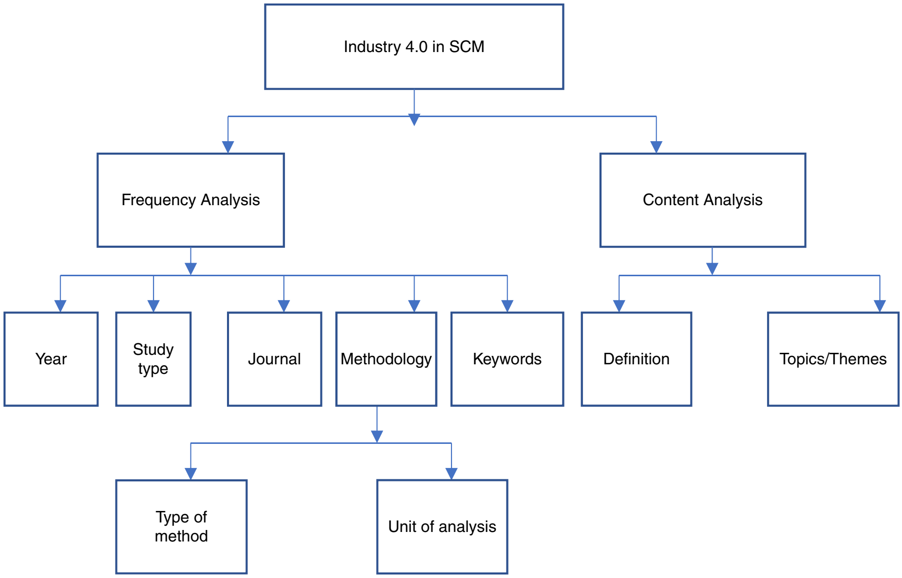

Figure 2.
Research methodology

- performance of digitized supply chains;
- drivers and barriers of Industry 4.0 in SCM;
- Industry 4.0 practices; and
- collaborative engineering and customization.

In Section 3 we present the results and findings of both the frequency and qualitative analyses.

3. Analysis of the literature

3.1 Frequency analysis

3.1.1 Type of article. The frequency analysis presents the descriptive results of our sample of 334 articles. We analyze the type of publication across sources. The overview of the findings is presented in Figure 3. Journals contribute 58 percent of the articles with 194 out

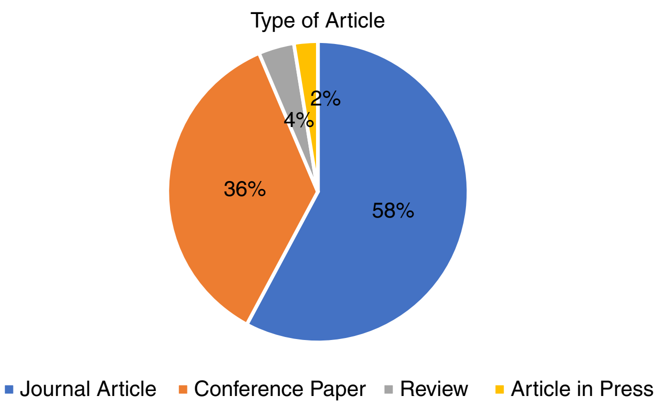

Figure 3.
Type of study

of 334 papers. In total, 36 percent of the publications are conference articles that account for 120 out of 334 papers. Out of 238 papers assessed in our study, 13 are review papers. Remaining seven studies that account for 2 percent articles are articles in the press.

3.1.2 Year wise Publications. In Figure 4, the allocation of the reviewed papers across the years is depicted. Figure 4 illustrates the presence of a growing trend in the number of articles since 2013, with a sudden steep increase in the number of articles from 2015 onwards. In the year 2013, there are seven articles that were published. This figure doubled in 2014 and increased by more than three times in 2015. In 2016, the number of articles showed a threefold surge and 71 articles were published; this number rose to 112 articles in 2017 and in the year 2018, till October, the number of articles published is 97. This distribution shows an immense surge in the literature across the years. An area of research receives acknowledgment in relation to the development of the number of publications if the number of publication in the scientific community doubles in 10–20 years (Beske-Janssen *et al.*, 2015). The literature in this area has already crossed this mark, and this stresses upon the emerging academic interest. This finding also confirms that the topic is widely acknowledged in the field of SCM.

3.1.3 Journal-wise publications. A large number of journals have published papers on Industry 4.0 and SCM. Figure 5 shows the distribution of articles across the top 10 journals.

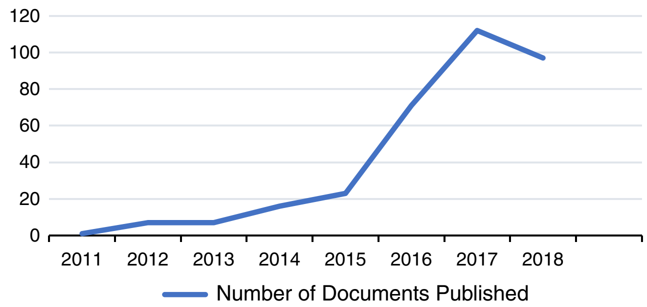

Figure 4. Number of documents published across years

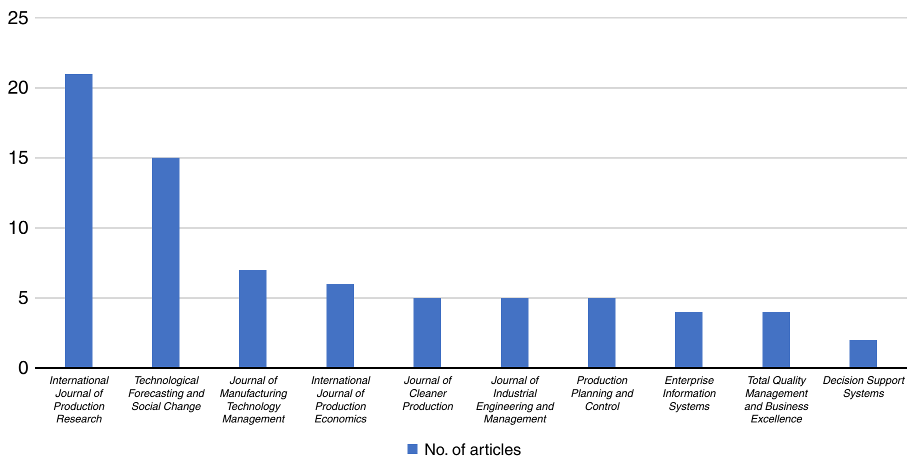

Figure 5. Number of articles published in top 10 journals

The top 6 journals contribute to about 18 percent of the publications with 59 of the 334 papers. The next 10 journals produced 35 out of 334 papers that contribute to 10.4 percent of the publications. The remaining journals with the least number of papers (less than three papers each) contribute to about 41 percent of the papers. The remaining articles are conference papers. Industry 4.0 has received extensive attention in the field of manufacturing and production, as evident from the list of journals shown in Figure 5. The topic is also widely covered under the journals which focus on sustainable operations management such as *Sustainability Switzerland* and *Journal of Cleaner Production*.

3.1.4 Country-wise analysis. The analysis by country gives a wide range of understandings. Figure 6 reports on the 12 most productive countries chosen by the selected articles for the Industry 4.0 and SCM research. The majority of publications concern Germany (54 articles) and the USA (50 articles), followed by Italy (33 articles), UK (26 articles) and China (25 articles). About 90 percent of the research comes from the 12 countries as shown in Figure 6. In the advent of the fourth industrial revolution, several European countries have announced their Industry 4.0 strategy in the past few years, leading to the development of technology roadmaps and research agendas (Santos, Mehrsai, Barros, Araújo and Ares, 2017). It is clear from Figure 6 that the majority of studies on Industry 4.0 in SCM come from the European countries.

3.1.5 Keyword analysis. Author consider keywords as a means to highlight the core content and theme of an article. Research trends can be revealed by keywords frequency analysis. Keywords frequency analysis can be used to uncover the research trends and transformations (Ji *et al.*, 2018). We built a co-occurrence network to analyze the authors' keywords (Strozzi *et al.*, 2017). In Figure 7 co-occurrence networks nodes are the authors' keywords taken from 334 papers. To perform the co-occurrence analysis, first, the authors' keywords of the 334 papers were selected. Keywords that appeared together for at least five times were considered for creating a co-word network. In this study, the co-occurrence keyword network is analyzed using VOSviewer software applying visualization of similarity clustering technique. VOSviewer determines the locations of items in a map by minimizing a function depending on a similarity measure (AS_{ij}) between items (van Eck and Waltman, 2011). AS_{ij} is defined as:

$$AS_{ij} = \frac{c_{ij}}{c_i c_j},$$

where c_{ij} is a measure of the co-occurrence of keywords i and j in the same document; c_i is the expected number of co-occurrences of i under the assumption that the co-occurrences of i and j are statistically independent; and c_j the expected number of co-occurrences of j under the assumption that the co-occurrences of i and j are statistically independent.

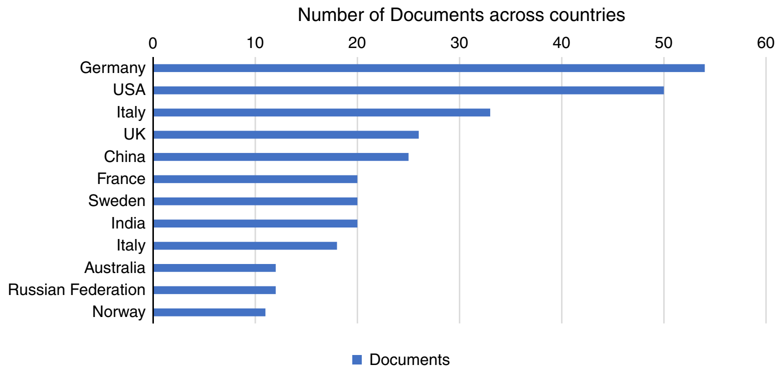

Figure 6.
Number of documents across 12 most productive countries

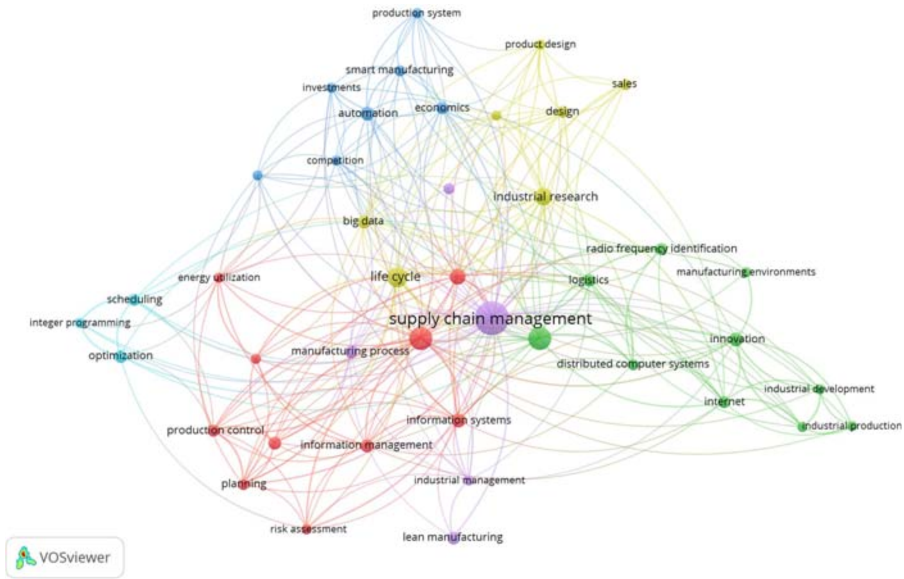

Figure 7. Keyword analysis

Figure 7 gives an analysis of the author's keywords from the 238 papers.

Co-occurrence analysis is based on the assumption that in a paper, authors' keywords reflect an adequate description of the content (Strozzi *et al.*, 2017). Research themes or patterns are revealed by co-occurrences around the same words. The data obtained by the analysis of keywords may be important to have an understanding regarding the themes related to the field for future works. For example, in Table I it can be seen that in the first cluster (Cluster 1) energy efficiency and energy utilization was a group of issues associated, among others, with the manufacturing companies. The most frequent and the most

Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6
Decision making	Distributed computer systems	Automation	Big Data	Industrial management	Integer programming
Energy efficiency	Industrial development	Competition	Design	Lean manufacturing	Optimization
Energy utilization	Industrial production	Economic and social effects	Industrial research	Manufacturing process	Scheduling
Information management	Innovation	Economics	Information and communication technology	Production process	
Information systems	Internet	Investments	Life cycle	SCM	
Manufacturing companies	Internet of Things	Production system	Product design		
Planning	Logistics	Smart manufacturing	Sales		
Production control	Manufacturing environment				
Risk assessment	Sustainability				
Sustainable development					

Table I. Clustering of keywords

interconnected component in the cluster was decision making. Here, this element exhibited a very strong relation with sustainable development. Areas of planning and production control are associated with information systems which form the core of Industry 4.0. In these areas, the authors also imposed the context of risk assessment on the debates presented in the publications. Here, information management lies in the center of the map and has numerous connections with a large number of other issues.

3.1.6 Nature of study. Table II presents an overview of the nature of the study. The research methods applied in relation to Industry 4.0 application in SCM literature employs different categories of research methods as described in Table II.

As evident from Table II, over 82 percent of the articles, in our review are conceptual papers. In line with the characteristics of a field that is emerging, the number of papers that seek to develop theory is also growing. In the stream of empirical studies, case study research, surveys and interviews contribute to just 8 percent of the reviewed papers. Literature reviews contribute to just around 5 percent of the literature. Mixed methods studies and experiments contribute to about 1 percent of the publications. Other mathematical models account for the remaining studies.

3.1.7 Unit of analysis. From the results of a unit of analysis, it is evident that about 40 percent of the papers (151 of 334) are focused on the plant/focal firm level. Fewer studies (25 of 334) emphasized on logistics in the era of Industry 4.0. About 30 studies indicated their study as industrywide. Just four studies focused on the supplier(s)' and the manufacturer(s)' perspective. Surprisingly, in a large number of studies (151 of 334), the unit of analysis is not specified. Most of these studies mention that their focus is on the supply chain. These studies neither focus on the supply chain actors nor the level of analysis. Multi-tier perspective is not explicitly dealt in the existing literature. Table III presents an overview of the literature based on a unit of analysis.

Nature of study	Sample articles	No. of studies
Theory/ Conceptual paper	Geerts and O'Leary (2014), Arnold (2018), Rauch *et al.* (2017), Trentesaux *et al.* (2016), Jensen and Remmen (2017), Barreto *et al.* (2017), Bechtsis *et al.* (2018), Strandhagen, Vallandingham, Fragapane, Strandhagen, Stangeland and Sharma (2017), Trstenjak and Cosic (2017), Tjahjono *et al.* (2017), Bogataj *et al.* (2017), Hwang *et al.* (2017), Zhong *et al.* (2017), Anderseck and Hille (2013), Dawid *et al.* (2017), Shamim *et al.* (2017)	277
Literature review	Costabile *et al.* (2017), Büyüközkan and Göçer (2018), Lu (2017), Xu *et al.* (2014), Thibaud *et al.* (2018), Ben-Daya *et al.* (2019), Filho *et al.* (2017), Oesterreich and Teuteberg (2016), Wu *et al.* (2016), Tachizawa *et al.* (2015), Bowles and Lu (2014), Randhawa and Ahuja (2017), Ghobakhloo (2018)	13
Empirical/case study	Rymaszewska *et al.* (2017), Zhang *et al.* (2013), Wakenshaw *et al.* (2017), Zaheer and Trkman (2017), Ooi *et al.* (2018), Lim *et al.* (2018), Rymaszewska *et al.* (2017), Strandhagen, Alfnes, Strandhagen and Vallandingham (2017), Qrunfleh and Tarafdar (2015), Yang *et al.* (2013), Schumacher *et al.* (2016), Martinez *et al.* (2010), Rachinger *et al.* (2019)	25
Delphi method	Tonelli *et al.* (2016), Kiel *et al.* (2017), Kiel *et al.* (2017)	3
Analytical modeling	Diedrichs *et al.* (2016), Dunke *et al.* (2018), Qi and Bi (2014)	3
Optimization	Lee (2017), Fiasche *et al.* (2016), Nagadi *et al.* (2018), Luthra *et al.* (2018), Veza *et al.* (2015), Hauder *et al.* (2017), Hsu and Yang (2017), Ivanov *et al.* (2016)	9
Mix method approach	Dossou and Nachidi (2017), Majeed and Rupasinghe (2017)	2
Experiment	Chan *et al.* (2017)	1

Table II.
Nature of study

Unit of analysis	Sample papers	No. of papers
Indicated as supply chain	Tonelli *et al.* (2016), Zhang *et al.* (2013), Lin *et al.* (2017), Geerts and O'Leary (2014), Bao *et al.* (2013), Grieco *et al.* (2017), Man and Strandhagen (2017), Büyüközkan and Göçer (2018), Qi and Bi (2014), Ben-Daya *et al.* (2019), Kumar *et al.* (2016), Majeed and Rupasinghe (2017), Strange and Zucchella (2017), Bogataj *et al.* (2017), Ganesan *et al.* (2016)	151
Focal firm/Plant level	Arnold (2018), Costabile *et al.* (2017), Dunke *et al.* (2018), Hwang *et al.* (2017), Longo *et al.* (2017), Rauch *et al.* (2017), Rymaszewska *et al.* (2017), Kiel *et al.* (2017)	124
Indicated as industry	Mrugalska and Wyrwicka (2017), Oesterreich and Teuteberg (2016), Štofová *et al.* (2017), Trentesaux *et al.* (2016)	30
Logistics	Barreto *et al.* (2017), Bechtsis *et al.* (2018), Diedrichs *et al.* (2016), Ivanov *et al.* (2016), Lu *et al.* (2017), Strandhagen, Alfnes, Strandhagen, and Vallandingham (2017), Strandhagen, Vallandingham, Fragapane, Strandhagen, Stangeland and Sharma (2017), Anderseck and Hille (2013), Hofmann and Rüsch (2017)	25
Multi-tier supply chain	None	0
Suppliers and/or manufacturers	Müller *et al.* (2018), Khemiri *et al.* (2017), Marques *et al.* (2017)	4

Table III.
Unit of analysis

3.2 Qualitative analysis

In this section, we address we present the findings from the qualitative analysis of the literature and address the three research questions.

3.2.1 Defining Industry 4.0 in the SCM literature. Although the term Industry 4.0 has received much attention recently, it still lacks a precise, generally accepted definition (Hofmann and Rüsch, 2017). An increasing interest in researching Industry 4.0 can be seen in the SCM literature. While the scholars in the field of SCM have indicated increasing interest in studying social issues, only a fraction of the studies consider this aspect while defining Industry 4.0. In Table IV we present the varying perspectives on the definition of Industry 4.0 in the SCM literature. For instance, Sanders *et al.* (2016) introduce the concept of future-oriented technologies, addressing the human-machine interaction paradigm related to Industry 4.0. In addition, Pereira and Romero (2017) focus on enumerating the "technologies of the future" in their definition, which involves Cyber-Physical Systems (CPS), IoT, Internet of Services (IoS), Robotics, Big Data, Cloud Manufacturing and Augmented Reality. The other aspects in the definition of Industry 4.0 further focus the concept of real-time improvements in process performances, in terms of productivity, security, energy efficiency and cost (Peruzzini *et al.*, 2017). Industry 4.0 principles necessitate an overall change by digitalization and automatization of every part of the company, along with the manufacturing process (Trstenjak and Cosic, 2017). Another addition to these definitions is done by Schlechtendahl *et al.* (2014) by focusing on the interconnectedness between the participants. Madsen and Mikkelsen (2018) further highlight the concept of automation through Industry 4.0 that includes self-configuration for resilience, self-adjustment for variation and self-optimization for a disturbance. Longo *et al.* (2017) emphasize on the human resource while defining Industry 4.0 as an intelligent network of CPS and human resources communicating over the IoT and the IoS. Barata *et al.* (2018) further argue that Industry 4.0 heavily relies on data sharing throughout the supply chain through interconnected business services, processes and information systems. These definitions encourage researchers to propose a unified definition of Industry 4.0 from the SCM perspective.

3.2.2 Emerging themes. A majority of papers focus on the conceptualization of Industry 4.0 in various aspects of supply chains management research. For example, Wu *et al.* (2016)

Article	Definition
Hofmann and Rüsch (2017, p. 25)	"Products and services, flexibly connected via internet or other network applications"
Sanders *et al.* (2016, p. 816)	"Industry 4.0 is the fourth industrial revolution applying the principles of cyber-physical systems (CPS), internet and future-oriented technologies and smart systems with enhanced human-machine interaction paradigms"
Pereira and Romero (2017, p. 1207)	"This emerging Industry 4.0 concept is an umbrella term for a new industrial paradigm that embraces a set of future industrial developments regarding Cyber-Physical Systems (CPS), Internet of Things (IoT), Internet of Services (IoS), Robotics, Big Data, Cloud Manufacturing and Augmented Reality"
Peruzzini *et al.* (2017, p. 806)	"Industry 4.0 paradigm is based on systems communication and cooperation with each other and with humans in real time to improve process performances in terms of productivity, security, energy efficiency, and cost"
Trstenjak and Cosic (2017, p. 1745)	"Industry 4.0 has been presented as an overall change by digitalization and automatization of every part of the company, as well as the manufacturing process"
Schlechtendahl *et al.* (2014, p. 145)	"An Industry 4.0 paradigm is an environment in which all participants are interconnected and sharing information with each other"
Madsen and Mikkelsen (2018, p. 91)	"Industry 4.0 refers to automation through the internet of Things is brought to an even higher level and expected to be self-configured for resilience, self-adjusted for variation and self-optimized for a disturbance"
Tjahjono *et al.* (2017, p. 1175)	"The vision of industry 4.0 emphasizes the global network of machines in a smart factory setting capable of autonomously exchanging information and controlling each other"
Longo *et al.* (2017, p. 144)	"Industry 4.0 goes with intelligent networks of Cyberphysical Systems and Human Resources communicating over the internet of Things and the Internet of Services"
Randhawa and Ahuja (2017, p. 173)	"Industry 4.0 heavily relies on data acquisition and sharing throughout the supply chain through interconnected business services, processes, and information systems"

Table IV.
Defining Industry 4.0 in supply chain studies

conceptualize smart supply chain as an umbrella term for developing systems for better communication, intelligent decision making and automation capabilities by supply chain players. Stefansson and Lumsden (2009) suggest the three major components of smart transportation management, namely, smart products, smart vehicles and smart infrastructure. The authors argue that the components of smart transportation have effects on supply chain performance. Ivanov *et al.* (2016) theorize a smart manufacturing networking concept as a scenario where machines and products interact with each other in the absence of human intervention.

Several studies underline the Industry 4.0 principles in SCM (Mrugalska and Wyrwicka, 2017; Müller *et al.*, 2018; Nunes *et al.*, 2017; Qi and Bi, 2014; Toh *et al.*, 2009; Tu *et al.*, 2018). The authors argue how the key technologies will help the implementation of Industry 4.0 standards in SCM. These technologies include CPS, IoT, Robotics, Big Data, Cloud Manufacturing, Augmented Reality, RFIDs and information and communication technology, to name a few (Ben-Daya *et al.*, 2019). Ghobakhloo (2018) through their review of literature have enlisted the design principles specific to Industry 4.0. These principles include interoperability, virtualization, decentralization, real-time capability, service orientation and modularity.

A growing number of studies focus on managing the change from traditional supply chains to digitized supply chains. These studies address issues like managing information systems for data security and confidentiality laws (Kodym and Unucka, 2016); defining responsibilities for effective and efficient handling of smart supply chains (Chen, 2015) and implementation guidelines for managing new technologies (Li, 2018; Santos, Mehrsai, Barros, Araújo and Ares, 2017).

Researchers foresee Industry 4.0 as means to bring economic and social change in the world. For example, Li (2018) argue that Industry 4.0 implementation in industrial networks will improve industrial capability through innovation-driven manufacturing. Scholars have also analyzed the effect of Industry 4.0 technologies on environmental sustainability (Garcia-Muiña *et al.*, 2018; Lopes de Sousa Jabbour *et al.*, 2018; Nascimento *et al.*, 2019). Industry 4.0 will lead to a reduction in costs through improved productivity and efficient resource utilization, recycling and reuse. The extant literature underlines and emphasizes quality over quantity, green development, optimization of the industry structure and nurturing human talent as some of the outcomes of digitalization. Oesterreich and Teuteberg (2016) and Reischauer (2018) assess the extent to which Industry 4.0 shapes manufacturing industries as well as the economic and social life of the individuals. The authors contend that the intended outcomes of Industry 4.0 are innovation systems that comprise of academia, business, society and politics. However, factors such as unskilled labor, obsolescence of older equipment and high consumer demand may have a negative impact on environmental performance (Bonilla *et al.*, 2018; Tsai and Lu, 2018).

Industry 4.0 systems enable quick and cost-efficient response by enhancing flexibility and lead to improved overall operational performance (Dubey *et al.*, 2017; Fatorachian and Kazemi, 2018). Tonelli *et al.* (2016) underline the key internal resources and drivers of operational performance in Industry 4.0. The authors identify improvement areas, and define process initiatives, key performance indicators and interventions to improve business alignment. Ooi *et al.* (2018) explore the relationship between the absorptive capacity of cloud computing technology and firm performance. Several studies (refer Table V) argue that Industry 4.0 implementation will lead to better performance in terms of productivity, costs, quality, sustainability, responsiveness and leanness.

Several authors underline the drivers and barriers of Industry 4.0 application in SCM (Table V). For example, according to Oesterreich and Teuteberg (2016) employees have to handle with growing job requirements and might encounter a higher level of mental stress due to the fear about job losses. This will emerge as a barrier in the form of employee resistance. Bienhaus and Haddud (2018) enlist the factors related to the digitalization of organizations and ways to overcome them. The authors segregate these factors as enabling technologies and key barriers. Several other scholars have also identified the barriers and enablers of Industry 4.0. On similar lines, Lin *et al.* (2018) enumerate the factors which lead to positive or negative response toward Industry 4.0 initiatives. The authors contend that the company size does not affect its response toward these technologies. From the operational point of view, there can be several problems to be encountered like the lack of standards for many technologies, higher requirements for computing equipment, increasing the need for enhanced communication networks. Issues like regulatory compliance, legal and contractual ambiguity might also pose a challenge for digitalization. On the other hand, rising global competition, data availability, enabling technologies and customers' eccentric firms will drive the change toward digitalization (Neugebauer *et al.*, 2016).

Ben-Daya *et al.* (2019) give a detailed account of the impact of Industry 4.0 technologies on various functions of the supply chain. The authors identify the role of IoT on SCM through the analysis of the literature based on the impact on supply chain processes. A major segment of literature studies shed light on "make" and "deliver" processes of supply chain management. Ben-Daya *et al.* (2019) present a detailed account of how the enabling technologies affect different functions of supply chain processes. Apart from manufacturing, a large number of articles provide a conceptual framework to create value for the servitization processes by using the data from Industry 4.0-based technologies such as IoT, big data and cloud computing (Opresnik and Taisch, 2015). Vandermerwe and Rada (1988) argued that many firms might improve competitiveness by increasing the services offered in their portfolio by Servitization. Scholars contend that the concept of servitization can be developed toward better value propositions and increased profitability, with the help of IoT (Bressanelli *et al.*, 2018;

Themes	Key topics	Key papers
Conceptualization of Industry 4.0 components in SCM	Smart manufacturing, smart logistics, smart products, smart supply chains	Anderseck and Hille (2013), Diedrichs *et al.* (2016), Ivanov *et al.* (2016), Strandhagen, Vallandingham, Fragapane, Strandhagen, Stangeland and Sharma (2017), Longo *et al.* (2017), Lu *et al.* (2017)
Principles for implementing Industry 4.0 in SCM	Key technologies (Cyber-physical systems, Internet of Things, Internet of Services, robotics, big data, cloud manufacturing and augmented reality, RFID, 3D manufacturing), design principles (decentralization, interoperability, flexibility, information security and confidentiality, virtualization, real-time capability, service orientation, modularity, smart product, smart factory, vertical integration, horizontal integration, Product personalization)	Ghobakhloo (2018), Mrugalska and Wyrwicka (2017), Müller *et al.* (2018), Nunes *et al.* (2017), Qi and Bi (2014), Shah *et al.* (2018), Toh *et al.* (2009), Tu *et al.* (2018)
digitalization outcomes	competition, economic and social change	Li (2018), Lin *et al.* (2017), Maslarić *et al.* (2016), Oesterreich and Teuteberg (2016), Reischauer (2018), Tseng *et al.* (2018)
Performance of digitized supply chains	Productivity, costs, quality, sustainability, responsiveness, lean manufacturing	Mrugalska and Wyrwicka (2017), Ooi *et al.* (2018), Qrunfleh and Tarafdar (2015), Sanders *et al.* (2016), Tonelli *et al.* (2016), Trstenjak and Cosic (2017), Tseng *et al.* (2018)
Managing digitized supply chains	Data security and confidentiality laws, defining responsibilities, implementation guidelines, flexibility	Veza *et al.* (2015), Santos *et al.* (2017), Kiel *et al.* (2017), Rymaszewska *et al.* (2017), Trstenjak and Cosic (2017)
Drivers and barriers of Industry 4.0 in SCM	Drivers: global competition, data, enabling technologies, customers Barriers: high cost, lack of skills, lack of infrastructure, data confidentiality issues	Tonelli *et al.* (2016), Lu (2017), Thibaud *et al.* (2018), Maslarić *et al.* (2016), Ben-Daya *et al.* (2019), Dallasega *et al.* (2017), Kache and Seuring (2017)
Digitized supply chain practices	Plan, source, make, deliver and reverse logistics, smart product development, monitoring capabilities, servitization through Industry 4.0	Ben-Daya *et al.* (2019), Filho *et al.* (2017), Strange and Zucchella (2017), Trstenjak and Cosic (2017), Coreynen *et al.* (2017), Bressanelli *et al.* (2018), Rymaszewska *et al.* (2017)
Collaborative engineering and customization	Gap between mass customization and mass personalization; price and level of service	Santos *et al.* (2017), Wang *et al.* (2017)

Table V.
Emerging themes in literature

Rymaszewska *et al.*, 2017). IoS promote manufacturing servitization by a strategic shift from selling products to selling an integrated product and service offering, i.e., a product-service system (PSS) (Martinez *et al.*, 2010).

The integration of PSS with CPS will lead to product-service bundles creating cyber-physical product-service systems. These technologies can be used to predict product performance, and manage the product life cycle and optimize product service needs (Lee *et al.*, 2014). Scholars contend that the concept of servitization can be developed to achieve better value propositions and increased profitability, with the help of IoT (Bressanelli *et al.*, 2018; Rymaszewska *et al.*, 2017). Coreynen *et al.* (2017) empirically examine the relationship between digitalization and servitization. The authors contend that digitalization is positively linked with industrial, commercial and value servitization.

Digitalization of assets and data exchange between industrial buyers and suppliers facilitate smart servitization. In smart servitization, the focus shifts toward considering the product as a means of delivering continual value to the customer, rather than the end itself. The manufacturer remains connected to customers via the product (Porter and Heppelmann, 2015). Through the analysis of data obtained from products, providers of product-service systems can gain an improved understanding of the use of their offering by their clients. Thus, the use of technology assists the suppliers in providing new functionalities, capturing and analyzing the insightful data and thus helping the suppliers to develop stronger bonds with customers. Therefore, customer relationships tend to become more intensive due to data-driven servitization (Kamp and Parry, 2017; Kiel *et al.*, 2017; Penttinen and Palmer, 2007). It is evident from the above analysis that Industry 4.0 applications have been widely studied in the literature, in the context of manufacturing and digitalization.

Collaboration networks describe the direction of horizontal integration, allowing manufacturers to focus on their competencies by offering customized products in any market. The ability to produce smaller lot sizes of personalized products requires highly efficient and effective smart factories (EFFRA, 2012). These manufacturing systems represent a future form of industrial networks having dynamic structures that evolve over time (Ivanov *et al.*, 2016). The smart factory involves the integration of physical and digital technologies with the phases of the product (Kolberg *et al.*, 2017). The integration between these areas provides more customization to the production and to the product, reducing the product development time. A vast stream of literature has addressed the topic of mass customization in the context of recent Industry 4.0 developments. By connecting computers, machinery and business processes, Industry 4.0 has enabled the production of high-quality and highly customized products (Fatorachian and Kazemi, 2018; Strozzi *et al.*, 2017; Zhong *et al.*, 2017). Industry 4.0 technologies are expected to fill the gap between mass customization and mass personalization (Santos, Loures, Piechnicki and Canciglieri, 2017; Wang *et al.*, 2017). Mass personalization production strategy by firms can be enhanced with the introduction of a new production system based on the implementation of Industry 4.0 technologies. Mass personalization entails a strategy of producing goods and services to satisfy individual customer's needs such that the values outperform costs for both customers and manufacturer (Zhou *et al.*, 2013). Customers will cooperate with manufacturers to gain value through the creation of personalized products adapted to the individual customer's requirements and needs. For example, direct customer input to design will enable companies to increasingly produce personalized products with shorter times and reduced costs (Wang *et al.*, 2017). Based on the technological concepts of radio frequency identification, CPS, the IoT, IoS and big data, Industry 4.0 will enable this novel form of personalization (Torn and Vaneker, 2019).

4. Discussion and avenues for future research

Industry 4.0 in the context of SCM lacks a unified accepted definition. Most studies define Industry 4.0 in the context of manufacturing. There is a dearth of literature on analytical models, as well as quantitative studies that can address practical issues regarding the implementation of Industry 4.0 in SCM. Empirical case studies may be developed to inform practitioners on how different supply chains differ in Industry 4.0 technologies. In this area, future research should give attention to the role played by different actors while implementing the principles of Industry 4.0. Examining the critical role of suppliers, manufacturers and retailers in a multi-tier supply chain can be one area of research. For companies, the supplier selection process is an essential measure of managing corporate rightfulness and reputation. Yu *et al.* (2015) shed light on how the supplier selection process is affected by digitalization. In light of the global attention to data security and confidentiality, impact that Industry 4.0 issues have on firms' reputations is of great importance. Future studies can focus on developing strategies to alleviate information security risk in activities such as smart sourcing and supplier selection decisions. Studies focusing on outcomes of digitized supply chains are extremely limited. Most of these studies focus primarily on data vulnerability and sustainability issues. Future empirical research in the area might explore measures such as improved quality, flexibility, improved responsiveness and other sustainability measures that can result from the supply chain being digitized. In light of the above, we summarize the future research avenues identified through this study as follows:

- Performance measurement: there is no unified approach to measuring and capturing the actual performance of a digitized supply chain. Only one study (Dweekat *et al.*, 2017) was found to have addressed the topic of performance measurement in the Industry 4.0 context. In the future, researchers may attempt to develop tools for measuring the performance of digitized supply chain.
- Studies on planning and sourcing: plan and source are major operational aspects of SCM. Future studies must look into this area. Research about planning and sourcing in the context of digitalization is limited and focuses mainly on the process of evaluation of suppliers. Future research in this area can look into topics such as buyer–supplier relationships and how relationships are influenced by Industry 4.0 implementation.
- Models to assess economic viability: the Industry 4.0 concept embraces a set of future industrial developments regarding CPS, Robotics, IoT, IoS, Big Data, Augmented Reality and cloud manufacturing. Several authors have developed models to assess the cost-effectiveness of investments in enabling technologies such as RFIDs. Lee and Lee (2010) develop the Supply Chain RFID Investment Evaluation Model to enhance RFID value creation, measurement and ways to maximize the value of RFID technology. CPS also apply identification technologies such as RFID tags. These tags provide data to assist intelligent services that may be used in manufacturing operations, logistics, quality audits and manufacturing strategies among others (Segura-Velandia *et al.*, 2016). However, the application is associated with high investments and complex process transformations (Irrenhauser and Reinhart, 2014). Organizations express their concern about the initial cost of implementing Industry 4.0 technologies. To weigh the advantages of digitalization against conventional SCMone needs to consider the return on investment, rather than the cost of implementation. Therefore, comprehensive studies that encompass the models to study the economic feasibility of Industry 4.0 adoption can be undertaken for future research.
- Trade-off between cost-effectiveness and sustainable performance: Industry 4.0 will lead to a reduction in costs through improved productivity and efficient resource utilization, recycling and reuse. Although several studies have contended that Industry 4.0 can be a facilitator of environmental sustainability, factors such as unskilled labor, high obsolescence of older equipment and high consumer demand may have a negative impact on environmental performance (Tsai and Lu, 2018). Both academics and practitioners would like to understand the potential effect of Industry 4.0 implementation, on the social performance of the companies. Future studies may focus on how to use Industry 4.0 technologies to achieve sustainable performance and cost-effectiveness. Therefore, we propose that future research in this area must consider minimizing the trade-off between cost-effectiveness and sustainable performance.
- Quality management in digitized supply chains: most of the quality management literature in the context of digitized supply chains deal with RFID tags. Through RFID and embedded systems missing resources can be calculated to eliminate quality defect and partial or total delivery failure (Chen, 2015). Studies in the

future can look into other quality management aspects of a digitized supply chain. For example, the relationship between Industry 4.0 implementation and facets of quality performance can be empirically examined. Future research can qualitatively assess the changing expectations of the quality managers in the context of a digitized environment. The research in this area can also look into how Industry 4.0 technologies can be utilized to implement the quality principles.

- Industry-specific studies: a few studies underlined big data applications in food and agricultural supply chain (Bao *et al.*, 2013), automotive supply chain (Lin *et al.*, 2018) and fashion supply chain (Grieco *et al.*, 2017). In the future, industry-specific empirical, as well as qualitative case studies, can be developed in the context of Industry 4.0 enabled supply chains.

5. Academic and managerial implications

From the study, it is clear that applications of Industry 4.0 are in the nascent stage. However, the technologies pertaining to Industry 4.0 present an enormous potential to revamp the SCM processes in areas such as improving efficiency, responsiveness, quality management, enhancing customer centricity and sustainable performance. Decision making in the Industry 4.0 environment is a complex process as compared to traditional SCM. Our analysis of literature will help the managers to understand critical enablers, barriers and the complexity involved with Industry 4.0 adoption. The managers need to understand the potential challenges and benefits associated with Industry 4.0 adoption and how these benefits may outweigh the challenges. Our study will help the managers to understand the principles for the implementation of enabling technologies and conceptualize Industry 4.0 technologies as an opportunity for achieving cost reduction and efficiency improvement. In Table V, we highlight the literature that sheds light on the key principles of Industry 4.0. We present issues that are of topical interest and have a bearing on the successful implementation of Industry 4.0. Managers get an insight into the factors that affect Industry 4.0 implementation and how some companies have adopted the enabling technologies by referring to the empirical studies investigated in our review. For instance, we underline the literature that highlights the key technologies and design principles for Industry 4.0 implementation while appreciating the critical economic and social outcomes that managers can expect from the implementation of Industry 4.0, the issues in managing the digitized supply chains and key practices among others. The increase in data availability because of Industry 4.0 has given prospects to the managers to not only improve the existing processes but also change them. Our review serves as a foundation for the managers to develop their initiatives and practices for a successful transition to Industry 4.0. In order to embrace all the potential benefits of Industry 4.0, managers must consider digitalization as a string of opportunities for transforming their business models. By disentangling the work on Industry 4.0 with particular focus on SCM, we help the managers recognize the different aspects of Industry 4.0 before embarking on such a game-changing phenomenon. A plethora of studies have highlighted the challenges and enablers to digitalization. It is observed in the literature that several issues such as regulatory compliance, legal and contractual ambiguity might also pose a challenge for digitalization and thus warrant interdisciplinary research approach. However, increased competition, data availability, enabling technologies, rising customers eccentricity will drive Industry 4.0. For example, the issues arising from information security and data privacy concerns are accompanied by technological as well as societal implications, and would therefore, require attention from the interdisciplinary research community.

Based on our analysis, we help future researchers to identify areas that are of practical and theoretical relevance. Our classification provides essential insights to the researchers regarding the significance of Industry 4.0 in SCM and as a potential avenue for future research. The study also highlights the ongoing adoption of new technologies in SCM, which can be further explored and expanded for transforming the supply chains. Also, academicians can take note of the state of research on Industry 4.0 and can appreciate what have been thrust areas. Further, we outline some key areas of research in the present domain in terms of performance measurement in the era of Industry 4.0, planning and sourcing with enabling technologies of Industry 4.0, economic viability of implementing Industry 4.0 including issues pertaining to sustainability, the quality management and industry-specific design of studies that can help researchers further extend the current body of work.

6. Limitations and conclusions

Studies in the past have underlined the impact of stand-alone technologies such as IoT, big data, RFIDs, among others in SCM and how they assist the firms in achieving competitive advantage. However, relatively a few number of studies have comprehensively looked at the effect of Industry 4.0 in supply chain management. The present study was built upon this gap and comprehensively analyzed the role of Industry 4.0 in supply chain studies by adopting systematic literature review approach. Literature indicates that the companies are moving toward Industry 4.0 to attain better process efficiency and competitiveness. These changes are supply chain wide and are marked by disruptive technological advancements that are blurring the boundaries between the physical and virtual world. Based on our classification of the literature by emerging themes, we found that the majority of studies focus on the particular functions of the supply chain. Most of the research is confined to two functional areas, i.e., manufacturing and logistics. Our review of the literature also highlights some clear benefits that can be identified from the implementation of Industry 4.0. The literature indicates that digitalization of supply chains will lead to an improvement in quality, flexibility, responsiveness. The readiness of new responsive manufacturing systems would create a pathway for the novel production strategy called mass personalization and create more value for both customers and manufacturers. Industry 4.0 would also foster manufacturing servitization by a strategic shift from selling products to selling an integrated product and service offering. Moreover, the collaboration between machines and humans could socially impact the life of the employees and society at large. Industry 4.0 affects manufacturing industries, and therefore it will impact the economic and social life of the individuals. From the analysis of the literature, it can be concluded that Industry 4.0 encompasses a large number of changes across the different aspects of SCM which are primarily driven by the Industry 4.0 technologies. By providing an understanding about the emerging themes in the area of digitalization, the role of its key technologies and design principles, its challenges and enablers as underlined in the literature, and implications on various supply chain processes and outcomes, this study makes a valuable contribution to and SCM literature.

We do note certain limitations in this work. First, the conclusions are drawn by considering peer-reviewed journal and conference articles in English. Therefore, other languages and other types of publications are excluded from our study. In the future, additional insights may be congregated by reviewing different bodies of literature such as reports and books. Second, we focus on the literature in the context of Industry 4.0. Therefore, the SCM studies that focus on enabling technologies for digitalization, but exclude the Industry 4.0 perspective have been omitted from the review. Despite these limitations, our study contributes to identifying the key themes used to address Industry 4.0 in the field of SCM. It also highlights the underexplored aspects of this topic, thereby emphasizing that the discussion on Industry 4.0 in SCM provides a favorable future research agenda.

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