Impact of Industry 4.0 on supply chain performance

Considering the crucial role Information Technology (IT) plays in achieving performance improvements in business processes, this paper aims to explore the potential impact of the fourth industrial revolution - Industry 4.0 and its associated technological advances on Supply Chain (SC) performance. This study is exploratory research, conducted based on inductive reasoning, which aims to bring new insights into the topic, and to provide forward-thinking for future research. Hence, through conducting a systematic literature review, the paper attempts to explore the impact of Industry 4.0 on SC performance and to conceptualise and develop findings into an operational framework underpinned by Systems Theory. Based on this research, the application of Industry 4.0-enabling-technologies is expected to bring about significant performance improvements in SCM by enabling a holistic approach towards supply chain management resulting from extensive supply chain integration as well as information sharing and transparency throughout the supply chain. Moreover, these technologies allow for huge performance improvements within individual supply chain processes such as procurement, production, inventory management and retailing through enabling process integration, digitisation and automation, and bringing about novel analytical capabilities.

Keywords: Industry 4.0, Internet of Things (IoT), Cyber-Physical Systems (CPSs), Big Data Analytics (BDA), supply chain processes, performance improvement

1. Introduction

Complex and constantly changing business environment and customer demand, and the need for flexibility and responsiveness in organisations are turning the spotlights to advanced technological innovations (Oberg and Graham 2016; Genovese et al. 2014; Lang et al. 2014; Chung and Swink 2009; Jonsson 2000). Organisations have realised the significance of the technological advances and consider technology as a strong strategic weapon for ensuring sustainable performance (Chavarría-Barrientos et al. 2017; Shrivastava, Ivanaj and Ivanaj 2016) and future success (Davenport 2006). Many companies are already applying e-business technologies to streamline their business processes (Sanders 2007), and to improve their operational performance through achieving process integration (Chen and Holsapple 2012; Wiengarten et al. 2013; Srinivasan and Swink 2015). And, now, they are heavily investing in automation and robotics to embrace more advanced technological innovations associated with the fourth industrial revolution - Industry 4.0 (Chung 2015). This industrial revolution has brought about significant benefits in manufacturing, resulting in the creation of smart factories through enabling extensive process integration (Rashid and Tjahjono 2016).

Industry 4.0, as an operational outlook, has been, mainly, discussed from the viewpoint of production in recent literature and industrial papers. However, it is believed that Industry 4.0 and its enabling technologies have the potential to affect every corner of factories and organisations and can bring about significant improvements in managerial disciplines such as supply chain and logistics management (Macaulay, Buckalew and Chung 2015; Baur and Wee 2015; Blau 2014). Particularly, the steady rise in automation of business systems, and the resulting efficiency and productivity benefits, and quality improvements are encouraging organisations to extend Industry 4.0 operational perspective to other organisational areas such as supply chain management (Lopez Research 2014; Redelberger 2014; Schuh et al. 2013). Given the increasingly critical role technology plays in organisational operations, this study, through conducting an explorative and systematic literature review, aims to investigate the impact of advanced technological innovations associated with Industry 4.0 on improving supply chain performance - as one of the greatest challenges in organisations (Neely 2005; Bhagwat and Sharma 2009; Martinez, Pavlov and Bourne 2010; Bititci, Firat and Garengo 2012).

The originality of this study lies firstly in its attempt to provide a comprehensive and consolidated approach towards the application of technological innovations associated with Industry 4.0 in supply chain management. Second, it provides analytical focus, based on systems theory, on the exploration of the impact of the application of Industry 4.0-enabling-technologies on individual supply chain processes and supply chain as a whole, and subsequently, on supply chain performance. Third, it proposes an integrated framework that demonstrates how supply chain performance improvements can be realised through the application of technological innovations associated with Industry 4.0.

2. Research background

This section provides a research background about industry 4.0 and its potential impact on achieving performance improvements in supply chain management, which leads to the development of research questions for the study. This is followed by an analysis of Systems Theory that lays the foundation for the development of the proposed Industry 4.0-based supply chain framework.

2.1. Industry 4.0

Following the first three industrial revolutions provoked by advances in mechanisation, electricity and IT, the introduction of the smart technologies into the manufacturing environment has brought about fourth industrial revolution - Industry 4.0 (Wiengarten and Longoni 2015). Industry 4.0 refers to the decentralisation of business processes brought about by technological advances. It is characterised by technological innovations such as Machine to Machine (M2M) communications, Internet of Things (IoT), Cybe-Physical Systems (CPSs), artificial intelligence and Big Data Analytics (BDA) (Brettel et al. 2014). Industry 4.0 represents a business environment where employees, machinery, devices, and enterprise systems are connected through CPSs and the Internet (Oberg and

Graham 2016). This industrial revolution has enabled smart process management and has provided new paradigms for industrial management (Moeuf et al. 2017). Industry 4.0-enabling-technologies, through integrating information and communication technologies within organisations, have enabled autonomous and dynamic manufacturing (Tortorella and Fettermann 2017; Fatorachian and Kazemi 2018), and through transforming control systems in business operations, have, significantly, improved the nature of products and services provided by organisations (Porter and Hepplemann 2014). Moreover, these technological innovations have enabled "efficient use of resources, making sustainable performance a key feature in smart factories" (Strozzi et al. 2017, p. 6572).

2.2. Supply chain performance

Supply chain performance is one of the challenging themes in supply chain management literature (Neely 2005; Bhagwat and Sharma 2009; Martinez, Pavlov and Bourne 2010; Bititci, Firat and Garengo 2012). Najmi and Makui (2012) measure supply chain performance through analysing flexibility, reliability, responsiveness, quality and asset management. Similarly, Bourlakis et al. (2014) consider performance indicators related to flexibility, efficiency, responsiveness, and quality. In another approach, based on Dreyer et al. (2016), performance improvements can be measured in terms of variety, innovation, time, price and availability.

Information sharing is considered as a key component for managing supply chain relationships and driving the success of supply chain performance (Baihaqi and Sohal 2013). To ensure effective information sharing, companies are investing in technological innovations to develop effective communication channels and collaboration mechanisms and, subsequently, to improve supply chain performance through enhanced information sharing (Govindan, Mangla and Luthra 2017).

A high level of process integration is, also, considered crucial for successful business performance (Gecevska et al. 2012). So, connectivity between various supply chain parties/processes is essential for enhancing supply chain performance (Lee and Whang 2000; Gunasekaran and Ngai 2004; Anand and Goyal 2009). Supply chain integration is critical for effective information exchange and the creation of end-to-end business processes (Chavez, Jacobs and Feng 2017). Enhanced integration can result in performance improvements in terms of cost, quality, variety, and service level (Narasimhan, Kim and Tan 2008).

Another factor that contributes to supply chain performance improvement is flexibility enabled by collaboration/integration throughout the supply chain (Datta 2017). As discussed above, integration can lead to improved collaboration through effective information sharing. This, in turn, can improve operational performance in terms of flexibility and responsiveness (Fawcett, Magnan and McCarter 2008).

Supply chain agility and resilience have, also, significant impact on supply chain performance (Altay et al. 2018) as these factors allow for effective supply chain risk management. Moreover, Enhanced visibility and transparency throughout the supply chain are believed to, significantly, enhance operational performance (Swift, Guide Jr. and Muthulingam 2019).

As supply chain practices cross-functional boundaries, it has been challenging to address the above-mentioned factors and to improve supply chain performance. To deal with this issue many companies have started to apply technological solutions (Najmi and Makui 2012) such as Information Technology (IT). IT, through connecting business systems, can lead to supply chain integration and, subsequently, to enhanced performance (Ruiz et al. 2011; Samaranayake 2013; Rashid and Tjahjono 2016). Many organisations are, already, applying information technologies through E-Business solutions to enhance their integration and operational excellence (Luo, Shi and Venkatesh 2018), and looking for the application of novel and innovative technologies to enhance their process integration and analytical capabilities.

Embedding Industry 4.0-enabling-technologies in supply chain management is considered as a promising strategy for addressing integration challenge, as these technologies are expected to revolutionise supply chain management by bringing about advanced levels of connectivity and comprehensive integration (Kache and Seuring 2017), and lead to huge performance improvements in the supply chain (Shrivastava, Ivanaj and Ivanaj 2016).

Given the potential of Industry 4.0 associated technological innovation on supply chain performance improvements and considering the fact that there is little insight on how performance benefits can be realised throughout the 'Industry 4.0 enabled supply chain', this research aims to explore the following research questions.

1) What are the key enablers of Industry 4.0 and their potential capabilities
2) How can industry 4.0 influence individual supply chain processes and supply chain as a whole
3) What impact improved supply chain processes can have on supply chain performance?

Having investigated the application of the abovementioned technologies in various supply chain processes, researchers attempt to propose an integrated 'supply chain framework' to operationalise Industry 4.0 perspective in supply chain management and to demonstrate how performance improvements can be realised throughout the supply chain.

3. Systems theory

In this study, systems theory is applied for analysing the interconnectivity between the components of a supra-system (individual supply chain processes within supply chain), and for exploring the impact of technological advances on supply chain performance. This provides the basis for literature review and development of a conceptual framework. The following sections (3.1-3.3) explain systems theory and discuss how it is relevant to organizational study, supply chain performance and technology adoption analysis.

3.1. Systems theory and organizations

Competitiveness in organisations depends on the ability to manage internal and external relationships. This requires establishing effective communication channels and information flow mechanisms to allow dynamic interactions with other business systems. Systems theory considers firms as holistic systems with a high level of integration and communication between the system components (individual business processes) that are involved in the value creation process (Grant, Shani and Krishnan 1994). So, based on systems theory, organisations are seen as interconnected processes with a high level of integration and information sharing between business processes. Systems thinking and systemic understanding enables identifying system components (various business processes/parties within the supply chain) and their relationships to each other (Rich and Piercy 2013) and allow for analysing the relationships between organisations and their surrounding environment (e.g. Lawrence and Lorsch 1967; Aldrich 1979). This results in understanding how the elements and components of a system interact and allows for understanding the dynamic behaviour of the system (supply chain in this context) (Oehmen et al. 2009).

3.2. Systems theory and supply chain performance

According to Gorane and Kant (2015), successful supply chain management requires analysing and improving both individual organisations performance and the entire supply chain performance (as a whole). This calls for a holistic approach to supply chain management. As discussed above, systems theory enables investigation of phenomena from a holistic approach (Capra 1997) as it allows for moving from a single firm level to the entire supply chain level, involving many organizations and processes in the supply chain (Mele, Pels and Polese 2010).

Based on this theory, value creation is related to the performance of both subsystems (individual supply chain processes/firms and parties throughout the supply chain) and supra-system (the whole supply chain). In other words, although the connectivity and cooperation within sub-system elements (Alter 2008) including different functions/processes within organisations can improve the supply chain, the whole supply chain excellence requires the integration between all parties/processes in the supra-system (firms involved in the supply chain). The greater integration between subsystems can lead to the creation of an integrative supra-system (end-to-end supply chain), where there is a high degree of information exchange in the value creation process (Mele, Pels and Polese 2010).

3.3. Systems theory and technology adoption

A systems approach allows for an understanding of socio-technical improvements (Waldman and Schargel 2006). Hence, it can allow for analysing the impact of the technological application on business processes. From a technological point of view, supra-system's successful performance requires subsystems' (processes/firms') technological developments and information systems to be aligned and integrated. This can ensure effective connectivity and harmonised information flow, and can, subsequently, lead to performance improvements. In other words, to enable harmonic interactions between processes within the supra system, it is fundamental to consider the technological integration of constituting processes (supply chain processes in this context) (Mele, Pels and Polese 2010).

So, systems theory, through highlighting the impact of connectivity and inter-relationships on supply chain performance allows for analysis of the impact of industry 4.0-enabling-technologies on subsystems (individual supply chain processes/firms involved) and can enable investigating the impact of their potential capabilities on supply chain (supra system) performance improvement. In other words, this theory can help analyse how advanced technologies enable extensive integration between individual supply chain processes and throughout the supply chain (supra system), and lead to potential improvements in supply chain performance (Wiengarten and Longoni 2015; Blome, Paulraj and Schuetz 2014; Xu 2011).

The rest of the paper is structured as follows. After the methodology and research process discussion, Industry 4.0 and its enabling technologies are discussed. This addresses the first research question. Secondly, key technological innovations' capabilities and their impact on supply chain management are explored. Third, the impact of Industry 4.0 perspective on individual supply chain processes are analysed. Finally, following the presentation and synthesis of key findings, a framework is proposed to demonstrate how performance improvements can be realised in the supply chain (research question 3).

4. Research methodology

This study is conducted based on exploratory research that through inductive reasoning aims to identify patterns and relationships (Hair and Sharpe 2015) between Industry 4.0

and performance improvements in SCM, and, through the development of a conceptual framework, attempts to make new contributions towards knowledge and emergence of new theories in supply chain discipline. As studies involving inter-organisational relationships are better studied in ways that generate qualitative data and allow for explorative and interpretive analysis (Maanen 1998), this study aims to use qualitative and explorative research paradigms to discover new approaches that will lead to potential business opportunities (Zikmund et al. 2013) in regards with supply chain performance improvements.

Exploratory research focuses on new topics on which little research has been carried out (Brown 2006), and aims to bring new insights into the topic and to provide forward-thinking for future research and investigation (Saunders, Lewis and Thornhill 2012). In this study, exploratory research is used to explore innovative business ideas for addressing performance improvement challenges throughout the supply chain, and to provide further insight into the impact of industry 4.0 on supply chain management.

Given the limited scope of research in this area, exploratory research is expected to bring new and valuable insights into the performance improvement challenge in supply chain management.

4.1. Research process

For this study, a systematic literature review was carried out to provide a better understanding of the research topic (Burgess, Singh, and Koroglu 2006). It is argued that this method, through enabling an evidence-based approach and identifying key scientific contributions to the field or research question, can provide valuable decision-making support for practitioners (Tranfield, Denyer and Smart 2003). Systematic literature reviews allow for capturing the state of research in the field through enabling the systematic synthesis of available studies. This method enables extracting findings from various studies to offer novel and more comprehensive understanding of phenomena being studied (Touboulic and Walker 2015). Hence, a systematic literature review can provide a comprehensive approach to map out the capabilities brought about by Industry 4.0-enabling-technologies and their impact on supply chain processes. Moreover, a systematic review method allows for developing a conceptual research process that can lead to creating a framework for the assessment of/analysis of novel and innovative research topics (Harden 2008).

The systematic review process in this study started with a scoping study (Phase 1 in Figure 1) to assess the relevance of the literature and to allow for the development of a conceptual basis for analysis of the research problem. It, also, helped with the identification of keywords and search terms, and allowed the researchers to decide on the search strings most appropriate for the study (Tranfield, Denyer and Smart 2003). To ensure including all the studies relevant to the research questions, a comprehensive search strategy was developed. So, for searching papers two categories of keywords and all possible combinations between them were used:

1. Supply chain management, supply chain processes, supply chain performance
2. Industry 4.0-enabling-technologies, technological innovations

Relevant categories of journals in ABS journal ranking list 2015 were used to identify appropriate journals for exploring research questions (please see Table 1). Then the identified Journals' database/websites were used for finding papers relevant to the research topic. Limiting the search to high-quality journal articles (mainly 4*, 4 and 3) enabled achieving control over the quality of the papers. Moreover, only six industrial reports which were produced by well-known research organisations, and could bring valuable insight to the research topic were considered in the literature review process (e.g.

Acatech, DHL and Cisco, Mckinsey). To ensure inclusion of all relevant supply chain performance literature, no restriction was made to the date of published articles, however, given the fact that Industry 4.0 is a new topic, most of the articles related to this area were published in the last decade. Primary research led to identifying around 160 papers. Initial screening (Phase 2 in figure 1) was done based on the relevance of the papers to research questions/objectives and based on the following two key criteria, leaving 128 papers in total.

1. Whether the paper looks at 'Industry 4.0 and the capabilities brought about by its enabling technologies' or 'supply chain processes/supply chain performance'
2. Whether the impact of applications of innovative technologies is relevant to supply chain improvements.

This was done by both reviewers to ensure the validity and reliability of the research process (Tranfield et al. 2003). A list of selected journals is provided below.

Table 1: List of selected journals

Journal categories in ABS ranking list, 2015 (mainly 3,4,4*)	**Information management**	**Operations and technology management**	**Operations research and management science**	**General management, ethics and social responsibility**	**Other journals**
Journals names and number of papers selected from them	MIS Quarterly (2) Expert Systems with Application (1) Information Systems Research (1) Industrial Management & Data Systems (2)	Supply Chain Management: An International Journal (6) Journal of Operations Management (4) International Journal of Production Economics (13) Production Planning & Control (29)	Management Science (1) Annals of Operations Research (2) Decision Sciences (2)	MIT Sloan Management Review (1) Harvard Business Review (3) British journal of management (2) Business & Society (1)	IBM System Journal (1) International Journal of Science, Engineering and Technology (1) Research Policy (1) The International Journal of Advanced Manufacturing Technology (1)

	Journal of strategic information systems (1) Decision Support Systems (2) Information Management & Computer Security (1)	Production and Operations Management (8) Computers in Industry (3) IEEE Intelligent Systems and Their Applications (1) International Journal of Operations & Production Management (7) International Journal of Production Research (10)		Journal of Business Ethics (1)	Sustainable Production and Consumption (1) Productivity Management (1) International Journal of Industrial Engineering and Management (1) Sensors (1) Journal of Management (2) Production Engineering (1) International Journal of Distributed Sensor Networks (1)

		Journal of Supply Chain Management (4) Journal of Business Research (2) Journal of Intelligent Manufacturing (1) International Journal of Technology Management (1) Journal of Business Logistics (2) Service Science (1)			Business and Society Review (1)
Total: 128	10	92	5	8	13

Selected papers were categorised in Mendeley based on their key theme and relevance to research questions.

The stage model (Thomas and Harden 2008) was applied for the analysis of literature. First, articles were coded (Phase 3 in Figure 1) based on the key themes and contribution to the research question/objectives. So, having identified key enabling technologies, the coding for the analysis of the impact of Industry 4.0 on the supply chain was done based on capabilities brought about by Industry 4.0 associated technological innovation. Similarly, for investigation of the impact of Industry 4.0 and its enabling technologies on individual supply chain processes, coding was done based on four main supply chain processes of procurement, production, logistics, and retailing, and operational improvements within them. The coding provided the basis for the development of descriptive themes/constructs (stage 2). This procedure was applied for both identifications of key technological enablers, their capabilities, and their impact on the supply chain. The data were extracted and organised/grouped in the same way for analysis of the impact of technologies on individual supply chain processes. The data were further analysed through thematic analysis (Phase 3 in figure 1) to develop analytical themes/constructs through interpretation (stage 3). Thematic analysis refers to the process of formulating and developing themes in qualitative research. It aims to identify patterned meaning across a dataset to address research questions being explored (Longhofer, Floersch and Hoy 2012).

Finally, through thematic synthesis (Phase 4 in Figure 1) and based on systems theory principles, the relationship and connections of the identified themes was, conceptually, modelled in a framework (Phase 5 in Figure 1) to create a meaningful whole out of the findings and to provide a theoretical conception of supply chain performance.

The Research process is illustrated in Figure 1. And, the category of coding and constructs identified are provided in Table 2 and Table 3.

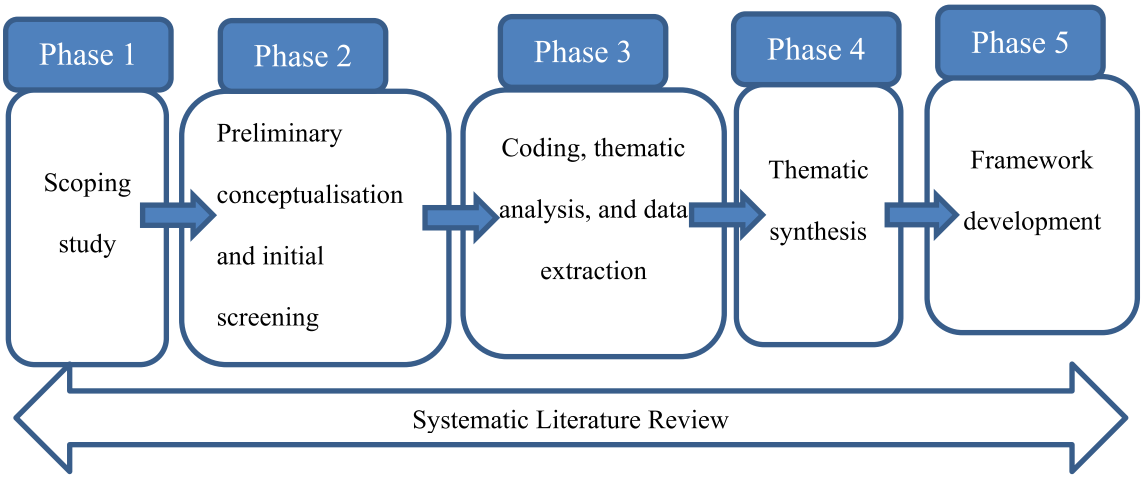


Figure 1: Research Process

The credibility was ensured through briefing sessions which were aimed at improving the analytical process through refining the researchers' ideas and interpretations. These sessions, in which data analysis procedure including conceptualization and thematic analysis and synthesis were discussed continually between the authors, helped with enhancing credibility through ensuring that categorization of themes and interpretation of research findings were done correctly. The researchers, also, addressed dependability through having an explicit research strategy with clear and comprehensive research strings, reliable database, explicit inclusion criteria, and a clear appraisal process. Study characteristics and the context in which the findings were derived were described, and studies were categorised based on their relevance to the research questions. Moreover, the concepts and themes emerging from the findings were clearly explained. These allowed for transferability and assessing the extent to which the results can be applied to the study context. Finally, confirmability was ensured by linking the contributions of each study to the findings (in terms of the identified concepts/themes) (Schloemer and Schröder-Bäck 2018).

5. Key industry 4.0-enabling-technologies

CPSs, IoT, BDA and Cloud technologies are considered as main drivers of Industry 4.0. In industry 4.0 enabled environment, integration and networking of smart embedded systems with each other and with the Internet have resulted in the merging of the cyberspace and the physical world, generating CPSs (Kagermann et al. 2013). CPSs are smart systems that combine communication and computing capabilities with physical and engineering systems. They include a set of cyber and physical resources that are aimed at accomplishing a set of defined tasks (Poovendran et al. 2012). CPSs, as one of the key drivers of Industry 4.0, can connect physical and virtual world through enabling high level of connectivity between software and hardware (Leitao, Colombo and Karnouskos 2016; Stojmenovic and Zhang 2015), and can lead to advanced communication between humans, machines, processes and products (Babiceanu and Seker 2016; Einsiedler 2013). In a CPS, computing elements enable communication with sensors and actuators. This allows for the connectivity of all distributed intelligence in the environment. An example of CPS is a smart production line with an intelligent machine capable of performing many work processes through communication with components (Fatorachian and Kazemi 2018).

IoT, as another key enabler, defines a global environment where the Internet is the centre of connectivity for all the connected and intelligent devices, processes and systems. This technological innovation, as an extension of the Internet, is characterised by a world of ubiquitous connectivity in which smart and Internet-enabled objects constantly communicate and feedback valuable information to support decision making (Brousell, Moad and Tate 2014). IoT allows for integrating smart technologies such as sensors, actuators, and other intelligent systems (Uckelmann, Michahelles and Harisson 2011), and, through transforming organisations and entire industries, is providing a novel paradigm in business operations (Agrifoglio et al. 2017). This is enabled by cloud computing, which, through the convergence of technologies such as networking, computing, and management systems, has provided a paradigm shift in the management of information systems (Helo and Hao 2017). The cloud computing technologies allow for borderless information sharing and accessibility (Harris, Wang and Wang 2015), and, through the application of computing tools, provide significant analytical capabilities for organisations. The computing and analytical power offered by high tech computers has resulted in the generation of BDA and has created a great platform for analysing big data generated from IoT (Zhong et al. 2015; Roden, Nucciarelli and Graham 2017; Song, Du and Zhu 2017).

Table 2: Definition of Industry 4.0-enabling-technologies

Enabling technology	Definition	Author/s examples
Cyber-Physical Systems (CPSs)	Smart systems combining communication and computing capabilities with physical and engineering systems and allow for connecting the physical and virtual world through enabling a high level of connectivity between software and hardware.	Poovendran et al. 2012; Leitao, Colombo and Karnouskos 2016; Stojmenovic and Zhang 2015
Internet of Things (IoT)	A global environment where the Internet is the centre of connectivity for all the connected and intelligent	Brousell, Moad and Tate 2014; Uckelmann,

	devices, processes and systems, which allows for integrating smart technologies such as sensors, actuators, and other intelligent systems.	Michahelles and Harisson 2011
Cloud Computing Technologies (CC)	Refer to the convergence of networking, computing, and management systems, which provide a paradigm shift in the management of information systems and allow for borderless information sharing and accessibility and, through the application of computing tools, provide significant analytical capabilities for organisations.	Helo and Hao 2017; Harris, Wang and Wang 2015
Big Data Analytics (BDA)	Use of computing and analytical power offered by high tech computers and advanced analytic techniques against very large, diverse data sets	Zhong et al. 2015; Roden, Nucciarelli and Graham 2017; Song, Du and Zhu 2017

6. Findings/Data analysis

The following information was extracted from the categorised literature to develop a basis for thematic synthesis and development of the conceptual framework.

6.1. The potential impact of Industry 4.0-enabling-technologies on supply chain management (as a whole/ holistic entity)

To successfully implement Industry 4.0 perspective, companies need to be prepared to adopt required technological innovations (Brettel et al. 2014; Nelissen and Schip 2014) and to understand their capabilities and potential benefits in business processes. The following section aims to explore Industry 4.0-enabling-technologies and their functionality and potential impact on supply chain management. The thematic analysis results are structured according to four key enablers of Industry 4.0 to explore their impact on supply chain performance through the identification of their capabilities.

6.1.1. Cyber Physical Systems (CPSs)

CPSs, through enhancing communication and information sharing, can result in more seamless and flexible operations (Oberg and Graham 2016; Chung 2015; Anand and Ward 2004; Jonsson 2000). The high level of connectivity enabled by the application of these systems can, also, lead to enhanced decision making by enabling real-time data collection from machines, processes, and business environments (Bi, Xu and Wang 2014). Similarly, based on Zhong et al. (2015), CPSs, as one of the main drivers of Industry 4.0, can allow for the automatic and real-time acquisition of data from different points throughout the supply chain, leading to optimised decision making.

Enhanced connectivity and automation, resulting from improved information sharing, can have a significant impact on supply chain performance (Wiengarten and Longoni 2015; Blome, Paulraj and Schuetz 2014; Strozzi et al. 2017). For instance, CPSs, through enabling a high level of integration and information exchange, can enable a better understanding of requirements of different parties throughout the supply chain and can enhance collaboration and cooperation between them. This can, subsequently, enhance the decision making and responsiveness in supply chain processes (Redelberger 2014; Chung and Swink 2009; Upton 1995), leading to improved product delivery and customer satisfaction.

6.1.2. Internet of Things (IoT)

IoT has already penetrated in some parts of the supply chain and is expected to revolutionise supply chain and logistics management by bringing advanced visibility into operations (Kache and Seuring 2017; Qiu et al. 2015). IoT intelligence can be embedded in products and processes, and manufacturing, inventory, and logistics infrastructure. Thus, in IoT-enabled-environment almost all objects including products, machinery, and devices, have sensors and are connected to each other and to the Internet (Macaulay, Buckalew and Chung 2015). The advanced level of connectivity, through enabling real-time access to information, can lead to advanced visibility (Kache and Seuring 2017), and significantly enhance supply chain management (Wamba et al. 2015).

Business opportunities provided by IoT are expected to be enormous (Thramboulidis and Christoulakis 2016). For example, IoT and its enabling technologies such as RFID can allow for developing self-monitoring capabilities where machines and devices can monitor and communicate their real-time performance (Harris, Wang and Wang 2015; Brousell, Moad and Tate 2014; McKelvey, Wycisk and Hülsmann 2009). IoT can, also, allow for flexibility at the process level (Oberg and Graham 2016), enabling a high level of responsiveness and proactivity. Moreover, IoT can enable advanced automation by integrating intelligent devices, systems, and production processes, and by enabling their connection to the Internet (Thramboulidis and Christoulakis 2016; Li et al. 2016; Thramboulidis 2015; Lopez Research 2014). Enhanced automation can, in turn, lead to improved productivity, efficiency and quality control (Chung 2015; Yu et al. 2015), improving operations throughout the supply chain.

6.1.3. Big Data Analytics (BDA)

BDA can revolutionise supply chain management (Waller and Fawcett 2013) by enabling the quick realisation of business value in organisations. These technological innovations, through quick and advanced analysis of data, can provide insights for substantial performance improvements within supply chain processes (Wamba et al. 2017; Nelissen and Schip 2014; de Oliveira, McCormack and Trkman 2012; Trkman et al. 2010). Similarly, Davenport (2006), Hazen et al. (2014) and Gunasekaran et al. (2017) argue that big data analytics can enable simultaneous and systematic data collection and analysis, optimising supply chain performance and leading to a competitive advantage. These analytics, through enabling real-time data stream analysis, can result in dramatic improvements in real-time problem solving and cost avoidance (Li et al. 2016; Lopez Research 2014; Waller and Fawcett 2013). This can have great implications for supply chain resilience and risk management. Big data processing tools can, also, provide valuable opportunities in terms of proactive maintenance and automation (LaValle et al. 2011), and, through improving operations and process reliability, can help supply chains to develop and deliver superior qualities that can be a source of competitive advantage (Akter et al. 2016; Wamba et al. 2015). As BDA allow for a real-time focus and simultaneous analysis of multiple data streams, they can result in the generation of valuable information for forecasting and planning future actions and behaviours (Li et al. 2016; Zhong et al. 2015). This is done through BDA developing behavioural patterns out of data analysis (Li et al. 2016; Shmueli and Koppius 2011), which results in the creation of detailed frameworks that allow for the identification of correlations between operational variables. These competencies can, significantly, enhance decision making and planning throughout the supply chain (Wamba et al. 2015; Banker 2014; Kagermann et al. 2013). Similarly, Guo et al. (2015) and LaValle et al. (2011) argue that in data-driven business environments, BDA can significantly improve supply chain and logistics decision making by enabling advanced data analysis. For example, companies can develop predictive models based on BDA to help with identifying the most profitable customers (Shmueli and Koppius 2011; Davenport 2006) and to enable a better understanding of their requirements (Mishra et al. 2016a). This, subsequently, can improve order acceptance decision making and allow for better planning throughout the supply chain (Gunasekaran et al. 2017; Schoenherr and Speier-Pero 2015).

6.1.4. Cloud computing technologies

Cloud computing technologies, through enabling borderless information sharing and accessibility, allow for the transmission of enormous amounts of information between different parties in the supply chain (Harris, Wang and Wang 2015). These technologies can form new enterprise-wide communication platforms and new forms of collaboration and coordination (Helo and Hao 2017; Akter et al. 2016), enabling high level of integration and real-time information sharing (Shamsuzzoha et al. 2016; Rashid and Tjahjono 2016; Chen and Deng 2015; Nelissen and Schip 2014; Koh, Gunasekaran and Rajkumar 2008). Cloud technologies can, also, enable remote communication of products, devices, and systems, and can allow for data generated in multiple processes and systems to be transferred to central data stores for subsequent aggregation and analysis (Brousell, Moad and Tate 2014). In other words, cloud systems can provide high storage capacity and high-speed computing, enabling quick and independent access to data from any location (Schuh et al. 2014; Hilbert and Lopez 2011). Considering the significant impact of responsiveness and visibility in supply chain management, this capability can provide significant support for decision making and planning (Helo and Hao 2017; Babiceanu and Seker 2016), and lead to reduced bullwhip effect in the supply chain (Tan et al. 2017).

Following the analysis of key technologies enabling Industry 4.0, the summary of key capabilities brought about by Industry 4.0-enabling-technologies and their impact on the supply chain are provided in Table 3.

Table 3: Key capabilities brought about by Industry 4.0-enabling-technologies and their impact on supply chain

Key enablers	**Capabilities (Descriptive themes)**	**The potential impact on supply chain performance (Analytical themes)**
CPSs	• Connectivity between software and hardware (Leitao, Colombo and Karnouskos 2016) • Advanced communication between machines and systems (Babiceanu and Seker 2016; Einsiedler 2013) • Enhanced information sharing/data exchange (Chung 2015; Anand and Ward 2004; Jonsson 2000) • Real-time and automatic data collection from machines, processes, and business environments throughout the supply chain (Zhong et al. 2015; Bi, Xu and Wang 2014)	• A better understanding of the requirements of different parties • Enhanced collaboration and cooperation • Enhanced decision making • Seamless and flexible operations • Improved responsiveness
IoT	• Ubiquitous connectivity between smart and Internet-enabled objects and systems (Macaulay, Buckalew, and Chung 2015)	• Improved decision making

	• Constant communication (Brousell, Moad and Tate 2014) • Advanced visibility into operations (Kache and Seuring 2017; Qiu et al 2015) • Self-monitoring capabilities (Harris, Wang and Wang 2015; Brousell, Moad, and Tate 2014; McKelvey, Wycisk and Hülsmann 2009) • Advanced automation (Thramboulidis and Christoulakis 2016; Li et al. 2016; Thramboulidis 2015; Lopez Research 2014)	• Monitoring and communicating real-time performance • Improved responsiveness and proactivity • Improved productivity, efficiency and, quality controls • Flexibility at the process level
BDA	• Simultaneous and systematic data collection and analysis (Davenport 2006) • Real-time data stream analysis (Li et al. 2016; Lopez Research 2014; Waller and Fawcett 2013;) • Providing valuable insights into operations (Nelissen and Schip 2014; de Oliveira, McCormack, and Trkman 2012; Trkman et al. 2010) • Proactive maintenance (LaValle et al. 2011)	• Performance improvements • Real-time problem solving • Developing superior qualities • Improved forecasting and planning • Developing operational frameworks and predictive models • Enhanced decision making and planning
Cloud computing technologies	• Borderless information sharing and accessibility (Shamsuzzoha et al. 2016; Rashid and Tjahjono 2016; Harris, Wang and Wang 2015; Chen and Deng 2015; Nelissen and Schip 2014) • High storage capacity and high-speed computing (Babiceanu and Seker 2016; Schuh et al. 2014; Hilbert and Lopez 2011)	• Enhanced collaboration and coordination • Enhanced integration • Quick and independent access to data from any part of the supply chain • Improved decision making and planning

6.2. *Impact of Industry 4.0 perspective on supply chain processes*

Key themes derived from stage 2 of the analysis were categorised and explained based on four key supply chain processes of production, procurement, logistics and retailing to allow for analysing the impact of Industry 4.0-enabling-technologies on their performance improvements.

So, having investigated the key enablers of Industry 4.0 and their functionality and impact on supply chain performance, in this section their impact on various supply chain operations is discussed to discover their potential benefits on individual supply chain processes.

6.2.1. Product development and production

The machine-to-machine and networked communications in industry 4.0-enabled-environment can result in the generation of smart factories and fully automated production systems (Fatorachian and Kazemi 2018). The high level of automation can, subsequently, lead to improved operational performance (Nevo and Wade 2011) and enhanced production efficiency and productivity (Leitao, Colombo and Karnouskos 2016; Chung 2015). Additionally, according to Jung et al (2016), Industry 4.0 can have a great impact on product design and development. For instance, integration of production systems and advanced design software in smart factories can enable visualisation and simulations of operations (Rashid and Tjahjono 2016), and can, significantly, improve product design/development and production processes.

Industry 4.0 perspective, through generating analytical and proactive capabilities, can allow for better analysis of demand patterns and fluctuations, and can significantly improve production planning and control (Li et al. 2016; Zhong et al. 2015). In addition, intelligent production and supply chain planning systems can consider constraints such as the capacity of machinery and changeover times to create optimised supply chain and production plans (Banker 2015; Huang et al. 2008).

Industry 4.0 perspective, through enabling transparency and integration, can enable a high level of flexibility and rapid implementation of individual customer requirements (Fatorachian and Kazemi 2018; Helo and Hao 2017; Oberg and Graham 2016). For example, technological innovations such as CPSs and IoT can bring about high level of visibility and connectivity between manufacturing and supply chain processes, and through enabling real-time information sharing and cooperation, can allow for responsiveness and rapid customisation and tailoring products to individual or local levels (Park et al. 2016; Brettel et al. 2014). Real-time information sharing can, also, result in developing a collaborative design (Shamsuzzoha et al. 2016), which in turn, can ensure product quality.

Furthermore, as in industry 4.0 enabled environment machines have self-controlling capabilities, they will be able to detect variations in production or assembly performance, for example, based on the dispatching speed of items in the assembly line (Chung 2015). This capability can allow for the identification of problems in production processes and can enable taking quick corrective actions to ensure product quality (Chung 2015; Brousell, Moad and Tate 2014).

Other Industry 4.0-enabling-technologies such as BDA can allow for supply chain innovation by enabling the integration of innovation competencies and resources throughout the supply chain (Tan et al. 2015). This can influence product development and innovation by enabling the integration of supply chain innovation perspective with internal Research and Development (R&D) view (Oberg and Graham 2016; Christensen, Olesen and Kjaer 2005), and can, consequently, lead to generating world-class production plans (Dubey et al. 2016). Similarly, according to Lang et al. (2014), effective information sharing, resulting from a high level of supply chain integration in Industry 4.o enabled business environments, can, significantly, enhance product innovation and development.

Moreover, improved supply chain visibility, resulting from the application of smart technological innovations such as IoT and BDA, can lead to quick product design and reduced prototyping lead time, and can, significantly, improve innovation cycle time (Kache and Seuring 2017; Tan et al. 2015). For instance, digital-to-physical transfer capabilities in Industry 4.0, such as 3D printing, which is enabled by cyber-physical connectivity, can allow for rapid prototyping and reduced time to market (Burnes and Towers 2016). As an example, this technology has enabled Local Motors Company to make new car models in a year compared to the industry average of six years (Baur and Wee 2015). Besides improving responsiveness, 3D printing can eliminate the inefficiency associated with individual item production and their physical transportation, since products can be, easily and efficiently, designed and produced (Nelissen and Schip 2014).

6.2.2. Fulfilment, procurement, and logistics

The transparency and integration resulting from the application of Industry 4.0-enabling-technologies can lead to effective order fulfilment management (Chen and Deng 2015; Guo, Li and Zhang 2014) by enabling enhanced information sharing and responsiveness throughout the supply chain. For example, cloud technologies can improve order fulfilment process by enabling real-time information access and enhancing communication and responsiveness throughout the supply chain (Harris, Wang and Wang 2015). Real-time information access can, not only, improve visibility and communication, leading to enhanced responsiveness and reduced inefficiencies through eliminating bullwhip effect (Tan et al. 2017), it can, also, enable disintermediation allowing for fewer transactions and transportation, thereby improving environmental impact through reducing fuel consumption and gas emissions.

Furthermore, CPSs and IoT can improve procurement and supplier relationship management by bringing visibility and improving decision making about supplier selection and purchasing process (Chung 2015; Qiu et al. 2015: Kagermann et al. 2013). Enhanced and effective purchasing can, subsequently, lead to pursuing sustainable supply chain practices (Paulraj 2011). For example, real-time information access and visibility can allow for periodic auditing of the suppliers, and ensure compliance of their performance with sustainability priorities, leading to improved supplier relationship management (Mani et al. 2015).

Moreover, IoT and CPSs within logistics including embedded intelligence in products, cities and infrastructure such as vehicles and mobile equipment (Redelberger 2014) can influence logistics management by bringing about productivity and efficiency improvements (Qiu et al. 2015; Macaulay, Buckalew and Chung 2015; Reinhart et al. 2013; Schuh et al. 2013). For instance, the embedded cyber-physical intelligence such as RFID tags and sensors can be applied in logistics management to enhance visibility through enabling monitoring and tracking capabilities (Hassan et al. 2015; Chung 2015; Modrak and Moskvich 2012; Amini et al. 2007). RFID technology can, particularly, enable real-time traceability and interoperability of resources, leading to improved planning and controlling (Hassan et al. 2015; Qiu et al. 2015: Zhang et al. 2011). Moreover, greater information availability, enabled by BDA and cloud-based systems, can significantly enhance tracking and tracing of products throughout the supply chain (Kache and Seuring 2017; Modrak and Moskvich 2012), leading to enhanced product availability, responsiveness and demand fulfilment. Besides having tractability implications, enhanced visibility and monitoring capabilities can lead to ensuring product quality through improving product flow throughout the supply chain. For example, a combination of cameras, sensors, and actuators can be used in vehicles/trucks to identify driver fatigue - for instance through monitoring of blinking frequency -, and to create alerts by activating seat vibration and voice alarms (Macaulay et al. 2015). This, by reducing accidents and collisions, can result in ensuring product integrity and quality, and reduced product waste as well as environmental damage.

Technological innovations such as BDA can, also, optimise freight transportations, as one of the main processes in logistics operations, by enabling supply chain integration and advanced information exchange (Harris, Y. Wang, and H. Wang 2015). Furthermore, efficient navigation and traffic congestion detection resulting from the application of IoT and CPSs can significantly improve distribution and logistics management by identifying the most appropriate routs and can lead to enhanced product safety, quality and speed of delivery (Bishop 2000). This capability can, also, significantly impact fuel consumption and emission of gases unfavourable to the environment (Banker 2014). Additionally, real-time information about traffic and product location can enhance product delivery and dependability by predicting possible delays and disruptions (Kache and Seuring 2017).

6.2.3. Inventory management

Sensors and RFID tags together with central and cloud-based systems can create remote positioning methods, and indoor/outdoor GPS-based systems (Redelberger 2014). This capability is expected to have a huge impact on inventory and distribution management by enabling advanced control over the movement and status of products throughout the supply chain (Zhong et al. 2015). For example, RFID tags attached to the products can result in the creation of smart inventory and allow for inventory to be aware of their destinations in their journey (Banker 2015; McKelvey, Wycisk, and Hülsmann 2009). This capability can significantly improve product distribution and delivery, and through enabling advanced control over product movement, can lead to enhancing all dimensions of sustainability. Moreover, the integration of RFID tags with inventory management systems can enable accurate inventory planning and control by bringing advanced visibility to inventory levels. This, in turn, can enhance inventory management by preventing costly out of stock situations and improving responsiveness and customer satisfaction (Quesada et al. 2008). The informed inventory decision making, resulting from real-time visibility of inventory, can consequently lead to increased operational efficiency (Hassan et al. 2015; Devaraj, Krajewski, and Wei 2007) and enhanced effectiveness.

Additionally, a combination of RFID tags and management systems in warehouses can enable processing large volumes quickly and efficiently (Chung 2015; Ranasinghe, Sheng, and Zeadally 2010). For example, during inbound and outbound delivery, cameras attached to the gateways can capture the data transmitted from RFID tags attached to the product, and through integration with warehouse management systems, can update information about pallets and items. This capability can, also, eliminate the time-consuming task of manually counting of pallets and products, leading to enhanced efficiency, and economic sustainability (Macaualay 2015).

The other key benefit of Industry 4.0-enabling-technologies such as CPSs and IoT in inventory and warehouse management is predictive/preventative maintenance. This capability, through foreseeing and preventing potential technical issues, can enhance machinery, equipment and device reliability, and lead to improved performance and enhanced efficiency (Gunasekaran et al. 2017; Waller and Fawcett 2013; LaValle et al. 2011). This, consequently, can result in improved responsiveness by reducing unexpected failures and disruption (Hu and Kostamis 2015; Koh and Saad 2006). For example, in warehouses, sensors attached to sorting machines can identify the levels of physical stress by measuring machines' temperature. This information can, subsequently, be integrated with analytics to enable scheduling maintenance appointments. The analysed data can, also, be used to calculate the expected lifetime of machines, and to predict and prevent potential failures and disruption (Chung 2015).

Furthermore, human-machine communication capability in the Industry 4.0 environment enabled by IoT, can have a significant impact on inventory management (Qiu et al. 2015). For example, picking technology developed by Knapp AG (warehouse logistics solutions) allows pickers to track and locate items precisely and quickly. Pickers wear headsets that demonstrate information on a 'see-through screen', and with their hands being free they have more control over pallets. This feature has reduced error rates by 40% and brought about significant cost reductions for the company (Baur and Wee 2015; Harris, Wand and Wand 2015). Moreover, sensors attached to products or logistics infrastructure can be used for monitoring product conditions and worker's health, especially in hazardous environments, for example by warning about chemical spills or unsafe gas emissions (Banker 2014; Hancke, Silva and Hancke Jr 2012). This can have great implications for health and safety as well as product quality.

6.2.4. Retailing

Industry 4.0 and its associated technologies can have a great impact on downstream supply chain processes such as retailing. For instance, a combination of beacons, sensors, analytics, and other IoT enabling technologies can enable smart retailing. For example, beacons, which are indoor positioning systems, can wirelessly connect to the Internet, and, through integration with analytics and other store applications, can recognise customers (Baxter 2016). Customer recognition capabilities created by IoT can enable companies to send push notifications to customers. Another example of the application of IoT in retail can be seen in smart shelves (Mishra et al. 2016b; Heim, Wentworth Jr and Peng 2009). Mondelez, the producer of snack foods, is using a combination of sensors and analytics to create smart shelves that advertise directly to customers based on their physical characteristics and their dwell times in front of their displays (Macaualay 2015). This feature, not only, enables smart advertisement, but also, can improve sales forecasting through optimising restocking. This, subsequently, can improve operational efficiency sustainability, and bring about increased revenues (Rai, Patnayakuni and Seth 2006).

Additionally, it is argued that the application of IoT and BDA in retailing can enable predictive/real-time monitoring, leading to increased efficiency, effectiveness and sustainability improvements (Shamsuzzoha, et al. 2016; Gecevska et al. 2012). The predictive and proactive management of unforeseen events such as disruptions can bring about huge advantages in retailing (Hu and Kostamis 2015). For instance, detailed weather and traffic forecasts enabled by IoT enabling technologies such as GPS systems, sensors and the Internet, can bring advanced level of visibility into potential disruptions in product movement and transportation (Harris, Wang and Wang 2015), enabling retailers to easily re-plan their replenishment programs and reschedule their deliveries without causing any problems or delays (Burnes and Towers 2016).

The summary of the impact of Industry 4.0-enabling-technologies on supply chain processes and the resulting performance improvements is presented in Table 4.

Table 4: Impact of Industry 4.0-enabling-technologies on supply chain processes and the resulting performance improvements

Supply chain process	The potential impact of Industry 4.0 on the supply chain process (Descriptive themes)	Performance improvements (Analytical themes)
Product development and production	• Detailed analysis of demand patterns and fluctuations; (Li et al. 2016; Zhong et al. 2015) • Identification of process constraints such as the capacity of machinery and changeover times (Banker 2015; Huang et al. 2008) • Visualisation and simulations of operations (Jung et al. 2016) • Rapid implementation of individual customer requirements enabled by a high level of flexibility (Helo and Hao 2017; Oberg and Graham 2016)	• Improved production planning and control • Improved product design/development and production process • Enhanced production efficiency and productivity

	• Customisation and tailoring products to an individual or local levels (Park et al. 2016; Brettel et al. 2014) • Developing collaborative design (Shamsuzzoha et al. 2016). • Detecting variations in production or assembly performance enabled by self-controlling capabilities (Chung 2015) • Reduced waste and rework resulting from predictive and self-monitoring capabilities (Chung 2015) • Enhanced product innovation and development (Tan et al. 2015; Hsu, Tan and Zailani 2016; Lang et al. 2014; Christensen, Olesen, and Kjaer 2005) • Rapid product design and prototyping and reduced time to market (Kache and Seuring 2017; Tan et al. 2015; Baur and Wee 2015)	
Fulfilment, procurement, and logistics	• Real-time traceability and interoperability of resources (Qiu et al. 2015: Zhang et al. 2011)	• Improved planning and control • Improved distribution • Effective order fulfilment management

	• Enhance tracking and tracing of products throughout the supply chain (Kache and Seuring 2017; Modrak and Moskvich 2012) • Optimised freight transportations (Harris, Wang and Wang 2015) • Efficient navigation and traffic congestion detection (Bishop 2000) • Enhanced product safety, quality, and speed of delivery (Bishop 2000) • Reduction of fuel consumption and emission of gases unfavourable to the environment (Banker 2014) • Enhanced product delivery and dependability by predicting possible delays and disruptions (Kache and Seuring 2017)	• Reduced Bullwhip effect • Improved procurement and supplier relationship management • Effective purchasing

Inventory management	• Creating remote positioning methods, and indoor/outdoor GPS-based systems (Redelberger 2014) • Advanced control over the movement and status of products (Zhong et al. 2015) • Preventing costly out of stock situations; improved customer satisfaction (Quesada et al. 2008) • Informed inventory decision making • Processing large volumes quickly and efficiently (Chung 2015; Ranasinghe, Sheng and Zeadally 2010) • Eliminating time-consuming task of manually counting of pallets and products (Macaualay 2015) • Enhancing machinery and devices reliability, enabled by predictive/preventative maintenance capabilities (LaValle et al. 2011) • Improved responsiveness through reducing unexpected failures and disruption (Hu and Kostamis 2015; Koh and Saad 2006)	• Improved product distribution and delivery • Accurate inventory planning and control • Increased operational efficiency

	• Predicting and preventing potential failures and disruption (Chung 2015) • Enabling operational risk management, thereby, ensuring product quality and employees' safety (Hack and Berg 2014) • Monitoring worker's health and safety (Banker 2014; Hancke, Carvalho e Silva and Hancke JR 2012)	
Retailing	• Customer recognition capabilities (Baxter 2016; Heim, Wentworth Jr and Peng 2009) • Advertising directly to customers through smart shelves (Macaualay 2015) • Improved sales forecasting through optimised restocking (Rai, Patnayakuni, and Seth 2006) • Predictive/real-time monitoring (Shamsuzzoha et al. 2016; Gecevska et al. 2012) • Advanced visibility enabling identification of potential disruptions/constraints in product movement and transportation (Harris, Y. Wang, and H. Wang 2015)	• Improved operational efficiency and productivity • Enhanced forecasting and planning • Improved responsiveness and revenue growth

	• Enhanced re-planning of replenishment programs and rescheduling of deliveries (Burnes and Towers 2016)	

7. Conceptual framework

The dynamic business environment is transforming competitive landscapes, and enhancing emphasis on the development of new business models, and the application of new operational outlooks (Bonn and Fisher 2011; Orlitzky, Siegel and Waldman 2011; Nidumolu, Prahalad and Rangaswami 2009) such as Industry 4.0 perspective.

Industry 4.0 and its enabling technologies such as CPSs, IoT, and BDA have, already, influenced manufacturing, resulting in the creation of smart factories (Thramboulidis and Christoulakis 2016), and bringing about huge productivity and flexibility benefits through improving manufacturing capabilities (Chung and Swink 2009). These technological innovations are expected to bring significant opportunities for other managerial disciplines such as supply chain management by enhancing performance throughout the supply chain and within individual supply chain processes.

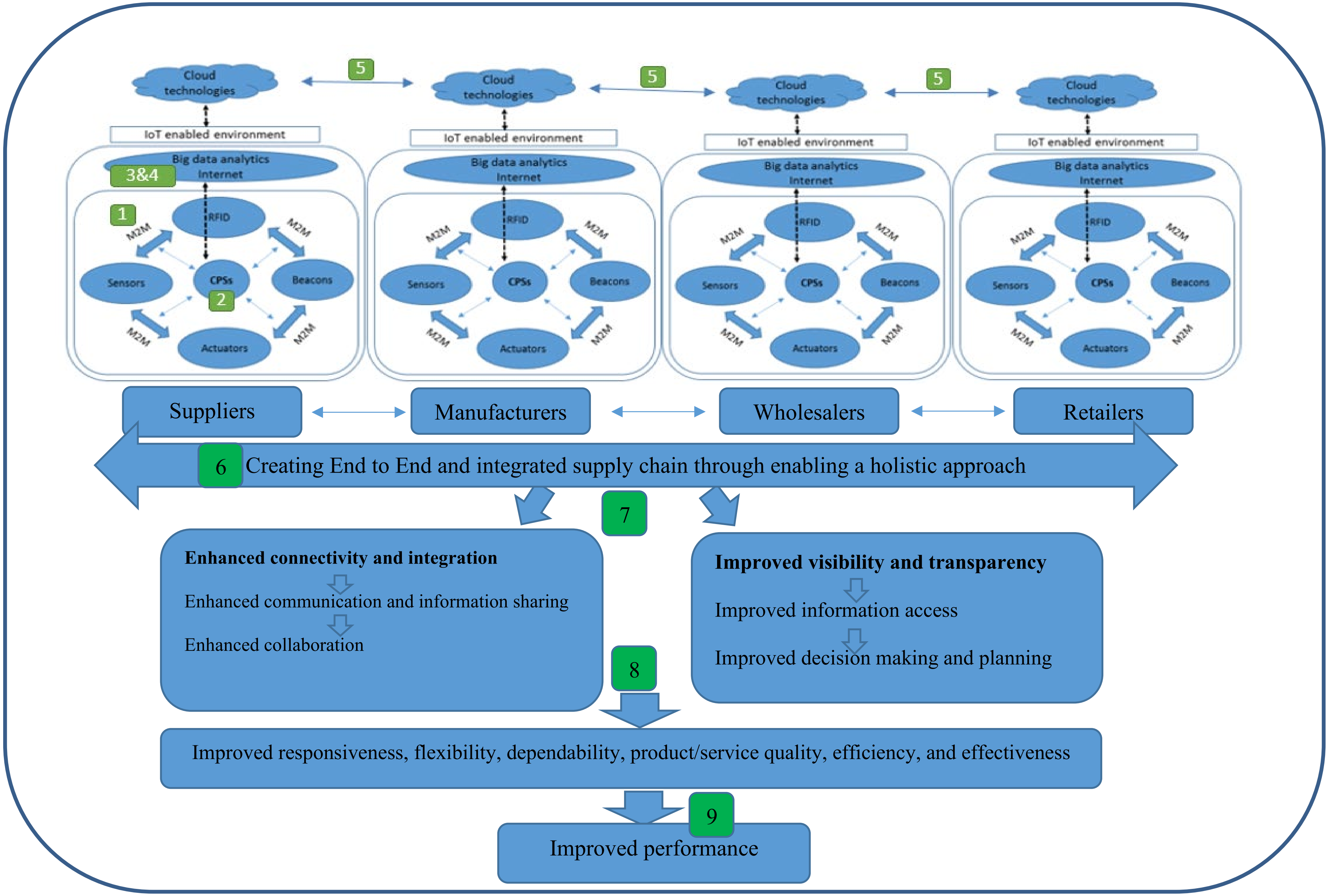
To harness the potential performance improvements provided by Industry 4.0 in supply chain management, which are yet to be seen in the years to come, companies need to develop new operational capabilities (Li et al. 2016; Brousell, Moad and Tate 2014; Nelissen and Schip 2014), and integrated supply chain models (Tachizawa, Alvarez-Gil and Montes-Sancho 2015).

Hence, this paper, having investigated Industry 4.0 perspective and having explored the impact of its enabling technologies, including IoT, BDA, CPSs, and cloud technologies, on supply chain performance and various supply chain processes attempts to propose a 'supply chain framework'. The framework includes the key industry 4.0-enabling-technologies, demonstrating how potential performance improvements can be realised throughout the supply chain. This framework is illustrated in Figure 2 and is explained below.

The main implication of Industry 4.0 and its enabling technologies for supply chain management is believed to be enhanced intra and inter-organisational integration (cross-functional and cross-enterprise integration). A combination of sensors and RFID tags, actuators and beacons attached to machinery, devices, and products can enable M2M communications, allowing for a high level of information sharing between them (1). This capability can lead to the creation of a Cyber-Physical environment where there is a high level of connectivity between advanced technological innovations (2). Various CPSs (with different interfaces and communication mechanisms) can be connected to a central information server to enable communication between them. Connecting this server to the Internet can result in the creation of IoT, where machinery, devices, and enterprise systems are connected to each other and to the Internet (3). In IoT enabled environment, BDA through analysis of data captured from various CPSs can enable a high level of connectivity and information sharing throughout the organisation (within individual systems and between sub-systems), leading to Intra-organisational integration and collaboration (4). Subsequently, by connecting CPSs and BDA to cloud-based technology, the analysed information can be accessible and available throughout the supply chain (5). This can, consequently, enable a high level of inter-organisational integration (supra-system integration) throughout the supply chain (6).

The above-mentioned technological innovations, as the main enablers of Industry 4.0, can enable a high level of interconnectivity and integration between people, devices, and processes, through connecting them to each other and to the Internet and cloud systems. This capability can lead to the creation of intelligent and integrated supply chains in which, systems, machines, and people can autonomously connect, communicate and control each other. The integration and interoperability of Industry 4.0-enabling-technologies affect supply chains mainly through enhancing 'integration', and ‘transparency’, enabling a holistic approach towards supply chain management. This leads to the creation of connected End-to-End supply chains where there is a high level of information sharing and access, and subsequently, greater communication and collaboration (7). These capabilities will allow for enhanced decision making and supply chain planning leading to performance improvements through improving responsiveness, flexibility, dependability, product/service quality, efficiency and effectiveness (8&9).

In terms of individual processes within the supply chain, the key impact of industry 4.0 technologies is realised through enabling integration, and digitisation and automation which result in the development of novel capabilities such as self-monitoring and self-controlling capabilities (1). This leads to creation of smart processes with high level of autonomy and analytical capabilities which, in turn, bring about huge improvements in operations within individual supply chain processes for example, through enabling advanced visualisation and simulation in production processes, advanced traceability in inventory and logistics operations, enhanced machinery and vehicles reliability in inventory processes, and tailored advertising in retail processes (2). These operational improvements will, subsequently, lead to supply chain performance improvement through improving performance dimensions of responsiveness, flexibility, etc. in the individual process level, and subsequently in the supply chain level (3&4).



Cloud technologies
IoT enabled environment
Big data analytics
Internet
RFID
Sensors
CPSs
Beacons
Actuators
M2M
1
2
3&4
5
Suppliers
Manufacturers
Wholesalers
Retailers
6
Creating End to End and integrated supply chain through enabling a holistic approach
7
Enhanced connectivity and integration
Enhanced communication and information sharing
Enhanced collaboration
Improved visibility and transparency
Improved information access
Improved decision making and planning
8
Improved responsiveness, flexibility, dependability, product/service quality, efficiency, and effectiveness
9
Improved performance

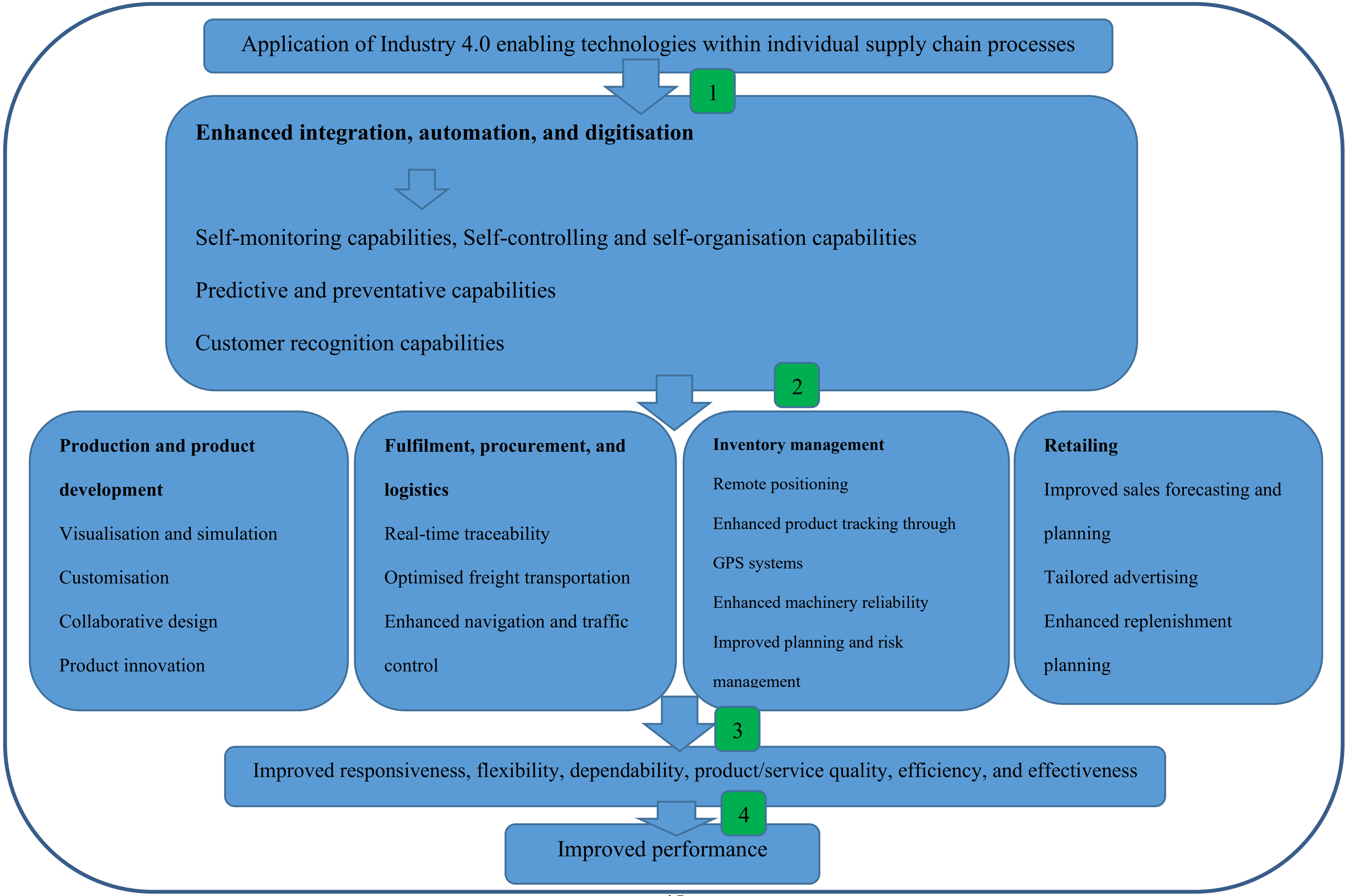

Application of Industry 4.0 enabling technologies within individual supply chain processes
1
Enhanced integration, automation, and digitisation
Self-monitoring capabilities, Self-controlling and self-organisation capabilities
Predictive and preventative capabilities
Customer recognition capabilities
2
Production and product development
Visualisation and simulation
Customisation
Collaborative design
Product innovation
Fulfilment, procurement, and logistics
Real-time traceability
Optimised freight transportation
Enhanced navigation and traffic control
Inventory management
Remote positioning
Enhanced product tracking through GPS systems
Enhanced machinery reliability
Improved planning and risk management
Retailing
Improved sales forecasting and planning
Tailored advertising
Enhanced replenishment planning
3
Improved responsiveness, flexibility, dependability, product/service quality, efficiency, and effectiveness
4
Improved performance

Figure 2: Proposed Industry 4.0 based supply chain framework

8. Conclusion

Industry 4 Industry 4.0 represents a fundamental paradigm shift in supply chain management. This industrial revolution and its enabling technologies including CPSs, IoT, and BDA can lay the foundation for the creation of integrated and end-to-end supply chains, where there is a high level of connectivity, transparency, autonomy, collaboration and flexibility throughout the supply chain. Industry 4.0 drivers including IoT, CPSs, and BDA are now almost pervasively available for organisations (Babiceanu and Seker 2016; Li et al. 2016). These technologies, through the comprehensive application, can lead to advanced levels of transparency and high level of integration throughout the supply chain (Kagermann et al. 2013) and can allow for dynamic interactions and real-time communications between supply chain parties (Oberg and Graham 2016; Ahmad and Mehmood 2015). Based on this study, at the supply chain level, Industry 4.0 can allow for a holistic approach towards supply chain management and lead to performance improvements through enabling extensive integration and connectivity. At the individual supply chain level, the main benefits of Industry 4.0 and its enabling technologies can be realised mainly through enhanced integration as well as automation and digitisation that lead to the creation of innovative analytical capabilities and, subsequently, performance improvements in individual supply chain process level.

9. Theoretical implications

As discussed, based on systems theory, improved performance within individual supply chain processes can enhance the performance of the whole supply chain (supra system) through the creation of integrated end-to-end business processes and enabling a high level of integration and information sharing. Equally, based on the findings of this study, the whole supply chain performance improvement can lead to enhancing the performance of individual supply chain processes (system elements/components). This new interaction emerged beyond what is predicted by systems theory and could be a valuable contribution to theoretical developments in this area. Hence, this study, not only, sheds light on Industry 4.0 topic and provides new insights into the performance improvement challenge within supply chains of organisations, but also, it provides a platform for developing new approaches towards systems theory.

10. Managerial implications

The exploratory and systematic literature review, which resulted in the development of the proposed framework, can provide significant support for decision making in organisations. The proposed framework can provide a better understanding of the impact of Industry 4.0 on supply chain management as it includes the interplay of key technological innovations required for creating integrated and end-to-end supply chains and demonstrates how capabilities brought about by Industry 4.0-enabling-technologies can lead to performance improvements in the supply chain. Therefore, it can provide an operational structure for embedding advanced technological innovations throughout the supply chain and can allow for integration, and realisation of performance improvements in supply chain management.

11. Future research

As this study was conducted through exploratory research and inductive reasoning, it can lay the foundation for the development and emergence of new theories about supply chain performance. This research can, also, offer other significant future research opportunities. For instance, considering the critical impact of the integration of supply chain processes on the development of end-to-end supply chains, which requires successful implementation and application of technological innovations, future research could focus on the investigation of organisational and cultural factors influencing the adoption of Industry 4.0 operational perspective in the supply chain management.

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