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The self-thinking supply chain

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Abstract

Purpose – An emerging theme in the practitioner literature suggests that the supply chain of the future – enabled especially by developments in ICT – will be autonomous and have predictive capabilities, bringing significant efficiency gains in an increasingly complex and uncertain environment. This paper aims to both bridge the gap between the practitioner and academic literature on these topics and contribute to both practice and theory by seeking to understand how such developments will help to address key supply chain challenges and opportunities.

Design/methodology/approach – A multi-disciplinary, systematic literature review was conducted on relevant concepts and capabilities. A total of 126 articles were reviewed covering the time period 1950-2018.

Findings – The results show that both IoT and AI are the technologies most frequently associated with the anticipated autonomous and predictive capabilities of future supply chains. In addition, the review highlights a lacuna in how such technologies and capabilities help address key supply chain challenges and opportunities. A new supply chain model is, thus, proposed, one with autonomous and predictive capabilities: the self-thinking supply chain.

Originality/value – It is our hope that this novel concept, presented here for the first time in the academic literature, will help both practitioners to craft appropriate future-proofed supply chain strategies and provide the research community with a model (built upon multidisciplinary insights) for elucidating the application of new digital technologies in the supply chain of the future. The self-thinking supply chain has the potential in particular to help address some of today's key supply chain challenges and opportunities.

Keywords Information systems, Performance management, Agile, New technology

Paper type Research paper

1. Introduction

A large number of academic and practitioner publications have acknowledged that supply chain management is undergoing significant changes due to the adoption of new digital technologies (Capgemini, 2016; DHL, 2016; Wu *et al.*, 2016; Haddud *et al.*, 2017). Breakthroughs in several fields, such as the Internet of Things (IoT), artificial intelligence (AI), robotics, autonomous vehicles and additive manufacturing are transforming all the steps in supply chain management (World Economic Forum (WEF), 2017). This is taking place in the context of the Fourth Industrial Revolution, a revolution that is characterized by an unprecedented advance in digital technology and which is blurring the lines between the physical, digital and biological spheres (Schwab, 2016). Amongst the breakthroughs that characterize the Fourth Industrial Revolution is the ability to collect and analyse massive amounts of data in an automated way, then use these data for decision-making and implement decisions in real time. Practitioner research suggests that there will be more than 50 billion devices connected to the internet by 2020 (Cisco, 2011), a trillion sensors connected to and transmitting information to analytical platforms in the cloud and 44 trillion gigabytes generated (DHL, 2015). In this context, information that was previously created by people will increasingly be machine-generated, whilst the entire supply chain will be connected, including parts, products and other smart objects used to monitor the supply chain (IBM, 2015). Based on these data, supply chains will be able to make decisions more accurately and in real time, to optimize operations, handle incidents that require risk-mitigation actions, avoid disruptions and satisfy an increasingly volatile demand (Calatayud, 2017).

Notably, many commentators argue that the supply chain of the future will be autonomous and have predictive capabilities (IBM, 2015; DHL, 2016; World Economic Forum (WEF), 2017). This, they say, will bring significant performance improvement in an increasingly complex and uncertain environment for supply chain management. Indeed, supply chains currently face a variety of risks due to growing internationalization and firm interconnection, higher demand volatility and faster supply chain speed (Christopher and Holweg, 2011, 2017). Driven by new digital technologies, the supply chain of the future will increasingly be self-aware, think by itself and require minimum, if any, human intervention to manage risks. The self-thinking supply chain will continuously monitor supply chain performance by analysing quintillion bytes of data generated by objects; forecast and identify risks; and automatically take actions to prevent risks before they materialize. The supply chain will autonomously learn from

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these activities and use such knowledge in future decisions. Importantly, large amounts of data and the use of powerful analytical and simulation models will allow the supply chain to predict the future with minimum error and take actions to, for example, address constant shifts in demand. The self-thinking supply chain will, thus, push supply chain flexibility and agility to limits yet to be discovered (Calatayud, 2017).

Despite these promising benefits for supply chain management (SCM), literature on self-thinking supply chain is scarce. The term is mentioned only infrequently in the practitioner literature in an attempt to predict future SCM trends with the simultaneous adoption of different new digital technologies (DHL, 2016; Calatayud, 2017; IBM, 2017). In the academic literature, however, current research mainly focuses on identifying the impact of a single new digital technology – such as IoT – on supply chain performance. Therefore, in this paper, we seek to understand, from both practical and theoretical perspectives, how multiple digital technologies will shape future supply chains. The literature on automated, predictive and self-thinking supply chains, and related concepts and capabilities, is reviewed. The insights from that review are then considered in the context of the current understanding of supply chain strategy and a new supply chain model – the self-thinking supply chain – is posited. The systematic literature review spans disciplines such as SCM, computer science, engineering and economics. It is our hope that this novel concept, described here for the first time in the academic literature, will help both practitioners to craft appropriate future-proofed supply chain strategies and provide the research community with a model (built upon multidisciplinary insights) for elucidating the application of new digital technologies in the supply chain of the future.

This paper is organized as follows: Section 2 lays out the methodology and procedures followed to conduct the systematic literature review; Section 3 presents the results of the systematic literature review; Section 4 discusses the impact of new digital technologies on SCM according to the extant literature; Section 5 introduces the self-thinking supply chain model and elucidates its contribution to supply chain strategy; and Section 6 presents the conclusions and outlines areas for future research.

2. Methodology

To explore the characteristics of a self-thinking supply chain, the systematic literature review technique was applied. This technique uses systematic methods to identify, select and critically evaluate the body of knowledge related to a given topic (Gligor and Holcomb, 2012; Rousseau *et al.*, 2008; Tranfield *et al.*, 2003). Unlike a traditional literature review, which might be influenced by the familiarity or preferences of the reviewer, a systematic literature review allows the researcher to gather, analyse and interpret a comprehensive body of available literature in a thorough and unbiased manner (Wang and Notteboom, 2014).

The systematic review technique is particularly relevant to the purpose of this paper. By avoiding the biases of conventional literature reviews, a systematic review allows the researcher to:

- summarize the accumulated body of knowledge related to the topic of interest;
- explore the topic through different perspectives; and
- develop reliable knowledge from a pool of knowledge dispersed across a broad range of studies (Gligor and Holcomb, 2012; Tranfield *et al.*, 2003).

Given that the pool of knowledge on new digital technologies and supply chain management is spread across a variety of academic disciplines, and that, according to practitioner literature, a self-thinking supply chain encompasses the use of different technologies, the systematic literature review is deemed appropriate to explore how multiple digital technologies will shape future supply chains. Indeed, a systematic review of automated, predictive and self-thinking supply chains, and related concepts and capabilities, allow us to explore available academic literature comprehensively, giving insights on the meaning, enablers and potential benefits of a self-thinking supply chain whilst bridging the gaps amongst different perspectives and developing a broad understanding of the research topic.

Applying the systematic review technique involves five stages (Figure 1):

1. problem formulation;
2. literature research;
3. selection and evaluation of literature;
4. research analysis and interpretation; and
5. presentation of results (Denyer and Tranfield, 2009; Gligor and Holcomb, 2012).

The problem addressed in this paper was formulated as follows: given that the pool of knowledge on new digital technologies and SCM is spread across a variety of academic disciplines, can we aim to develop an integrated framework to understand the defining aspects of a self-thinking supply chain and its potential benefits from both practical and theoretical perspectives? The literature was researched by interrogating the data set Scopus, one of the largest repositories of academic articles. Literature research comprised five stages. In the first stage, keyword search was performed using the words "self-thinking" AND "supply chain", together with related words such as "autonomous" OR "predictive" AND "supply chain", in papers and conference proceedings published between 1950 – the earliest available year in the data set – and February 2018. In the second stage, studies were chosen and evaluated according to a set of specific criteria that referred to:

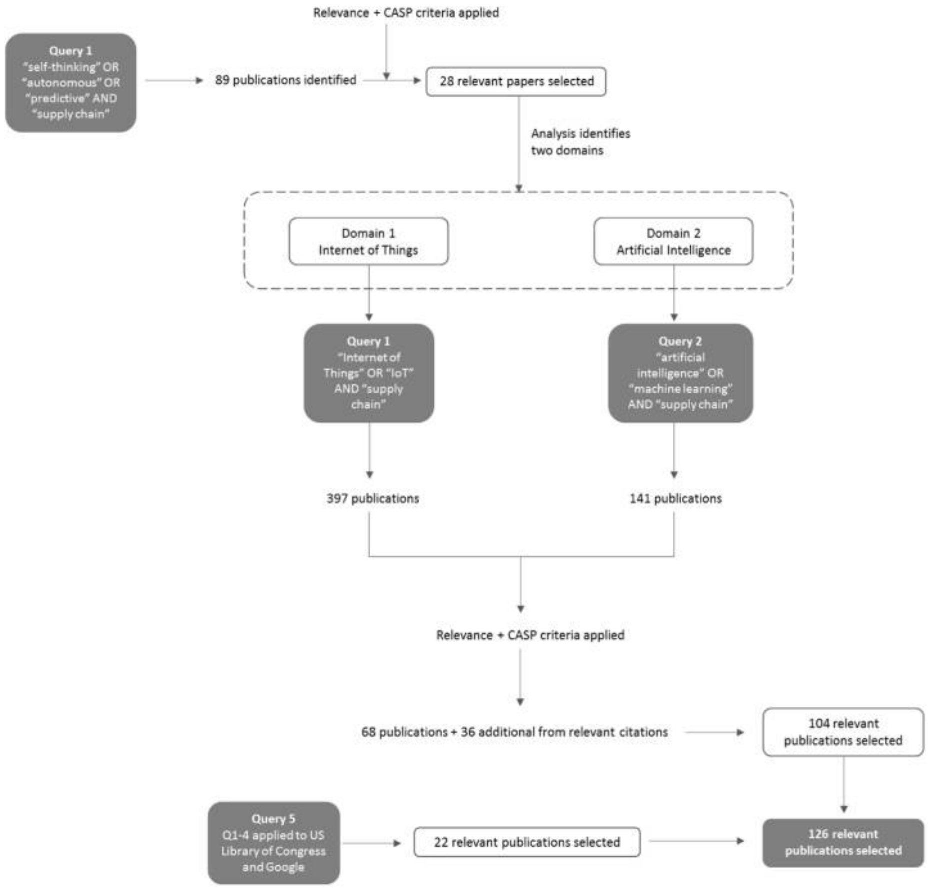
- the relevance of the study to the research problem; and
- the quality of the study. In agreement with Wang and Notteboom (2014), the Critical Appraisal Skills Program (CASP) checklist was used to evaluate the quality of the studies.

Studies selected in stage two were analysed to identify shared patterns amongst them. The analysis showed that studies could be grouped into two domains:

1. studies exploring the use of IoT in SCM; and
2. studies exploring the use of AI in SCM.

In the third stage, the data set was further interrogated using keywords that referred to such domains. In the fourth stage, search results were evaluated according to the relevance and quality criteria applied in stage two. References included in the

Figure 1 Graphical illustration of the literature search process and results



papers collected were used as guidance for further exploration of the literature. In addition, literature citing the papers collected were identified and analysed. In all queries, words closely related to self-thinking such as "smart" or "intelligent" were considered as well. In the fifth stage, the review of articles was complemented by searching:

- the catalogue of the US Library of Congress (the biggest library catalogue in the world) for books that could be related to the topic; and
- Google search engine, using the same keywords that were used in the Scopus query, to account for working papers and reports relevant to the topic published by other sources, such as national and international organizations.

Search results were evaluated according to the relevance and quality criteria applied in stage two.

3. Results

The first stage of the literature research resulted in 89 articles. In stage two, the 89 articles were evaluated according to the relevance and quality criteria, with 28 articles satisfying such criteria (Table I). Next, the articles selected were preliminarily analysed with the objective of identifying shared characteristics that could be used to group and classify them into different categories. The analysis showed that articles could be classified into two broad domains:

1. articles exploring the use of IoT in SCM, including studies with a focus on planning and management of activities that integrate supply and demand within and across companies;
2. articles exploring the use of AI in SCM, including studies that develop and apply different types of algorithms to dynamically solve supply chain optimization problems.

These categories were then used to further query the database, looking for articles relevant to the research problem.

In the third stage, the database was interrogated by searching for words related to the two domains identified in the previous phase: IoT and AI. The words "Internet of Things" OR "IoT" AND "supply chain" were searched for the first domain, resulting in 397 articles, among which 56 articles satisfied the relevance and quality criteria. Next, the words "artificial intelligence" OR "machine learning" AND "supply chain" were selected for the second domain, resulting in 141 articles, amongst which 23 articles satisfied the selected criteria. In addition, a third search was performed using the keywords "Internet of Things" OR "IoT" AND "artificial intelligence" OR "machine learning" AND "supply chain" to identify articles encompassing both types of technology, thus combining both domains. This search resulted in 22 articles, amongst which 17 articles satisfied the selected criteria. Overall, after applying the relevance and quality criteria to the results, 68 articles were selected, making up the basis for further

Table I Papers that satisfied the relevance and quality criteria (1950-2018)

No.	Authors/Year	Title	Domain
1	Gu (2018)	Fast Discrepancy Identification for RFID-Enabled IoT Networks	IoT
2	Fore *et al.* (2017)	Intelligent supply chain management system	IoT and AI
3	Merlino and Sproge (2017)	The Augmented Supply Chain	IoT and AI
4	Ben-Daya *et al.* (2017)	Internet of things and supply chain management: a literature review	IoT
5	Yuvaraj and Sangeetha (2016)	Smart supply chain management using internet of things (IoT) and low power wireless communication systems	IoT
6	Wu *et al.* (2016)	Smart supply chain management: A review and implications for future research	IoT and AI
7	Wang and Wang (2015)	Multi-agent based intelligent supply chain management	AI
8	Cui (2015)	Improving supply chain resilience with employment of IoT	IoT
9	Yan *et al.* (2014)	Intelligent supply chain integration and management based on cloud of things	IoT
10	Bowles and Lu (2014)	Removing the blinders: A literature review on the potential of nanoscale technologies for the management of supply chains	IoT
11	Zhang *et al.* (2013)	Application analysis of Internet of Things on the management of supply chain and intelligent logistics	IoT
12	Ameri and McArthur (2013)	A multi-agent system for autonomous supply chain configuration	AI
13	Kumar *et al.* (2013)	A decision support system for control mechanism of inventory in a dynamic supply chain system considering supply-price trade-off using control theory	AI
14	Mettler *et al.* (2012)	An intelligent supply chain design for improving delivery reliability	AI
15	Siurdyban and Møller (2012)	Towards intelligent supply chains: A unified framework for business process design	AI
16	Lozano-Nieto (2012)	Radio frequency identification in the smart supply chain	IoT
17	Jiang and Hao (2011)	Research on the development of intelligent logistics based on internet of things	IoT
18	Bintrup (2010)	Behaviour adaptation in the multi-agent, multi-objective and multi-role supply chain	AI
19	Collins *et al.* (2010)	Pushing the limits of rational agents: The trading agent competition for supply chain management	AI
20	Butner (2010)	The smarter supply chain of the future	IoT and AI
21	Martinez-Sala *et al.* (2009)	Tracking of Returnable Packaging and Transport Units with active RFID in the grocery supply chain	IoT
22	Schoenemann *et al.* (2009)	Flexible semantic services to facilitate innovative and dynamic ubiquitous supply chain networks	IoT
23	Li (2008)	Adaptive multi-agent modeling in intelligent supply chain management	AI
24	Li *et al.* (2010)	Intelligent supply chain management with automatic identification technology	IoT
25	Liang and Li (2007)	Integration of intelligent supply chain management (SCM) system	IoT and AI
26	Lopez *et al.* (2007)	Intelligent supply chain by using prognostic logistics	IoT
27	Ounar *et al.* (2007)	Customer-supplier relationship management in an intelligent supply chain network	AI
28	Lumsden and Stefansson (2007)	Smart freight to enhance control of supply chains	IoT

analysis. The earliest article included in the data set had been published in 2007 and the most recent in 2018. This time period is consistent with the exponential growth of academic interest in the subject of digital technologies applied to SCM. Indeed, the simple search for the keywords "digital" AND "supply chain" on Scopus showed that 80 per cent of the academic publications found (1,128 articles) were published in the period 2007-2018. In addition to the articles selected for analysis, both references contained in and literature citing these articles were analysed and also included when they satisfied the selected criteria.

In the fifth stage, the literature research was complemented by querying the catalogue of the US Library of Congress and Google search engine, using the same keywords from previous phases. Arising from the five stages of the literature research, 126 studies were selected and analysed (Figure 1).

Table II shows the five journals with the highest number of articles selected through the literature search process.

4. IoT, artificial intelligence and SCM

SCM aims to get, in the right way, the right product, in the right quantity and right quality, in the right place at the right time, for the right customer at the right cost (Mangan and Lalwani, 2016). However, growing supply chain complexity, higher demand volatility, unprecedented technological changes and supply chain speed are making SCM increasingly challenging (Christopher and Holweg, 2017; Fore *et al.*, 2017). In 2017, 32

Table II Main sources of the articles selected

Journal	No. of articles selected
International Journal of Production Economics	11
The International Journal of Logistics Management	5
The International Journal of Logistics Management	4
International Journal of Production Research	4
Journal of Operations Management	3

per cent of S&P 500 companies were affected by supply chain disruptions (Resilinc, 2018). To overcome supply chain risks and vulnerabilities, academic and practitioner literature suggests that smarter supply chains must be built (Butner, 2010). These supply chains will use a range of technologies to respond to changing environments, with or without human intervention (Wu *et al.*, 2016). Therefore, available literature anticipates that a revolution on how supply chains work and are managed lies ahead (Zjim and Klumpp, 2015).

Practitioner research argues that, in the future, supply chains will be autonomous and will have predictive capabilities (IBM, 2015; DHL, 2016; World Economic Forum (WEF), 2017). Using IoT sensors, quintillion bytes of data will be generated across supply chain operations. AI will be deployed to analyse information in real time, monitor operations across the globe, predict the future with minimum error rate, and take actions to adjust to rapidly changing environments (DHL, 2016). Such supply chains will be self-thinking, requiring minimum, if any, human intervention (Calatayud, 2017). In spite of the promising benefits of the self-thinking supply chain found in practitioner literature, academic research on this and related topics is scarce. Our systematic literature review found no articles exploring the self-thinking supply chain and only 28 articles referring to related concepts such as "autonomous", "predictive", "smart" or "intelligent" supply chain. These articles are spread across different fields, including SCM, computer science, engineering and economics. The analysis of the selected articles gave insights into in particular two new digital technologies that are associated with autonomous, predictive, smart or intelligent supply chains, namely, IoT and AI. As shown in Table I, half of the initial 28 articles retrieved referred to the use of IoT to improve SCM. In turn, nine articles discussed the application of AI in SCM. Finally, five articles explored the benefits of both IoT and AI for SCM. The sub-sections that follow analyse both technologies according to the 126 publications retrieved in the systematic literature review. Table III provides a summary of our findings and categorizes the main research related to the topic under examination.

4.1 Internet of things and SCM

The systematic literature review revealed that academic interest on IoT and SCM is fairly recent. Indeed, the oldest article in our data set was published in 2004. That article analysed the promises of applying RFID technology for SCM and suggested that the ultimate goal was "to create an 'Internet of things' in which everyday physical items are networked together" (Luckett, 2004, p. 50). More recently, interest in IoT and SCM has been increasing: 44 per cent of the 397 articles found in Scopus were published between 2016 and 2018. In 2017, Ben-Daya *et al.* published an article which analysed the literature on IoT and SCM. Whilst those authors' work is certainly a good reference point for this paper, in our systematic literature review, we retrieved additional work not included in Ben-Daya *et al.* (2017), particularly regarding the transmission mechanism by which IoT impacts on SCM, as well as the different technologies encompassed by IoT and the interaction of IoT with other new digital technologies. As mentioned before, literature is spread across different disciplines, with computer science (64 per cent of publications retrieved), engineering (52 per cent) and business and management (24

Table III Literature review summary

Domains	Main topics discussed in the literature	Relevant literature
1. IoT and SCM	1.1 IoT definition	Vermesan *et al.* (2011); Gnimpieba *et al.* (2015), Reaidy *et al.* (2015); Zhou *et al.* (2015), Ben-Daya *et al.* (2017); Dweekat *et al.* (2017), Lu (2017); Yan (2017)
	1.2 IoT enablers	Delen *et al.* (2007), Lee and Ozer (2007); Gimenez and Lourenco (2008), Sarac *et al.* (2010); Zhu *et al.* (2012), Zhang *et al.* (2013); Lin *et al.* (2011); Xu *et al.* (2014), Reaidy *et al.* (2015); Ben-Daya *et al.* (2017), Dweekat *et al.* (2017); Lu (2017), Yan *et al.* (2017)
	1.3 IoT impact on SCM	Delen *et al.* (2007), Sarac *et al.* (2010); Lozano-Nieto (2012), Cui (2015); Gnimpieba *et al.* (2015), Reaidy *et al.* (2015); Zhou *et al.* (2015); Zjim and Klumpp (2015); Ben-Daya *et al.* (2017), Dweekat *et al.* (2017); Gonul *et al.* (2017), Gunasekaran *et al.* (2017); Haddud *et al.* (2017), Hofmann (2017); Hofmann and Rusch (2017), Lu (2017); Rezaei *et al.* (2017); Wu *et al.* (2015); Yan (2017), Yan *et al.* (2017); Dunke *et al.* (2018), Gu (2018)
2. AI and SCM	2.1 AI and prediction accuracy	Kochak and Sharma (2015), Slimani *et al.* (2015); Susto *et al.* (2015), Lee *et al.* (2016); Nikolopoulos *et al.* (2016), Singh and Challa (2016); Slimani *et al.* (2016), Yang *et al.* (2017).
	2.2 AI applied to specific supply chains	Guo and Wong (2013), Wong *et al.* (2013); Abukhousa *et al.* (2014), Farahani *et al.* (2016); Santos *et al.* (2017), Dellino *et al.* (2017); Lu and Wang (2017), Fikar (2018); Nayak and Padhye (2018)
	2.3 AI techniques and supply chain optimization problems	Bintrup (2010); Mettler *et al.* (2012), Sinha *et al.* (2012); Ameri and McArthur (2013), Kumar *et al.* (2013); Dounias and Vassiliadis (2015), Wang and Wang (2015); Fikar (2018)

per cent) being the fields with higher numbers of publications. In terms of the geographic areas of authors' affiliation, China (34 per cent), the USA (14 per cent) and the UK (8 per cent) are leading knowledge creation in this field. In the next sub-sections, the publications retrieved are analysed according to three aspects of IoT technology discussed in the literature: its definition, its enablers and its impact on SCM.

4.1.1 IoT definition

A number of articles locate the beginning of IoT in the late 1990s, when the term was coined by Ashton to refer to uniquely identifiable objects (things) through RFID technology and their virtual representations in an internet-alike structure (Zhou *et al.*, 2015; Papert and Pflaum, 2017; Rezaei *et al.*, 2017). Since then, and particularly in the last three years, many IoT definitions have been suggested in the literature; some are more specific to the technologies encompassed by IoT, whilst others are more comprehensive and include the purpose of the technology (Haddud *et al.*, 2017; Hofmann and Rusch, 2017). Regarding the former, most of the definitions retrieved in the literature search suggest that IoT technology refers to at least three elements:

1. technology for data collection;
2. technology for data transmission; and
3. technology for data analysis (Reaidy *et al.*, 2015; Dweekat *et al.*, 2017; Lu, 2017).

According to Gnimpieba *et al.* (2015), the added value of IoT is precisely the integration of different layers of sensors, data transmission and storage, setting the data collected available to users. Likewise, Lu (2017) states that the IoT integrates various devices equipped with sensing, identification, processing, communication and networking capabilities. Vermesan *et al.* (2011) and Reaidy *et al.* (2015) focus on the network characteristic of IoT, referring to it as a:

> Dynamic global network infrastructure with self-configuring capabilities based on standard and interoperable communication protocols where physical and virtual "things" have identities, physical attributes, and virtual personalities, use intelligent interfaces, and are seamlessly integrated into the information network (Reaidy *et al.*, 2015, p. 29).

Other IoT definitions are more comprehensive, in the sense that they include the purpose of the technology. For example, Zhou *et al.* (2015) refer to IoT as a "devices or sensors connected world where objects are connected, monitored, and optimized through wired, wireless or hybrid systems" (Zhou *et al.*, 2015, p. 1). Gnimpieba *et al.* (2015) state that IoT is an evolution in computer technology and communication that aims to connect objects together via the internet. According to the authors, the flow of information and events generated by the interconnection of these objects is used to facilitate their tracking, management, control and coordination. Likewise, Yan (2017, p. 730) suggests that the IoT is:

> An internet-based intelligent network which is capable of transferring real-time information, as well as identifying, tracking and managing products through advanced technologies such as radio frequency identification (RFID), infrared sensor, global positioning system and laser scanner.

Ben-Daya *et al.* (2017) go beyond the purpose of technology to include the expected impact of IoT on SCM. According to the authors, IoT is:

> A network of physical objects that are digitally connected to sense, monitor and interact within a company and between the company and its supply chain enabling agility, visibility, tracking and information sharing to facilitate timely planning, control and coordination of the supply chain processes (Ben-Daya *et al.*, 2017, p. 3).

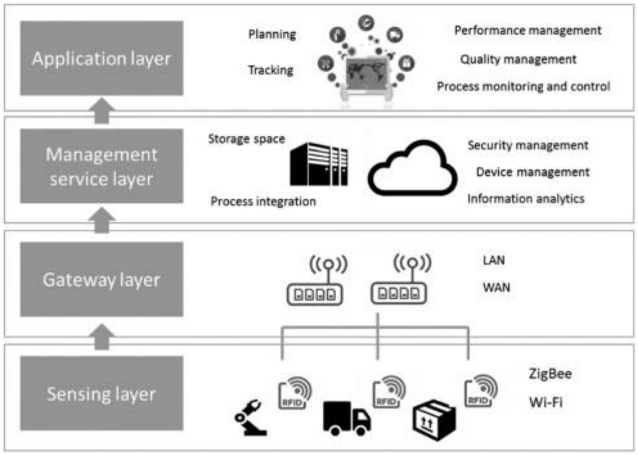
4.1.2 IoT enablers

Part of the literature retrieved analyses the enablers of IoT. Similar to the case of IoT definition, some articles limit their focus to RFID technology, whilst others include a wide range of technologies that enable data collection, transmission and processing. Literature on RFID technology is abundant, as this technology has been applied in the field of SCM for years (Sarac *et al.*, 2010; Zhu *et al.*, 2012). RFID is "a wireless communication technology that can identify specific targets using radio signals and read and write relevant data without mechanical or optical contact between the system and the target" (Yan *et al.*, 2017, p. 2). According to Zhang *et al.* (2013), RFID is the key technology enabling IoT systems. The technology is based on an integrated circuit with an antenna or tag, which can store information. These tags can be placed on different objects along the supply chain to sense their properties. Some tags allow additional information to be written onto them as the tags pass through different parts of the supply chain (Lee and Ozer, 2007). Tag information is retrieved through readers and wireless technology. In contrast to barcodes, readers do not need contact or line of sight to retrieve tag information; hence, the location/orientation of the reader does not matter as long as the tags are within the range of the reader's signal (Delen *et al.*, 2007). In turn, tags can be passive or active. Whilst the former require no internal power and respond to signals emitted by the readers, the latter are self-powered and have the capacity to send out signals to readers, allowing them to be read faster, at greater distances and with less interference (Lee and Ozer, 2007; Yuvaraj and Sangeetha, 2016).

Beyond RFID, Lu (2017) suggests that an IoT system consists of industrial wireless networks (IWN), including machines and equipment, networks, the cloud and terminals. Zhang *et al.* (2013) and Reaidy *et al.* (2015) mention as part of an IoT system technologies such as Wi-Fi, Bluetooth, ZigBee, Embedded devices (RFID or wireless sensor networks) and applications. Dweekat *et al.* (2017) provide further insight into the technology encompassed by IoT, distinguishing four layers of technologies (Figure 2):

1. The sensing or perception layer, which consists of three components:
   - object identification properties, such as RFID tags, or any property of objects that can be sensed (e.g. shape, size, temperature, etc.);
   - reader tools and sensors; and
   - means to create short-area networks, such as Wi-Fi, ZigBee, etc.
2. The gateway and network layer, whose role is to connect objects or things and allow them to share and exchange information. It contains a gateway, an internal network or a local area network (LAN) to connect this second layer (gateway) with the first one (sensing layer) and an external network or wide area network (WAN) to communicate with other networks.
3. The management service layer, which relies on middleware technology that allows data storage and interaction amongst multiple devices and processes

Figure 2 Supply chain IoT architecture



Source: Authors based on Dweekat *et al.* (2017)

running on one or more machines. It is in charge of information analytics, security control, process modelling and device management.

4 The application layer, where collected and transmitted data are saved and processed through certain techniques, and objects or things are managed and controlled.

Similarly, Xu *et al.* (2014) and Ben-Daya *et al.* (2017) suggest that a typical IoT network includes four main essential layers:

1 a sensing layer that integrates different types of "things" like RFID tags and sensors;
2 a networking layer that supports information transfer through a wired or wireless network;
3 a service layer that integrates services and applications through a middleware technology; and
4 an interface layer to display information to the user and that allows interaction with the system.

According to Anusha *et al.* (2017), this tier contains applications for activities such as environment monitoring, service management, information management, technical management and cloud services. In turn, according to Gimenez and Lourenco (2008) and Lin *et al.* (2011), the interface layer includes material requirements planning (MRP), enterprise resource planning (ERP), advanced planning and optimization (APO), warehouse management systems (WMS), customer service management (CSM), e-procurement and e-fulfilment. These applications process data and provide information to make decisions in different SCM processes. For example, MRP facilitates planning, scheduling and inventory control in manufacturing processes. WMS provides data to optimize operations in warehouses or distribution centres. CSM analyses customer data with the goal to improve customer service and assist in customer retention. ERP integrates data on several key aspects in SCM such as purchasing, inventory management, vendor management, sales and financial planning.

4.1.3 IoT impact on SCM

In the field of SCM, there is a large body of literature that discusses the impact of information and communication technologies (ICTs) on supply chain performance. This literature suggests that ICTs can improve supply chain connectivity, which refers to the collaborative electronic linkage of partners up and down the supply chain (Closs and Swink, 2005; Sanders *et al.*, 2011; Calatayud *et al.*, 2016). In turn, connectivity is the critical enabler of supply chain visibility, allowing for the removal of technological barriers amongst supply chain members and the more effective management of supply chain operations (Golicic *et al.*, 2002). Indeed, visibility is defined as the capability of sharing on-time and accurate data considered to be key or useful to operations, throughout the entire supply chain (Caridi *et al.*, 2014; Nooraie and Parast, 2015; Somapa *et al.*, 2018). Likewise, higher visibility leads to enhanced supply chain integration (Brusset, 2016; Gonul *et al.*, 2017), defined as the coordination of operational, logistical and planning data to improve production planning, inventory management and distribution (Li *et al.*, 2009). As stated by Sanders *et al.* (2011, p. 179):

> The very foundations of the supply chain integration concept rest upon the assumption that collaboration takes place between supply chain partners, which is only made possible through bidirectional flows of voluminous rich information, including operations and planning data.

With increased connectivity, visibility and integration, better supply chain performance can be achieved (Fawcett *et al.*, 2007; Nooraie and Parast, 2015; Somapa *et al.*, 2018). Literature on supply chain integration suggests that the higher the degree of integration amongst partners across the supply chain, the better a firm performs (Frohlich and Westbrook, 2001; Song and Panayides, 2008), and that the presence of information technologies and information connectivity is crucial to facilitate integration across the supply chain (Gosain *et al.*, 2004; Song and Panayides, 2008). Amongst the benefits of enhancing connectivity and visibility are better inventory control (Fawcett *et al.*, 2007; Narasimhan and Kim, 2001); shorter order fulfilment lead-times and product development cycles (Erhun and Tayur, 2003; Fawcett *et al.*, 2007); better monitoring of customer behaviour (Fawcett *et al.*, 2007); enhanced capacity to design, monitor and implement logistics plans (Gunasekaran and Ngai, 2004); greater logistics flexibility and improved delivery and logistics assets performance (Closs and Swink, 2005; Gosain *et al.*, 2004); and better risk management (Hiromoto *et al.*, 2017).

As evidenced by these studies, the relationship between ICT and supply chain performance is indirect, as it is mediated by the capability of ICT to increase supply chain connectivity, visibility and/or integration (Li *et al.*, 2009). Wu *et al.* (2016) and Gonul *et al.* (2017) illustrate one way in which this mediated relationship works. Deploying ICTs such as RFID enables tracking and tracing of goods in a supply chain. Through a collaborative platform, such information can be shared amongst supply chain partners in real time. Increased information sharing along the supply chain – in other words, higher connectivity – fosters supply chain visibility, allowing in turn for continuous adjustments to reduce replenishment lead-times, inventory levels, batch size and by improving demand forecasting (Yu *et al.*, 2010; Qrunfleh and Tarafdar, 2014; Wu *et al.*, 2016).

Leveraging on these studies, recent literature on IoT has investigated the specific impact of this technology on supply chain performance. Gnimpieba *et al.* (2015) emphasize that, before IoT, supply chain collaboration was not possible, as the identification, traceability and real-time tracking of goods in supply chains was limited in terms of data availability and systems interoperability. In turn, Ben-Daya *et al.* (2017) specified that what was lacking thus far was not the availability of information but rather the technologies for collecting and processing big data and sharing it with supply chain partners. With IoT, a large amount of information can be collected, transferred, stored and shared in real time. Importantly, supply chain partners can be immediately informed when an event of interest occurs. This information can be accessed through a variety of devices (tablet, mobile phone, notebook PC), enabling real-time operation monitoring and decision-making, especially regarding potential supply chain disruptions (delayed container, infrastructure congestion, etc.) (Ben-Daya *et al.*, 2017). Indeed, automated, real-time object identification is the core value of IoT (Rezaei *et al.*, 2017; Yan *et al.*, 2017). The visibility and traceability enabled by IoT technologies can significantly boost supply chain performance (Gunasekaran *et al.*, 2017; Dweekat *et al.*, 2017; Haddud *et al.*, 2017; Dunke *et al.*, 2018). Specifically, with IoT, each event can be immediately recognized and recorded; supply chain partners have access to all of the generated data; these data improve performance and risk monitoring and inform decision-making towards optimization; decisions are immediately available to all valid parties; and plans are updated and implemented based on the new decisions (Cui, 2015; Dweekat *et al.*, 2017; Gonul *et al.*, 2017; Rezaei *et al.*, 2017). For example, Dweekat *et al.* showed that the use of IoT in dairy supply chains reduced expiry waste percentage between 45 and 75 per cent in milk retailing. This was possible because the expiry date for each product was monitored daily, it was visible to all supply chain members and it improved distribution and demand forecasting with actual daily real-time information, instead of depending merely on the forecasted values using historical data. In turn, Hofmann (2017) showed that the speed of data transmission amongst supply chain partners had the greatest potential to enhance performance by significantly improving inventory management, if compared to data volume and variety. Therefore, the author suggested that, to increase the potential benefit of IoT on SCM, data needed to be captured, processed and transferred as fast as possible.

Empirical evidence on the impact of IoT on SCM is growing. For the most part, studies focus on the use of RFID technology in different processes, nodes and types of supply chains. This is due to the fact that RFID has been applied in the field of supply chain for several years now. Evidence can be found, for example, in Delen *et al.* (2007), Sarac *et al.* (2010), Lozano-Nieto (2012), Reaidy *et al.* (2015), Yan (2017), Yan *et al.* (2017) and Gu (2018). Most of the studies conclude that the information made available through the adoption of RFID technology in a supply chain is critical to improve supply chain operations, through increased visibility and integration between participants. Indeed, the key value from RFID lies not in the technology itself, but on the use supply chain actors make of the information generated. According to Moradpour and Bhuptani (2005), the real value of these data are in leveraging the information to monitor operations performance, discover patterns, ask new questions and make better business decisions.

However, it is erroneous to assume that generating data is all that matters to improve supply chain performance (Wu *et al.*, 2017). Instead, data need to be effectively managed, analysed and fed into models and computer programs to help the decision-making processes (Ben-Daya *et al.*, 2017; Fore *et al.*, 2017). IoT can provide data for two types of decision-making in supply chains: manned or automated (Wu *et al.*, 2017). Most of the literature retrieved refers to decisions made by humans to improve supply chain performance (Haddud *et al.*, 2017). However, IoT may also allow machine-enabled decision-making with minimum or no human intervention (Zhou *et al.*, 2015). Zjim and Klumpp (2015) suggest that the use of IoT to feed intelligent, automated systems will create a revolution in SCM. Similarly, Hofmann and Rusch (2017) propose that the digital dimension of the supply chain – where IoT-generated data will be collected across the entire physical end-to-end supply chain – will provide the critical information for autonomous and self-controlled systems to operate. Finally, Lu (2017) suggests that an IoT system, together with self-optimization and autonomous decision-making mechanism, will increase machine and equipment productivity.

In spite of these potential gains outlined in the literature, studies on the relationship between IoT and autonomous supply chain decision-making are still scarce. The search performed showed that there were only 22 articles combining IoT with autonomous decision-making in SCM. Interestingly, 90 per cent of these studies are conference papers presented between 2016 and 2018, evidencing the novelty and incipient nature of this area. Amongst them, 64 per cent belonged to the field of computer science, 45 per cent to engineering and 32 per cent to business and management (papers could belong to more than one field). Authors' affiliations were mainly located in China, Australia and the UK. Amongst the limited number of articles available, particularly relevant to this study is the work of Wu *et al.* (2017), which explores the combination of different technologies to conceptualize the "smart supply chain". Such a supply chain is characterized by its high degree of cyber-physical interconnection through the use of IoT, which provides data for intelligent, large-scale decisions to optimize performance. In a smart supply chain, most of the processes are automated. Objects can sense the environment and respond to it. Therefore, human intervention is kept to a minimum. Similarly, Rezaei *et al.* (2017) propose a model for supply chain performance monitoring in which IoT-generated data feed decision-making at both the strategic level, performed by human intelligence, and the operational level, which is performed by machine intelligence. Whilst these studies provide a general analysis of and an estimation on how new digital technologies will impact SCM, the majority of the articles identified in our systematic literature review focus on either a specific subject in SCM or a specific type of supply chain. For example, Hiromoto *et al.* (2017) focus on the use of IoT and AI to develop a cyber-secure supply chain risk management architecture. Bogataj *et al.* (2017) and Lu and Wang (2017) suggest that IoT and AI can be used to enhance quality monitoring and improve decision-making in perishable supply chains. Kusiak (2017) discusses the implementation of such technologies in smart manufacturing and the emergence of Industry 4.0. However, to our knowledge, there is currently no comprehensive study in the academic literature on the combined application of IoT and AI in SCM.

4.2 Artificial intelligence and SCM

Together with IoT, AI is the technology most often mentioned in practitioner research as the enabler of the autonomous, predictive supply chain (IBM, 2015; World Economic Forum (WEF), 2017). It is suggested that, in the near future, a variety of algorithms will be used to continuously monitor supply chain performance by analysing quintillion bytes of data generated by objects; forecast and identify risks; and automatically take actions to prevent risks before they materialize (Calatayud, 2017). Together with the large amounts of data generated by IoT, the use of powerful analytical and simulation models will allow the supply chain to predict the future with minimum error and take actions to address any deviation from expected performance (DHL, 2016). Regarding academic literature, the extensive database query we performed resulted, however, in very few articles specifically referring to AI and supply chains. Similar to the case of IoT, most of the studies retrieved were conference papers, evidencing the recent interest and application of these technologies to SCM. Indeed, whilst AI emerged in the 1950s as the science and engineering of making intelligent machines, advances in computer science have only recently made it possible to explore the potential of AI technology (Tatnall and Davey, 2017). Most of the studies retrieved belong to the fields of computer science (82 per cent) and 75 per cent of them were published in the last 10 years. Regarding the geographical location of authors' affiliations, 35 per cent were in the USA, 18 per cent in the UK and 13 per cent in China. It should be highlighted though that, when we explored references cited in the studies retrieved, we found a large body of literature that studied the use of AI on specific supply chain processes or activities, such as transportation, predictive maintenance and demand forecasting (Lee *et al.*, 2011; Bogataj *et al.*, 2017; Cozar *et al.*, 2017; Hill and Bose, 2017; Klumpp, 2017; Yang *et al.*, 2017). Nevertheless, only a handful of these papers refer to AI from a supply chain perspective.

Indeed, Min (2015) shows that, whilst AI has increased, its role in improving managerial decision-making processes, and subsequently enhancing supply chain efficiency by avoiding the sub-optimization of problem solutions, is still marginal. Whilst the author certainly makes a significant contribution in exploring the application of AI to different supply chain processes, the study focuses on one type of AI only: the genetic algorithm. The work of Yeh *et al.* (2016) makes a further contribution to the study of the potential of AI for supply chain global optimization by showing how AI can help reduce operating costs at the supply chain level and enhance customer satisfaction. Merlino and Sproģe (2017) also look at AI from a supply chain perspective and suggest that the use of predictive technologies to model future scenarios will help improve the effectiveness of supply chain operations, whilst at the same time, develop a deeper understanding of the interactions of the various drivers on supply chain performance. However, their work remains at the exploratory level, forecasting that, whilst there is still a long way to go before autonomous transportation is more common, the advent of Industry 4.0 and smart factories all powered by AI and IoT "will make running a supply chain as easy as pushing buttons" (Merlino and Sproģe, 2017, p. 310). Similarly, when discussing the level of AI implementation in supply chain decision-making, Zijm and Klumpp (2015) suggest that unmanned decisions are already being made at some levels in the supply chain such as transportation, where automated vehicles with GPS-based navigation systems decide the route to take whilst interacting with the environment. Aside from transportation, the authors forecast that, in the future, AI applications will lead to automated production systems that will agilely adjust to real-time demand information, as well as to automated logistics systems that will decide to switch supplier when receiving real-time information about supply shortages or disruptions. In spite of these predictions, none of the studies retrieved comprehensively analyses the potential of AI technology for the broader supply chain.

The majority of the papers identified through our systematic literature review focus on more specific aspects of AI applied to supply chains, allowing us to group them in three categories, namely, those papers that apply AI to:

1 increase the capacity to accurately predict demand or maintenance;
2 analyse the potential or the use of this technology in specific supply chains; and
3 explore the types of AI techniques used in the literature to respond to supply chain optimization problems.

These categories are discussed below.

4.2.1 AI and prediction accuracy

Demand forecasts are critical for efficient SCM because they provide firms with the advantage of planning and anticipating for future needs (Slimani *et al.*, 2015). Given that any error in demand forecasting can create significant losses along the supply chain – as traditionally illustrated by the bullwhip effect – research on the use of AI as a forecasting technique is growing. The articles retrieved through the systematic literature review show that, at the supply chain level, research is particularly focusing on testing the application of different AI algorithms to this field; comparing the effectiveness of AI algorithms in demand forecasting, and between AI and traditional techniques; and improving the accuracy of AI for demand forecasting under data constraints (Kochak and Sharma, 2015; Nikolopoulos *et al.*, 2016; Singh and Challa, 2016; Slimani *et al.*, 2016).

The other area where AI is being applied to increase prediction accuracy is asset maintenance. The purpose of this is to reduce and eliminate the number of failures occurring during product use as any breakdown of machine or equipment may lead to disruption for the supply chain (Lee *et al.*, 2016). Whilst there are a large number of studies in computer science that explore this topic, and it would require a separate study to review them all, in this paper, we include examples found in the SCM literature. Lee *et al.* (2016) study AI applications for classifying the likely failure pattern and estimate the machine condition for the faulty component. Susto *et al.* (2015) present a multiple classifier machine learning methodology for predictive maintenance that allows dynamic decision rules to be adopted for maintenance management, and that can be used with high-dimensional and censored data problems. Yang *et al.* (2017) develop a predictive model based on a particle filtering method to increase the accuracy in estimating time to failure, thus enabling "just-in-time" asset maintenance.

4.2.2 AI applied to specific supply chains

Amongst the papers retrieved, some studied the use of AI in specific industries or supply chains. Farahani *et al.* (2016) surveyed the use of this and other digital technologies in the automotive supply chain. Finding that firms in the supply chain were not equipped properly to cope with the opportunities and disruptions coming with those technologies, they provided a recipe for automotive supply chain managers on how to create a digital supply chain management agenda. Guo and Wong (2013), Wong *et al.* (2013) and Nayak and Padhye (2018) analysed the use of different types of AI – e.g. expert systems, neural networks, fuzzy logic and genetic algorithm – in apparel supply chains, as a means to address operational challenges such as variable production volumes and high demand volatility. Abukhousa *et al.* (2014) and Santos *et al.* (2017) explored the application of AI in health-care supply chains and suggested AI-based methods to optimize operations. Similarly, Dellino *et al.* (2017), Lu and Wang (2017) and Fikar (2018) proposed AI-based decision support systems to optimize processes in perishable supply chains. In the case of such supply chains, Lu and Wang (2017) combined IoT and AI technologies to enhance quality control of perishable food products in the cold chain industry. They provided an intelligent solution to ensure product traceability through IoT, and they optimized complex logistics problems such as load planning and route planning with AI.

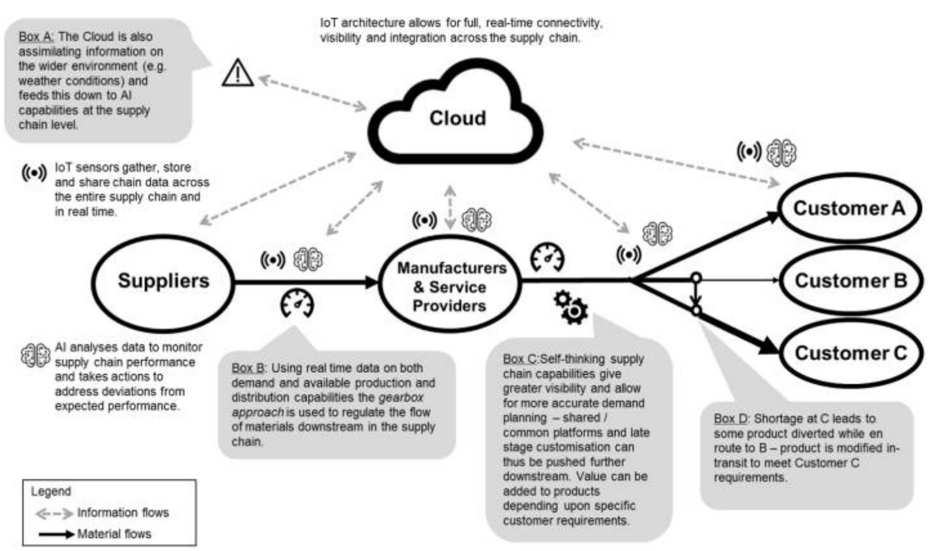
4.2.3 AI techniques and supply chain optimization problems

SCM problems are complex optimization problems. Whilst a wide range of techniques have been applied to solve such problems, traditional mathematical methods have proven insufficient in accurately tackling them (Dounias and Vassiliadis, 2015). Due to recent progress in computer science, AI has emerged as a technology that promises to help overcome optimization problems in SCM. AI comprises nature-inspired algorithms such as genetic algorithms (GA), fuzzy systems, neural networks (NN), ant colony optimization, particle swarm optimization, memetic algorithms, artificial immune systems and DNA computing (Vassiliadis and Dounias, 2009). Amongst these, GA are the most frequently applied to solve supply chain challenges (Icarte, 2016). The reason for this is that GA are mathematically less complex than other AI algorithms, and they can handle different types of functions and constraints (Xu and Ding, 2011). The use of nature-inspired algorithms to solve specific supply chain challenges has been increasing in the last decade, particularly in distribution management, for example, in the cases of the travelling salesman and vehicle routing problems (Mettler *et al.*, 2012; Dounias and Vassiliadis, 2015). Other cases include inventory location, planning and cost minimization, as well as supplier selection problems (Bintrup, 2010; Sinha *et al.*, 2012; Ameri and McArthur, 2013; Kumar *et al.*, 2013; Wang and Wang, 2015). Recent studies have used AI to solve multiple supply chain challenges at the same time. For example, Fikar (2018) developed an AI-based system aimed at reducing cost and food waste in perishable supply chains. For this, the AI-based system works simultaneously on optimizing both inventory management and delivery strategies. With the continuous growth of data availability on supply chain processes and improvement of computational techniques, it is expected that AI will become one of the most critical technologies for SCM over the next few years (Merlino and Sproge, 2017).

5. Towards the self-thinking supply chain

Figure 3 illustrates our proposed model of a self-thinking supply chain set within its wider, information-rich ecosystem. In the self-thinking supply chain, there is a high degree of connectivity between cyber systems and physical objects through the use of IoT. Such IoT technology is ubiquitous through the deployment of sensors, short- and long-range networks and internet-enabled applications. Quintillions of data are generated, stored and analysed through IoT and AI in real time. This enables continuous monitoring of supply chain performance and early identification and management of potential risks. Increased connectivity amongst supply chain partners enabled by IoT, together with AI, allows for more accurate demand forecasting, predictive maintenance and

Figure 3 The self-thinking supply chain



continuous optimization. With AI, decision-making is machine-generated and processes are automated. Objects can sense the environment (through IoT) and respond to it according to AI-made decisions. Changes can be made at the micro level (e.g. at individual nodes in the supply chain) to optimize supply chain wide performance. Efficient, accurate, fast and simultaneously orchestrated responses can, thus, improve supply chain performance in an increasingly complex and uncertain world. Using real-time data on both demand and available production and distribution capabilities, the *gearbox approach* (Mangan and Lalwani, 2016, p. 179) (Figure 3 – Box B) can be used to regulate (speed up/slow down) the flow of materials downstream in the supply chain. For example, in the international clothing supply chain updates on congestion at port container terminals might lead to increased use of (more expensive but faster) air transport for the shipment of time-sensitive fashion items. In practice, managers in such supply chains endeavour to optimize the air–sea distribution mix and self-thinking supply chain capabilities allow them to do this more accurately. Supply chain "control towers" enabled by state-of-the-art digital capabilities are now becoming a more common feature of many global supply chains.

5.1 The self-thinking supply chain can enhance agility

One of the most commonly discussed – and desired – supply chain performance attributes is that of agility. More generally, this capability allows supply chains to respond more quickly to market demand and is a key ingredient in the practice of mass customization. There has been much discussion over the last *circa* 20 years on the role of agility in supply chain strategy. Christopher *et al.* (2006), building upon the work of Fisher (1997) and others, put forward a taxonomy for selecting global supply chain strategies and which uses both predictability of demand for products and replenishment lead-times. Their taxonomy also incorporates lean and agile philosophies as appropriate; they argue that a "one-size-fits-all" approach to supply chain strategy will not work, and that companies need to continually assess their product range and market characteristics so that changing scenarios may be identified and appropriate supply chain designs configured. This is the approach also taken by other authors such as Gattorna (2010) who argues for a dynamic capability in supply chain designs so that they can respond to any changes. He argues against designing supply chains for specific products because different types of demands can, in fact, exist for the same product, even amongst the same customer depending on when and why he/she wants to buy the product. Similarly, Christopher and Holweg (2011) have pointed to the need for structural flexibility and adaptability in supply chain design, given the prevailing volatility and turbulence in the business environment. More recently, Qamar and Hall (2018) investigated the distinctions between lean and agile organizations within the UK automotive sector. Whilst there is ongoing debate around the correct sequencing of lean and agile capabilities/processes/supply chain nodes – there is, nevertheless, an emerging consensus in both the literature and in practice that:

- agile capabilities are a key pillar of many supply chains; and
- lean and agile approaches are not mutually exclusive.

The self-thinking supply chain allows for greater agility, adaptability, flexibility and responsiveness through its ability to act quickly and autonomously. This is especially the case with supply chains dealing with products characterized by short lead-times and unpredictable demand. Harvesting and analysis of data on inventory levels, demand requirements and performance of individual supply chain operations allows supply chains to be leaned as far as possible. The self-thinking supply chain, thus, facilitates the most judicious (optimized) mix of lean and agile supply chain strategies and practices to be pursued. It is notable that, today, many supply chains facilitate mass customization – postponed production strategies allow late stage customization, through a decoupling point, of final products downstream in the supply chain. Key in this regard is deciding where and when to do the final product customization – and this is dependent upon both production capabilities (advances in same are discussed in the next sub-section) and (importantly) clarity of information on customer requirements. With its superior levels of data availability and analysis the self-thinking supply chain allow this decoupling point to be pushed further downstream towards the customer, as there is now greater visibility and clarity around specific demand requirements (Figure 3 – Box C).

The self-thinking supply chain can also improve supply chain risk management (SCRM). There is a growing awareness in recent years (Christopher and Holweg, 2011, 2017; Simchi-Levi *et al.*, 2014) of the impact of volatility and risk on supply chains. The sources of such risk are disparate and well documented. The key requirement is for supply chains now to be able to *sense* and *respond* accordingly – a requirement facilitated by the many capabilities of the self-thinking supply chain and concomitant too with the aforementioned agile supply chain capabilities. In a self-thinking supply chain, weather conditions could, for example, be continuously monitored in real time to assess demand for weather dependent merchandise – e.g. ice cream – thus minimizing the risk of stock outs; similarly, the impact of weather on supply chain operations can be continuously monitored, especially in the case of stretched supply chains with nodes in disparate locations (Figure 3 – Box A).

5.2 The self-thinking supply chain can support additive manufacturing capabilities

According to the OECD (2016), a new production revolution is occurring because of a confluence of technologies – these include digital technologies, new materials and new processes such as synthetic biology. The nature of products that are manufactured is changing, especially with developments in materials science and decarbonization, with a shift evident too to lighter products with a higher value/volume ratio and lower transport cost sensitivity. Some products, of course, have been completely dematerialized (e.g. music CDs replaced by services such as Spotify); more widespread, however, is the trend towards servitization (combining products and services). Aligned with the growth noted above in mass customization is a shift in production capabilities driven in particular by the digital revolution. Direct digital manufacturing (DDM) allows manufacturers to produce parts directly from a CAD file, thus eliminating timelags and investment in tooling, and lowering required production lot sizes (a shift then in focus from economies of scale to economies of scope). DDM takes advantage in particular of additive manufacturing technologies such as 3D and 4D printing (the latter embeds a transformation capability into the product – e.g. heating the product will alter its shape). Aligning this capability with mass customization has heralded the era of the "maker movement" where the consumer becomes part of product design and production (e.g. customers investing in their own 3D printers and "manufacturing" on demand their required products). Consumers, thus, become "prosumers" who both produce and consume their own products; this also cuts down on, for example, the need to carry spare parts and other products that may not be needed. Value add to products in transit may also become more common in the future, e.g. 3D printing of products on-board ships that act as "rolling warehouses" and "floating factories". This allows products to be customized closer to demand (Figure 3 – Box C). In Figure 3 (Box D), notice how material flows can change even when goods are in transit, and such changes may be both autonomous and predicated on analysis of real-time data (e.g. an author is announced as a major book prize winner in a particular country, instantly driving up demand for their book in that market – the supply chain may, thus, automatically divert product to that market without human intervention). Furthermore, the product itself may even change to comply with customer requirements; in a recent review of digitization in the global logistics business, the Economist (2018) magazine, for example, gives an example of consignee labels being printed in transit as new orders arise (in the case of our book example, this then might be labelling individual books, rendering them shelf ready, to accord with customer C's requirements); a (more radical) 4D printing illustration would, for example, be the addition of ingredients to an in-transit product and its further refinement (e.g. cooking) specific to a particular market's requirements. The (widely varying) predictions in both the literature and in media concerning the future potential of 3D and 4D printing are outside the scope of this paper – suffice to note for now that the fascinating changes in production capabilities when combined with self-thinking supply chain capabilities have the potential when used together to radically alter supply chain flows[1].

6. Conclusions

Durach *et al.* (2017, p. 76) suggest that "systematic literature reviews in SCM need to embrace findings that challenge the preconceived picture of the theoretical framework to thus stimulate the development of new or alternative explanations". In this paper, we have put forward a new explanation, a new supply chain model – the self-thinking supply chain. The systematic literature review showed how the supply chain of the future – enabled by developments in ICT (especially IoT and AI) – will be autonomous and have predictive capabilities, bringing significant efficiency gains in an increasingly complex and uncertain environment. This self-thinking supply chain has the potential in particular to help address many of today's key supply chain challenges. We have shown that, whilst it can contribute to the common supply chain strategies, it is especially apposite in the context of the growing demand for agility. The self-thinking supply chain concept may have a significant contribution to make especially in the context of poor and disadvantaged countries. Operating in such environments presents particular supply chain challenges (e.g. availability of logistics services, ability to track and trace freight). A key policy aim of international development organizations is to close the "digital divide" and maximize digital dividends for all (World Bank, 2017). Whilst not underestimating the challenges involved (both technical/ infrastructure and regulatory), it is anticipated that, in the context of the Fourth Industrial Revolution, information systems connectivity will increase at an exponential rate (Calatayud, 2017, p. 11), allowing poor and disadvantaged countries in particular to participate more fully in global supply chains. Once the digital divide amongst such countries is reduced, they will be able to use the various requisite self-thinking supply chain capabilities (e.g. use IoT sensors at ports to locate and thus speed up the flow of containers through their ports, thus enhancing port performance, and in turn, national logistics performance) and participate more fully and more efficiently in global trade. Indeed, it could be envisaged that such countries could quite quickly go from having few supply chain capabilities to having self-thinking supply chain capabilities. A particularly apposite analogy can be found in the telecoms sector: some developing countries had up until quite recently no telecoms infrastructure; however, with the digital revolution rather than build fixed line telephone networks, they jumped instead from having poor telephone networks to building state-of-the-art mobile communications networks, thus neatly jumping one stage of development!.

Although there are limits to what can be included in any one paper, it is important to briefly consider the relevance of an emerging, exciting and most relevant (in the context of the self-thinking supply chain) technology, namely, blockchain. It should be noted that very few publications retrieved through the systematic literature review focused on this technology (DHL, 2016; IBM, 2017). This is likely because this technology is at an early and nascent stage with relevant publications yet to emerge or perhaps still in press. Nevertheless, its potential to address supply chain challenges is very promising. This technology can help create and share information in an immediate, unalterable and transparent fashion throughout the supply chain, without the need to set up costly centralized information sharing systems. By using distributed ledger technology, all of the information shared in the network is stored in each node, making it easier to access and trace transaction history. Any change to the information stored in the distributed ledger must be approved by consensus by all the nodes in the network. Once the change is approved, the information is immediately stored in each node. This makes the system more resilient to failure or targeted attacks. In addition, as blockchain uses cryptography to guarantee the information stored in the distributed ledger, it makes it virtually impossible to alter the information already stored without having the consensus of the nodes in the network (ITF, 2018). This is an important feature to avoid forgery and fraud in the information shared, ensure materials provenance and allow for end-to-end product traceability. For example, together with the use of IoT, real-time sensor-generated information can be encrypted, validated and shared amongst supply chain partners to ensure that the temperature, humidity and quality conditions of materials and products have been unaltered in their flow thorough the supply chain (Kim and Laskowski, 2016).

Finally, the decentralized feature of blockchain eliminates the need for third parties to validate the information shared, which in turn, reduces transaction costs and increases transparency (Iansiti and Lakhani, 2017). In essence then, blockchain capabilities complement and enhance self-thinking supply chain capabilities; combined together, they have the potential, along too with the fascinating changes in production capabilities discussed above, to transform supply chain flows.

The self-thinking supply chain concept will help both practitioners to craft appropriate future-proofed supply chain strategies and provide the research community with a model (built upon multidisciplinary insights) for elucidating the application of new digital technologies in the supply chain of the future. Four immediate streams of further research in this regard can be envisaged, namely:

1. quantifying the benefits of such technology adoption (both specific individual technologies and combined technologies) for supply chain performance in different contexts (geographies, products) – the authors are currently progressing a project in this regard in the context of developing countries in Latin America;
2. designing and calibrating self-thinking supply chain architectures, again for different contexts;
3. investigating the risk of cyberthreats on the self-thinking supply chain; and
4. investigating – from both managerial and policy perspectives – how the self-thinking supply chain alters the locus of control and balance of power in the supply chain; does it give more control to the customer/consignee and/or conversely does the proliferation of data on all aspects of supply chain operations give rise to data privacy issues? (e.g. a customer doing an internet search on a new product discovers it is delivered to their home next day without an order having been placed but with an offer of a discount if they decide to buy it).

The self-thinking supply chain heralds a new and exciting era in supply chain capability. As well as presenting an opportunity for economic and societal benefit, it also presents a fertile ground for further academic research.

Note

1 For more insights into the likely nature of future product flows, see, for example, the work of the UK Government Office for Science *Foresight* projects – www.gov.uk/government/collections/foresight-projects.

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