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A Conceptual Framework for Understanding the Impact of Internet of Things on Supply Chain Management

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ABSTRACT

We propose a conceptual framework for understanding the impact of the Internet of Things (IoT) on Supply Chain Management (SCM). We adopt the resource-based view theory and argue that IoT resources empower internal supply chain capabilities to address external challenges and, in the process, enhance the supply chain competitiveness. We explain how IoT will likely impact supply chain capabilities and indirectly enhance SCM competitive advantages, which in turn help meet SCM challenges. We provide some managerial implications and show the need for new decision models dictated by the IoT environment. Finally, we outline the limitations of the proposed framework and suggest future research directions.

Keywords: *internet of things, supply chain management, supply chain challenges, supply chain capabilities, supply chain IoT framework*

1. INTRODUCTION

In today's complex business environment, supply chains face numerous internal and external challenges. Many supply chains are operating globally over wide geographical areas and are vulnerable to many risks (Butner, 2010). Customers are more and more demanding in terms of product customization (Collin *et al.,* 2009), price (Lau, 2012) and level of service (Tummala *et al.,* 2006). Product complexity is also increasing due to the rapid changes in technology and the continuous introduction of new products to the market (Christopher, 2016). Furthermore, the external environment is highly dynamic due to sudden changes in regulation (Boyd *et al.,* 2003), economic (energy cost, prices and availability of raw materials, currency exchange rates), social (unrest, demanding customers), and natural factors (extreme weather conditions, earthquakes, tsunamis) (Park *et al.,* 2013). In order to meet such challenges, supply chains need to develop adequate capabilities to survive in such a demanding environment. Supply chains need to have the necessary end-to-end visibility to be synchronized through appropriate integration and collaboration mechanisms. A supply chain that has the right capabilities exhibits unique characteristics that set it apart and enable it to deal effectively with today's challenges. These characteristics include resilience, velocity, traceability, and reliability.

Information technology (IT) has been and continues to be an essential enabler of effective supply chain management in order to meet its challenges (Ben-Daya *et al.,* 2019). Internet of things (IoT) is a new IT revolution providing a paradigm shift in SCM and offering tremendous opportunities to deal more effectively with SCM challenges (De Vass, 2021). Following a systematic literature review on IoT and supply chain management, Ben-Daya *et al.* (2019) called for more research in this area and the need to develop both conceptual and analytical models to understand the impact of IoT on supply chains. A conceptual framework will aid in describing the state of knowledge, outline the underpinnings of important concepts in the area (Varpio *et al.,* 2020), and aids in identifying and positioning new research contributions within the existing literature (Maxwell, 2013). A conceptual framework is also considered the first step in building theory (Weick, 1995; Meredith, 1993). Thus, in this paper, we develop a conceptual framework to contribute to understanding the role of IoT in supply chain management. We wish to answer an overarching research question: What is the impact of IoT on supply chain management? To do so, we conceptualize the field of IoT and supply chain management. Aided by the resource-based view theory, which is used to address what is needed to manage such supply chains (Treiblmaier, 2018), we propose a conceptual framework for understanding the impact of IoT on SCM. The goal of the framework is to open the door for research on the interface of IoT and supply chain management.

Our main contributions in this paper are: (1) Present a conceptual framework that can allow us to study the impact of IoT in supply chain management. (2) Identify key supply chain challenges, capabilities, and competitive advantages and discuss their relationships. (3) Identify the impact of IoT on supply chain capabilities. (4) Present ideas for future research in this new and important area of smart supply chains.

The rest of the paper is organized as follows. We define IoT and its role as an enabler in the supply chain in Section 2. We present our research methodology and a conceptual framework in Section 3. In Sections 4, 5, and 6 we discuss in detail supply chain challenges, capabilities, and competitive advantages, respectively. The impacts of IoT on supply chain capabilities, competitive advantages and challenges are discussed in Sections 7, 8 and 9, respectively. Finally, we present our conclusions, managerial implications, need for new decision models, limitations, and future research directions in Section 10.

2. INTERNET OF THINGS AND ENABLING TECHNOLOGIES

2.1 Definition

IoT has been defined in several different ways (e.g., see Ben-Daya *et al.,* 2019), given our focus on IoT and how it related to supply chain management, we adopt the definition provided by Ben-Daya *et al.* (2019): *"The Internet of Things 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."* This definition incorporates the major supply chain processes and stresses the potential role that IoT can play within a supply chain.

2.2 Enabling Technologies

Many technologies need to be integrated to provide an IoT-based complete solution. An IoT network is generally composed of four layers (Xu *et al.,* 2014). A sensing layer that includes different IoT devices such as RFID tags, sensors, or actuators. A networking layer that enables, through a wired or wireless network, information transfer. The third layer integrates services and applications using middleware technology. Finally, an interface layer to display information and enables user-system interaction (**Figure 1**). The third and fourth layers are sometimes merged into one application layer.

To support these four layers, many key technologies are required for an efficient implementation of an IoT complete solution (Lee and Lee, 2015):

- **Radio Frequency Identification (RFID):** It enables identifying, tracking and transmitting information.
- **Wireless Sensor Networks (WSN):** It is a main component of an IoT system and is composed of a network of sensors. These sensors are used for tracking and monitoring different devices for different measures such as the location, the temperature, the pressure, etc. (Rayes and Salam, 2016). Sensors are able to cooperate and communicate with RFID tags (Lee and Lee, 2015).
- **Middleware:** it allows developers to communicate with heterogeneous IoT devices.
- **Cloud computing:** It represents a set of internet-based computing resources that are shared and accessed by different users. Cloud computing allows for the collection and sharing of IoT data between devices, systems, people, and companies. IoT devices generate a large amount of data that should be analyzed by important computing resources to enable efficient and timely decision making (Lee and Lee, 2015). Cloud computing represents a good alternative to buy and manage expensive data centers (Bonomi *et al.,* 2014). Mixing on-premise and cloud resource led to the concept of fog computing (Bonomi *et al.,* 2012). The edge computing concept has emerged with IoT development. It is very similar to fog computing with the main difference of the location of the computing processing instead of being on the premises of the company will be located as close as possible to the source of data represented most of the time by the IoT devices. The main advantage is to lower the information traffic through communication networks with fewer cybersecurity risks.

In addition to the above technologies, big data analytics plays a crucial role in the efficiency of an IoT system. Indeed, such systems produce a huge amount of data that is often stored on cloud platforms and should be analyzed in real-time to aid in timely decision making.

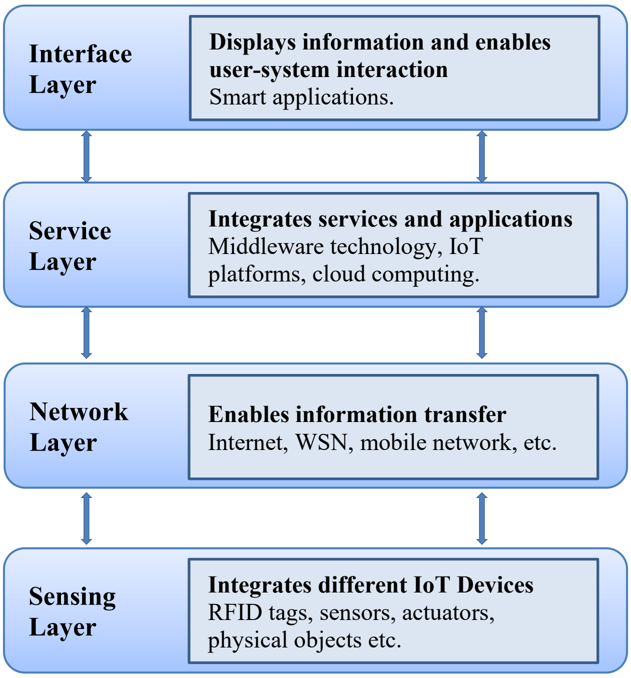

Figure 1 The Four-Layer IoT Architecture (Xu *et al.,* 2014)

Blockchain technology will also play an important role in trust-building among supply chain partners and security issues related to IoT (Kshetri, 2018; Wang *et al.,* 2018). Blockchain is a distributed ledger database, a continuously expanding chain of records (blocks) that are linked and secured via cryptography, creating a networked audit trail of transactions (Bashir, 2017). This makes it a reliable database, which is collectively maintained by a decentralized and trustless method (Tian, 2016). As such, blockchain technology allows two or more entities that may or may not know or trust each other to securely exchange value over the internet without including a third party (Abeyratne and Monfared, 2016). Eliminating the need for intermediaries or control entities removes friction in all types of transactions. Blockchain has the ability to get a distributed network to reach a consensus regarding the state of data and agree on the rules of the network. Therefore, change by one user can only be implemented if accepted by all parties. This feature enhances transparency and trust (Abeyratne and Monfared, 2016).

Gurtu and Johny (2019) also showed in a recent literature review the enormous potential of blockchain technology for increasing the efficiency of SCM. Sivula *et al.* (2021) recently studied the requirements for blockchain implementation in supply chains through theoretical and empirical approaches. In the same context, in a literature review, Queiroz *et al.* (2019) captured some of the benefits of blockchain in SCM and provided the following examples:

- Tracking and providing visibility through the entire supply chain optimizes the information flow and generates cost reduction (Wu *et al.*, 2017).
- Facilitating smart contracts, which benefit the factories and their networks by reducing transaction costs (Christidis and Devetsikiotis, 2016).
- Improving the pharmaceutical supply chain information sharing, making SCM more trustworthy and secure. Consequently, it could strengthen procedures for detecting fake medicines in global trade (Mackey and Nayyar, 2017).

These examples show that blockchains can enhance visibility and collaboration, two key SCM capabilities discussed in detail in Section 5.

3. RESEARCH METHODOLOGY AND A CONCEPTUAL FRAMEWORK

3.1 Research Methodology

We propose a framework for understanding the important role that IoT can play in supply chain management. While IoT has been acknowledged as an important enabler of supply chains (e.g., Ben Daya *et al.*, 2019), the impact of IoT on supply chain performance is still unclear (e.g., Haddud *et al.*, 2017; Abdel-Basset *et al.*, 2018). In this paper, we draw from the resource-based view and supply chain management literature to develop a framework for understanding the potential impact of IoT on supply chains. The resource-based view theory is a framework that is used to describe, explain, and predict how a firm can use and control resources to achieve competitive advantage (see Wernerfelt, 1984; Grant, 1991; Rungtusanatham, 2003). In our context, we have taken the resource to be IoT and we are interested in understanding how it can be used to control and improve supply chain capabilities. Based on the reviewed literature, which included 162 studies from Scopus (132 papers, 22 conference proceedings and 12 books), we identified five main supply chain capabilities: collaboration, innovation, integration, quality, and visibility. These capabilities are employed to address supply chain challenges. From our literature review, we found that there are five major supply chain challenges: competition, fast-changing markets, globalization, matching supply and demand, and sophisticated customers. The outcome of the application the resource-based theory in our context is the improvement of the supply chain competitiveness. Based on our literature review, we identified four major supply chain competitive advantages: reliability, resilience traceability, and velocity. To ensure the validity of our framework, it was independently evaluated by the authors and their findings from the literature review in Ben Daya *et al.* (2019). This process took several iterations until the researchers' views converged on the validity of the framework (Grayson and Rust, 2001).

3.2 Conceptual Framework

One line of resource-based view theory argues that a competitive advantage can be gained by building a firm's organizational capabilities, including information-based processes (Amit and Shoemaker, 1993). Thus, in our framework, we focus on a firm's supply chain capabilities and their links with supply chain competitive advantages. Wu *et al.* (2006) argued that IT-enabled supply chain capabilities allow a firm to take advantage of its IT resources. **Figure 2** illustrates the proposed framework.

As shown in **Figure 2**, we propose to investigate the impact of IoT on supply chain capabilities and how a firm can take advantage of those capabilities to meet its challenges. We note that there is a lack of literature that focuses on identifying and studying supply chain challenges and capabilities. Therefore, one of our goals in this paper is to present, define and discuss the roles of these two important concepts in supply chain management. In addition, we note that in **Figure 2** we focus on supply chain management as the subject of analysis, rather than a specific firm or a supply chain.

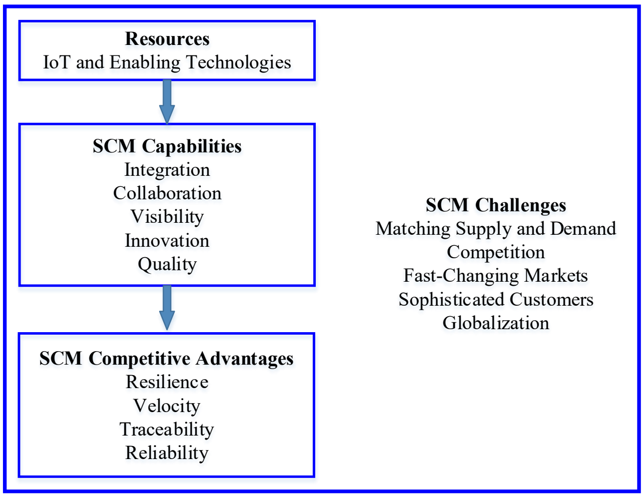

Figure 2 Framework for Understanding the Role of IoT in SCM

The competitive advantages of supply chain management that can deal with its challenges are also identified. IoT can be viewed as an enabler for enhancing the effectiveness of the identified capabilities that will help the supply chain gain its needed competitive advantages to deal with its challenges. Using the resources-based view theory we posit that IoT, and its enabling technologies enhance SCM Capabilities. The latter include collaboration (Golgeci *et al.*, 2017), innovation (Soosay *et al.*, 2008), integration (Asamoah *et al.*, 2021), quality (Peng *et al.*, 2016) and visibility (Ivanov, 2021). By tackling SCM challenges, which include competition, fast-changing markets, globalization, matching supply and demand, and sophisticated customers (Chopra and Meindl, 2016), SCM capabilities help in building supply chain management completive advantages that include reliability (Walker *et al.*, 2000), resilience (Carvalho, 2012), traceability (Canavari, 2010) and velocity (Carvalho, 2012). The main elements of this framework are discussed in more detail in Section 3 to 7. The purpose of this framework is to provide a clear understanding of the impact of IoT on SCM that allows for the identification of new research direction in an IoT environment. We believe that IoT will have a profound impact on decision making, planning and control methods within SCM.

The elements of SCM challenges, capabilities, and competitive advantages are discussed in Sections 3, 4, and 5 respectively. The relationships between the components of the proposed framework are discussed in Sections 7-9. In particular, the impact of IoT on SCM capabilities is discussed in Section 7. The relationship between SCM competitive advantage, capabilities and challenges are discussed in Section 8 and the impact on SCM challenges is discussed in Section 9.

4. SCM CHALLENGES

In this section, we identify the main supply chain challenges categories that need to be taken into considerations in any effective supply chain management strategy. According to highly cited SCM textbooks (e.g., Chopra and Meindl, 2016; Simchi-Levi *et al.*, 2008; Christopher, 2016), the following classes are very common: globalization, competition, fast-changing markets, the difficulty of matching supply and demand, and sophisticated customers. As shown in **Figure 3**, these challenges can be classified into three categories: (1) *Operational* that address the issues of matching supply and demand such as procurement and demand management; (2) *Market* which include challenges such as competitors supply chain strategies, changing market dynamics and an increasingly sophisticated customer in an era of ease of access of data where consumers are gaining more marketing powers; and (3) *Environmental* challenges that stem from supply chain efforts to source material and services and serve customers all around the world.

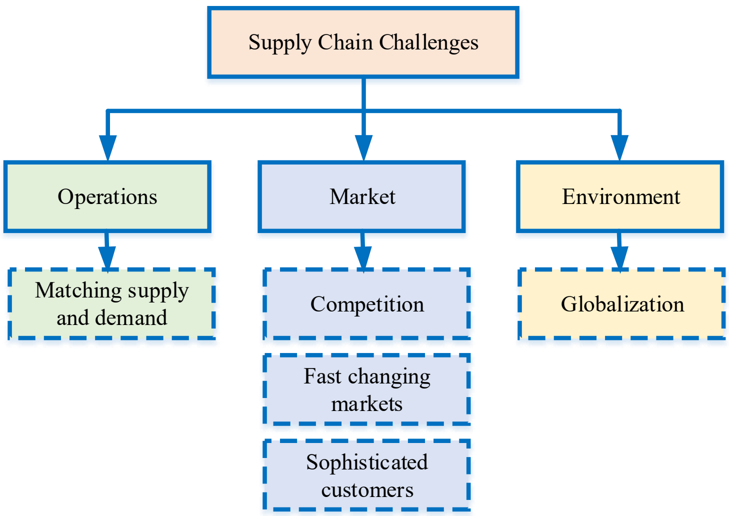

Figure 3 Supply Chain Management Challenges

4.1 Matching Supply and Demand

Matching supply and demand is a major challenge to all supply chains due to the uncertainties in supply and demand (Cachon and Terwiesch, 2008). In many cases, firms have to decide production levels months before demand is realized. However, any deviations from these early commitments result in inefficiencies in the form of lost sales, obsolete inventory, and inefficient utilization of resources. These challenges are amplified for global supply chains as they have to deal with a more complex network and the management of operations across a wide geographical area. Matching supply and demand challenges require supply chain capabilities, such as visibility and supply chain integration and collaboration between all supply chain partners.

4.2 Competition

The fierce competition that characterizes today's business environment is a challenge to supply chains fueled by globalization, stringent customers' requirement, and a volatile market environment. Companies are forced to compete globally even if they are local due to the presence of global companies in their backyard and also due to the fact that their local customers have access to the global market (Abrahamsson and Aronsson, 1999). The competition is also tougher due to more transparency in product variety and pricing options that are provided through e-commerce.

Competition between supply chains has seen a growing interest from the supply chain management literature (Antai, 2011). Several normative strategies for achieving a supply chain competitive advantage have been suggested in that literature (Hassini, 2008). Several approaches have been used for modelling the operationalization of chain-to-chain competition: ecological niche theory (Antai, 2011), complex adaptive systems (Langdon and Sikora, 2006), economic network model (Zhang, 2006), network capabilities (Rice and Hoppe, 2001).

Furthermore, IoT is viewed as a key enabler of servitization business models (Ardolino *et al.* 2018b; Cenamor *et al.*, 2017). Servitization is defined as "the innovation of an organisation's capabilities and processes to better create mutual value through a shift from selling product to selling PSS" (Baines *et al.* 2009, pp. 555) and PSS as "a system of products and services which are jointly capable of fulfilling specific client demands" (Manzini and Vezzoli, 2003, pp. 851). A recent work (Gurtu, 2019) reviewed and analysed the literature about combining products and services. Since IoT provides timely information on how products are being used by customers, it has the potential of enabling firms to offer innovative products and services, and in redesigning their current business models based on this information (Rymaszewska *et al.*, 2017). This helps firms avoid price-based competition, secure market share, and create new and stable revenue streams (Baines *et al.*, 2007). To survive these competitive forces, supply chains are required to constantly build and improve their innovation and quality capabilities.

4.3 Fast-Changing Markets

There are many drivers of change in the market ranging from economic factors to changing customer preferences to rapid changes in technology. Some market changes can be attributed to the changes in customer preferences (Lee, 2004). Others can be due to economic, regulations, and social factors (Chopra and Sodhi, 2004). However, the overarching reasons can be attributed to innovation (Seo *et al.*, 2014) and technology (Sher and Lee, 2004). It is not only the pace of change and the rate of introduction of new products that present challenges but primarily the disruptive nature of change. The latest industrial revolution is poised to affect firms in unprecedented ways. Companies who cannot adapt to these changes will find it more difficult to catch up later. Clear visibility throughout the supply chain and its environment, innovation and IT enablers are key capabilities for dealing with fast-changing markets.

4.4 Sophisticated Customers

One of the main goals of supply chain management is creating customer value and a quick response to customer requirements (Simchi-Levi *et al.*, 2008). Managing customer expectations to provide such value is becoming a major challenge. Customers are becoming increasingly empowered based on pervasive access to online information through social networks. They have access to more choices and multi-channels (Neslin *et al.*, 2006) and as a result their expectations are becoming higher and higher. With the advent of mobile channels, the popular press has coined the term omnichannel, where the borders between different channels have been blurred (Verhoef *et al.*, 2015). Recently there is a move to omnichannel. This is forcing supply chain partners to reconsider their competitive strategies (Brynjolfsson *et al.*, 2013) as we see fewer geographic barriers and an increase in consumer awareness through services such as tracking, traceability, and customization. This has been recently enhanced through the proliferation of platform economies. Deloite has defined platform economies as "a socio-economic system, powered by digital platforms, that allow sharing of assets and resources, between individuals, businesses and governments, with the goal of increasing utilization and promoting access over ownership of assets and resources". Multisided platforms can be used to access more customers globally and enhance competitiveness (Ardolino *et al.*, 2016). Dealing with sophisticated customer expectations requires SCM capabilities such as innovation, quality, and proper use of information technology.

4.5 Globalization

With the lowering of trade barriers and advances in information and communications technologies (especially the internet), many supply chains went global looking for the opportunity offered by globalization. These include access to new markets, lowering production and procurement costs, taking advantages of incentives offered by many governments trying to attract foreign direct investment, and improving competitive edge. However, global supply chains also face many challenges (Youngdahl *et al.*, 2010). Global supply chains are much more complex in terms of size; more suppliers and production facilities spread over wide geographical areas. Components and raw materials could be sourced from different suppliers in different countries assembled into a final product in a production facility and then sold in a different country. This global environment creates many risks not faced by local supply chains, such as dealing with different cultures and regulations, volatile exchange rates, longer lead times and risks of disruption due to natural disasters, social unrest, to name few risks (Chopra and Sodhi, 2004). In this challenging and risky context, Gurtu *et al.* (2019) proposed a comprehensive framework to improve the quality of offshoring decisions. To manage these globalization challenges, supply chains need to be equipped with visibility, integration, and collaboration capabilities.

5. SCM CAPABILITIES

There is a lack of literature that examines the concept of supply chain management capabilities. Most of the literature focused on single firms' capabilities. For example, Amit and Schoemaker (1993) view a firm's capability as its capacity to use resources to achieve a predefined end. We extend this understanding of capability to a supply chain and *define supply chain management capabilities as the supply chain's ability to meet its challenges*. As discussed in Section 3.2, we group supply chain management capabilities into five categories: Integration, Collaboration, Visibility, Innovation, and Quality.

As shown in **Figure 4** and detailed in the subsequent subsections, visibility capabilities are a driver for the integration and collaboration capabilities. The latter are closely related, complement each other, and are co-requisites for innovation and quality capabilities.

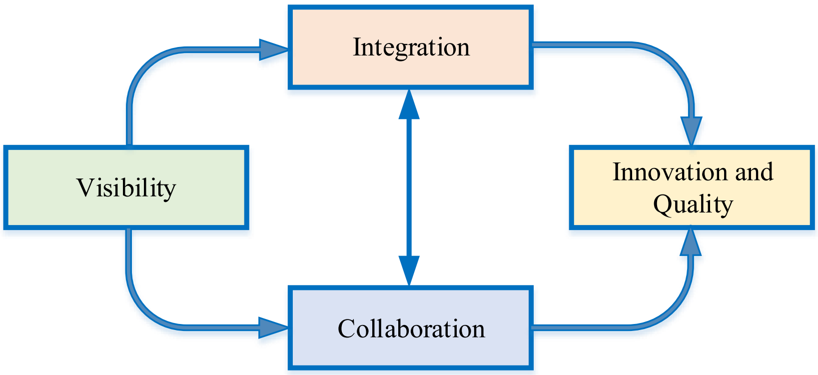

Figure 4 Supply Chain Management Capabilities

5.1 Integration

Supply chain integration (SCI) is defined in the literature from many different perspectives. The scope varied from internal to external integration. Three main SCI dimensions were cited: suppliers' integration, internal integration, and customers' integration. The means for achieving integration include information sharing, collaboration, and coordination. Sabir *et al.* (2014) added shared decision making, technology and a high level of trust between supply chain partners. The objectives of SCI mostly relate to the improvement of the operational performance by the more efficient flow of products, service, information, money, and decisions (Stevens *et al.*, 2016; Flynn *et al.*, 2010; Wong *et al.*, 2013).

5.2 Collaboration

Supply chain collaboration received a lot of attention from both researchers and practitioners. Companies have been very successful in improving the efficiency of their internal activities (Fawcett *et al.,* 2008). However, they quickly realized that they had to extend these efforts to the wider supply chain in order to survive in a very competitive environment. This broader view allows firms to integrate supply and demand in order to deliver better performance (Barratt, 2004). Such integration requires close collaboration with suppliers and customers. Discussion of supply chain collaboration in the literature focuses on three issues (Cao and Zhang, 2013):

(i) The antecedents, enablers, or precursors of SCC, i.e., the conditions that lead to or affect supply chain collaboration.
(ii) The main elements or attributes that characterize SCC; and
(iii) The consequences of SCC, or collaborative advantage that relates to the desired synergistic outcome of collaboration that would have not been achieved if the collaborating partners acted alone.

5.3 Visibility

While there is a consensus on the importance of supply chain visibility, it has been defined in many different ways. Definitions that have been proposed in the literature focus on two themes: (1) Nature of visibility, often described through the ability to access and share information through the supply chain and (2) Properties of shared information: such as accuracy, trust, timeliness, usefulness, and quality. Visibility aids with both external and internal integration capabilities. In the former, visibility plays a critical role in relaying information on the downstream (demand) and upstream (supply) sides of the supply chain as well as their surrounding environment (market). For the latter, we believe that internal integration requires both information technology capabilities and strong cross-functional capabilities, for we see internal integration as a prerequisite to external integration.

5.4 Innovation

We note the scarcity on research that is specifically focused on supply chain innovation. TI Innovation can happen at the product or process level. It can occur within a company, across a supply chain or the whole industry. Its main goals are to support operational efficiency, service effectiveness and value creation. Innovation plays a role that goes beyond operational efficiency and value creation. It is an important driver for gaining a competitive edge.

5.5 Quality

In the past, most quality management initiatives were focusing only on internal quality activities. However, more recently, firms started developing quality management strategies that include, in addition to internal operations, coordination, collaboration, and sharing of information with upstream and downstream supply chain partners. In fact, end-customer satisfaction can only happen if all supply chain partners share the same focus on continuous improvements in quality and value-added services (Frederick, 1998). Sharing of information, in particular, is key to any effective supply chain quality management strategy. Sharing and availability of timely information can be crucial for traceability purposes.

6. SCM COMPETITIVE ADVANTAGES

Few papers focused exclusively on supply chain competitive advantages. Li *et al.* (2006) studied the impact of supply chain management practices on competitive advantages. They defined a supply chain competitive advantage as "the extent to which an organization is able to create a defensible position over its competitors". They discussed traditional competitive advantages that included delivery/dependability and time to market. However, in the new era of digitization, new competitive advantages are needed due to the emergence of new challenges. Most of the recent literature focused on only a single competitive advantage (Tukamuhabwa *et al.,* 2015; Carvalho *et al.,* 2012; Dabbene *et al.,* 2014; Chen *et al.,* 2017b). Based on the studied recent literature, four main competitive advantages are proposed: resilience, velocity, traceability, and reliability.

6.1 Resilience

Tukamuhabwa *et al.* (2015) reviewed the literature on supply chain resilience. They identified several characteristics of supply chain resilience: adaptive capability and capacity, preparation, response, time recovery to the original or better state, connectedness and control, robustness, competitive advantage, and cost-effectiveness. They have also proposed key strategies to build resilience: flexibility, creating redundancy, collaboration, and agility. Ponomarov (2009) defines supply chain resilience as "the adaptive capability of a firm's supply chain to prepare for unexpected events, respond to disruptions, and recover from them in a timely manner by maintaining continuity of operations at the desired level of connectedness and control over structure and function." Soni *et al.* (2014) developed a supply chain resilience index to measure the level of supply chain resilience. The index is based on ten enablers varying from supply chain agility, collaboration, information sharing, sustainability, risk and revenue sharing to trust, visibility, creating risk management culture, adaptive capability and supply chain structure. The developed index takes into account the value of those enablers and the degree of dependence among them. Resilience can be improved by implementing the right risk management and assessment strategies. Gurtu and Johny (2021) presented in this context a recent and comprehensive literature review about supply chain risk management.

6.2 Velocity

Carvalho *et al.* (2012) defined supply chain velocity from two perspectives: the ability to complete an activity as quickly as possible from an agility perspective, and the speed to recover from disruption from a resilience perspective. The latter perspective has also been taken by Ahimbisibwe *et al.* (2016) and Tukumuhabwa *et al.* (2015). Velocity more generally represents the distance over time. In a supply chain context, time is considered as the duration to move products and materials from one end to another in the supply chain (Ahimbisibwe *et al.,* 2016; Christopher and Lee, 2004). We need, therefore, to decrease time to increase the velocity. Four dimensions of supply chain velocity were identified in the literature: supply chain empowerment, supply chain adaptability, supply chain speed, and supply chain innovations (Ahimbisibwe *et al.,* 2016; Dubey *et al.,* 2014; Tukumuhabwa *et al.,* 2015).

6.3 Traceability

While tracking is often related to downstream supply chain processes, such as tracking shipments to the customer, traceability is concerned with upstream processes to determine the source and properties of a product (Bechini *et al.,* 2008). Opara (2003) defined traceability in the supply chain, with specific reference to the food supply chain, as the "collection, documentation, maintenance, and application of information related to all processes in the supply chain in a manner that provides a guarantee to the consumer and other stakeholders on the origin, location and life history of a product as well as assisting in crises management in the event of a safety and quality breach". He also divided traceability in food supply chains into six elements. To generalize those elements to any supply chain, we propose the following key elements of traceability in supply chains: *product traceability, process traceability, domain-specific traceability, inputs traceability, quality traceability, and measurement traceability*. Zhou and Piramuthu (2015) proposed three levels of supply chain traceability: *physical flow traceability, process traceability, and service traceability*.

Dabbene *et al.* (2014) have suggested four quantities to measure the level of traceability: (1) *breadth* (amount of information that is collected on the product), (2) *depth* (how far is the product traced in the supply chain), (3) *precision* (accuracy in locating product as well as identifying its features) and (4) *access* (the speed in communicating product information to all supply chain partners). The benefits to traceability are manifold: improvement in product quality and safety, crisis management and facilitating coordination (Opara and Mazaud, 2001). Traceability also plays an important role in product recall management, product valorization and security (Dabbene *et al.*, 2014).

6.4 Reliability

Chen *et al.* (2017b) defined supply chain reliability as the "ability of a supply chain to fulfill end-customer demand to the desired level continually over the planning horizon, despite the risks of external and/or internal shocks to the system and prior to any risk mitigation efforts". They developed a framework to evaluate supply chain reliability. They first evaluate the reliability on a node level and then extend it to the whole supply chain using buyer-supplier relationships. They defined the reliability of node i as the "ability to satisfy immediate demand before any risk-mitigating actions, preventive or post-disruption, are taken". The reliability of a node is estimated as the probability to satisfy its immediate buyer (internal, environmental and supply risks). The reliability of a node depends on its own risks and the reliability of its suppliers. The reliability at the product level is estimated by propagating the reliability of the different nodes until reaching the final demand node. Finally, the reliability of the whole supply is estimated as a weighted average of all products' reliability.

7. IOT IMPACT ON SCM CAPABILITIES

7.1 Impact on Integration

The means for achieving integration include information sharing, collaboration, and coordination. SCI's main benefits from IoT include information sharing, identification, and communication for internal and external integration. Regarding information sharing, many works dealt with implementing IoT for facilitating information sharing and virtualization for a different type of supply chain. IoT can help indeed in the supply chain virtualization as exposed in Verdouw *et al.* (2013) where the author developed an IoT based framework for that purpose. IoT can also help in information sharing for synchronizing production and transportation (Qiu *et al.*, 2015) or for real-time monitoring and end-to-end visibility of the supply chain, which allow better and faster decisions (Tadejko, 2015).

The impact of IoT on internal and external integration in supply chains through RFID technology is multifaceted and concerns, for example, warehouse and inventory management and transportation. RFID data reduces inventory and increases service levels (Condea *et al.*, 2012). It also improves inventory accuracy by matching real inventory to recorded inventory and prevents fraudulent inventory shrinkage (Dai and Tseng, 2010; Goyal *et al.*, 2016; Cui *et al.*, 2017; Fan *et al.*, 2014). IoT shelf management significantly reduces processing times (Yan *et al.*, 2014) and can also send and monitor different information such as temperature and humidity data (Yan *et al.*, 2014). IoT-enabled shelves easily detect misplaced items (Mathaba *et al.*, 2017; Fan *et al.*, 2014)

IoT through RFID technology have also an important impact on external supply chain integration by optimizing transportation. Ferreira *et al.* (2010) have compared the latest IoT technology, such as sensor networks, to more traditional RFID tags and barcodes. They argue that IoT provides monitoring of quality, real-time responsiveness, and price optimization. Yan *et al.* (2014) have compared IoT transportation systems to traditional data management systems. They noted that the impressive savings in time can be valuable for online and significantly reduce their logistics costs.

7.2 *Impact on Collaboration*

We make use of the proposed definition of supply chain collaboration (Section 5.2) to highlight the key role of IoT in enhancing the key elements of collaboration. These elements include information and resource sharing, goal congruence, decision synchronization, effective communication, and joint knowledge creation. For effective collaboration to take place, these elements need to be addressed simultaneously. Simatupang and Sridharan (2005) proposed a Collaborative Supply Chain Framework (CSCF) made up of the following interconnected elements: collaborative performance system (CPS), information sharing, decision synchronization, incentive alignment, and integrated supply chain processes (**Figure 6**).

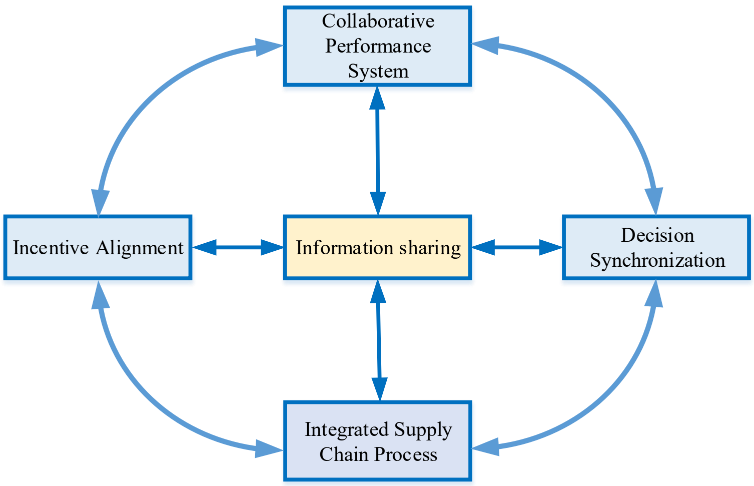

Figure 6 Collaborative Supply Chain Framework (Simatupang and Sridharan, 2005)

The framework suggests that information is the central issue needed by the partners to control their supply chain processes and improve performance. An IoT solution reduces the lead-time between data collection and decision making by providing partners with real-time information. This enhances various elements of collaboration such as effective communication, decision synchronization, and joint knowledge creation. For many researchers, trust is vital for supply chain collaboration. Collaboration requires the sharing of benefits and risks. The commitment to face these risks requires a high level of trust (Wu *et al.*, 2014). Without trust, potential conflicts and unfairness can escalate faster, leading to a negative impact on supply chain relationships and the improvement of overall performance (Ramon-Jeronimo *et al.*, 2017).

Despite the availability of the technologies needed for information sharing, these technologies have difficulties dealing with the lack of trust in supply chains. This lack of trust is due to three challenges brought to the traditionally centralized trust mechanism: self-interests of supply chain members, information asymmetry in production processes, costs and limitations of quality testing and inspections (Chen *et al.*, 2017a). Blockchain is a promising technology to address these problems and makes it possible to share information across the supply chain to enhance many aspects of supply chain collaboration.

7.3 *Impact on Visibility*

IoT in supply chains allows for the possibility of realizing traceability with complete information by providing real-time temporal and spatial information on the product flow through a supply chain (Zhou and Piramuthu, 2015). Such complete and real-time information can be critical in detecting and resolving inconsistencies and safety crises as soon as they arise in the supply chain. This is possible through the ability to map physical network flows to causal reasoning networks (Zhou and Piramuthu, 2015).

To understand the potential impact of IoT on supply chain visibility, let us reconsider the example from **Figure 7**.

In this modified network, we assume that the supply chain is equipped with IoT sensors so that the provenance of final product components can be accurately traced to their origins. To illustrate, consider final product G that uses both sub-assemblies D (red) and E (green). With an IoT-enable sensor, we would be able to distinguish the components in G (red and green). If a product recall is issued due to faulty raw material B, we can accurately identify the lot of 10 G products that have to be recalled, instead of recalling all of the G lot (30 units). Similarly, if C is faulty we would only recall a lot of 20 G products.

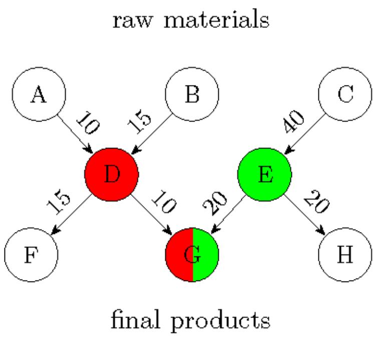

Figure 7 Traceability Performance Indicators Example with IoT Impact (Adapted from Dabbene *et al.,* 2014)

Using IoT-enabled sensors, we would revise our traceability performance indicators as follows. The batch dispersion cost (BDC) is unchanged and equal to six. The worst-case recall cost WCRC is now

$$\begin{aligned} \mathrm{WCRC}_{IoT} &= \max\{(15+10), (15+10), (20+20)\} \\ &= \max\{25,25,40\} = 40 \end{aligned}$$

which is also due to recalling material C. However, note that with IoT we were able to improve WCRC by 20%. Finally, the average recall cost is ARC = 30 which has improved by about 36%! This illustrative example shows that by using IoT we can significantly improve visibility and in turn quality defect identification.

7.4 Impact on Innovation

The integration of IoT in supply chains coupled with blockchain technology has led interesting and innovative supply chain solutions. One innovation in combining IoT and blockchain is to aid with supply chain provenance (Armstrong, 2016). Provenance is defined as the "source or origin; or, the history of ownership of a valued object or work of art or literature" (Merriam-Webster, 2018). There are several start-ups, such as Prevenance and Skuchain, which have introduced innovative technology that combines IoT and blockchain.

Another innovation that is closely linked to IoT is the concept of smart contracts "pieces of software that represent a business arrangement and execute themselves automatically under pre-determined circumstances" (The Economist, 2016). Although the concept has been postulated earlier (Szabo, 1994), it has gained steam and practical relevance only recently, thanks in part to the advances in IoT. Smart contracts can facilitate coordination in supply chains and reduce the operating costs of collaboration and integration while at the same time reducing errors that may otherwise be induced by human interventions.

IoT is also expected to be a key enabler for industrial companies (especially large ones) to become industrial service providers (Ardolino *et al.*, 2018a). For example, Hitachi is developing Message Queuing Telemetry Transport (MQTT) protocol that is based on IoT to remotely assist in operating and maintaining their large industrial equipment (Shiobara and Nakajima, 2017).

Caputo *et al.* (2016) have shown the importance of IoT in innovation in manufacturing processes. Innovation is facilitated by the collection of data in embedded sensors in the manufacturing production system as well as in the downstream supply chain by collecting data on the product cycle and quality. Urbinati *et al.* (2018) have argued that IoT, as an enabler of digital transformation, plays a critical role in building companies' capabilities in open innovation, "the distributed innovation process based on purposively managed knowledge flows across organizational boundaries" (Chesbrough *et al.*, 2014, pp. 17). For example, Procter and Gamble's "Connect and Develop" program has used IoT and related technology together with analytics to support its open innovation process (Dodgson *et al.*, 2006). IoT innovation in service and open innovation will aid IoT-enabled supply chains to become more connected, customer-focused, and agile.

7.5 Impact on Quality

We make use of the introduced definition of SCQM to highlight the key role of IoT in enhancing the key elements of SCQM. This includes IoT role in (i) quality continuous improvement activities throughout the supply chain; (ii) customer and supplier collaboration and relationships; (iii) sharing of information in the supply chain; and (iv) enhancing traceability.

Quality continuous improvement tools used by manufacturers to control product quality such as statistical process control can be used in the broader supply chain context. These SPC tools can be used also in a supply chain context to optimize quality characteristics such as on-time delivery, mishandling rates, temperature excursion rates, and so on (Zhang et al, 2011). With IoT data regarding shipment damages and delays, SPC analysis can be applied to similar supply chain issues to get warnings as soon as such a variable goes out of control.

Sharing information is crucial for enhancing quality improvement activities across the supply chain. While IoT makes it possible to obtain the needed information for decision making in real-time, blockchain provides the framework for the safe exchange of information as needed and thus deals effectively and enhances the trust issue.

In the past, companies hear most from customers when something goes wrong. In an IoT environment involving smart and connected products, firms obtain online data about the customer experience with the product such as use, performance, customer preferences, and customer satisfaction (Porter and Heppelmann, 2015). This timely information provides insights that can enhance customer experience and satisfaction and indicates areas where a customer could benefit from additional product capabilities or services. In 2013, for example, batteries in two Tesla

Model S cars were punctured and caught fire after drivers struck metal objects in the road. The conditions and speeds leading to the problem had not been simulated in testing. The company then sent a software update directly to all vehicles that would reduce the chances of future occurrences of this problem. In fact, the software update would permit the vehicle to raise their suspension under those conditions to minimize the problem (Porter and Heppelmann, 2015).

In an IoT environment, we can go beyond monitoring and problem solving to machines adapting to changes automatically which is the essence of IoT. For example, robots not only can execute processes more accurately to reduce variation and enhance quality, but they can also continually learn to improve and automatically adapt to variations in manufacturing requirements enhancing both quality and productivity (Bigos, 2017). Monitoring machines and taking proactive maintenance action before failure that can lead to a quality problem is another example.

Supply chain traceability with complete information is critically important in SCQM. The frequent recalls that made headlines in recent years are a clear indication of the need for traceability. Traceability is particularly vital in some fields such as perishable products in the food supply chain and medicine in the pharmaceutical industries (Zhou and Piramuthu, 2015). Examples will be provided in the next section.

8. IOT IMPACT ON COMPETITIVE ADVANTAGES

Internet of things impacts directly SCM capabilities as discussed in the previous section. Enhanced SCM capabilities in turn impact SCM competitive advantages and allow a supply chain to deal effectively with its challenges. Collaboration in a supply chain is what integrates the network as a whole. This is needed to build supply chain resilience (Sheffi, 2001). There is a consent in the literature that collaboration is an essential element of building supply chain resilience (Tukamuhabwa *et al.*, 2015). The fundamental principle of supply chain collaboration is that the sharing of information across the chain can decrease uncertainty (Christopher and Peck, 2004), increase visibility (Faisal *et al.*, 2006), operational effectiveness and efficiency, and enhance customer service. This competitive advantage help dealing effectively with the challenges of sophisticated customers, matching supply and demand, and fast changing markets.

In Section 6.2, we discussed velocity in the context of a supply chain. We argued that velocity is the ability to complete an activity in a timely manner through supply chain empowerment, adaptability, speed, and innovation. As such, we find that velocity directly impacts all five supply chain challenges: it allows a supply chain to match demand and supply for sophisticated customers in fast changing markets. In addition, velocity as a competitive advantage empowers a supply chain to reach global customers faster and more efficiently that its competitors. On the other hands, velocity is supported by four supply chain capabilities: integration, collaboration, visibility and innovation. Integration and collaboration between the supply chain partners ensures seamless flows and reduces lead times through visibility and innovation in coordination and information sharing processes.

IoT, through different types of sensors and devices, can help in ensuring supply chain traceability. To achieve this traceability, innovative solutions are needed and should involve the collaboration and the integration of the different partners of the supply chain to provide supply chain visibility, safety, and quality. Full process and products traceability help in dealing with many supply chain challenges such as competition, fast-changing markets, sophisticated customers and globalization.

As discussed in Section 6.4, reliability is concerned with the supply chain ability to satisfy customer demand prior to any risk-mitigating actions. As such, reliability has an immediate impact on the supply chain challenges relating to customers and demand, namely, fast changing markets, matching demand and supply and sophisticated customers. On the other hand, reliability goals can be achieved through supply chain capabilities: integration, collaboration, visibility, and quality. Close integration and collaboration between the supply chain partners allows for coordination of demand information with suppliers and customers to increase the chances that it is satisfied on time. Visibility allows each party in the supply chain to gain useful, accurate, trusted, secure and timely information on demand. Finally, continuous quality improvement facilitates the achievement of customer satisfaction.

There are several examples from the real word that illustrate how supply chain capabilities can create competitive advantage which in turn help address the supply chain challenges. For example, Dell, by pioneering the direct model in selling computers, has increased its inventory velocity through virtual integration with its suppliers and customers which in turn allowed it to better satisfy its customers demand, increase product customization, by allowing the customer to reconfigure their computer requirements, and gaining a larger market share (Magretta, 1998). The example of Nokia and Philips illustrates how resilience can be increased through collaboration with suppliers. When a small fire occurred in one of Philips plants, it caused its closure for weeks to ensure that the semiconductor fabrication plant meets the delicate machinery and silicon wafers cleaning standards. This disruption has resulted in the delay of producing four million phone handsets for Nokia, one of Philips main customers. To overcome this disruption Nokia had worked closely with Philips to the point that "for a little period of time… [they] operated as a one company regarding [the missing] components" (Sheffi, 2005). They have jointly come up with a rescheduling and rerouting plan to make up for most of the shortage in some other Philips plants. In addition, they worked closely with their other customers in Finland, Japan, and the USA to make up for any shortage. Finally, as an illustration of the reliability competitive advantage, we can cite the example of Hewlett Packard (HP) that procured AMD's Opteron processors, that can handle 32- and 64-bit application, despite having co-founded with Intel the development of 64-bit Itanium processor (Clark, 2005). By doing so HP has sought to build a collaborative relationship with AMD to learn the technology and hedge against any possible future technology risks.

9. IOT IMPACT ON SCM CHALLENGES

In the previous section, we discussed the impact of IoT on key supply chain capabilities, which will indirectly impact SCM challenges as mentioned in Section 4. In this Section, we provide real-world example of how IoT helps with SCM challenges. In particular, we consider challenges in the areas of food supply chain, maintenance management, logistics management and matching supply with demand.

The food supply chain is a challenging domain since it deals with perishable products and involves many actors along the chain. It is estimated that one-third of the food produced worldwide is lost or wasted according to the FAO (Gustavsson *et al.*, 2011; FAO, 2019). IoT enhances visibility throughout the supply chain, which in turn facilitates integration and collaboration between the different parties. Food quality, safety, and traceability can be achieved in ways that were not imaginable before through very innovative solutions. For example, Hyperledger's Sawtooth Platform combines blockchain with IoT to improve the seafood supply chain (Forbes, 2018). An IoT sensor is attached to the fish when it is caught by a fisherman. The sensor will emit information such as location, temperature, and humidity. This information is used to monitor the quality of seafood while it is being transported and can also be shared with the buyer to assess the status of seafood before buying it.

In the area of maintenance, using IoT from connected equipment and systems, it is possible to detect deviations in process parameters and signal signatures and identify any patterns that can lead to failure. Such anomalies are detected using machine learning methods applied to the massive data provided by IoT sensors. The ability to carry out maintenance only when needed and to avoid breakdown can have a tremendous impact on equipment uptime and productivity and on products and service quality. IoT technology allows also remote monitoring of assets enabling businesses to provide maintenance as a service.

With the growth in supply chains, it is becoming a challenge to keep track of the source of products as well as track them through the distribution channel. With IoT, it is possible to have a connected fleet (Newman, 2018) where any transportation mode (ship, rail, air, and truck) will be connected throughout the supply chain. Such a supply chain is sometimes referred to as Logistics 4.0 (Forbes, 2018). IoT can also be used to increase the reliability of logistics systems. For example, Union Pacific uses IoT sensors in its rail cars that send 20 million temperature readings per day to its data. The company uses big data analytics to decide which rail cars should be taken out for inspection and servicing. This IoT-based preventative maintenance has on average pulled out three cars per day saving the company delay costs that can add up to $40 million per defective rail car (Forbes, 2018).

Matching supply and demand is a key challenge in supply chain management and is a source of significant competitive advantage if managed well. The difficulty in matching supply and demand is due to three main factors (Asthana, 2018): demand uncertainty, supply uncertainty and lack of synchronization among supply chain partners. IoT-enhanced supply chain capabilities can deal adequately with all these issues and help the firm better match supply and demand. The difficulty in obtaining accurate demand forecast is due mainly to an information gap between what customers want now and in the future and firms' perception of this demand. IoT devices that stay active after the customer purchases the product will provide rich information to companies better know and understand their customers. This can reduce the demand uncertainty and make it easier, and less costly, to match demand to supply.

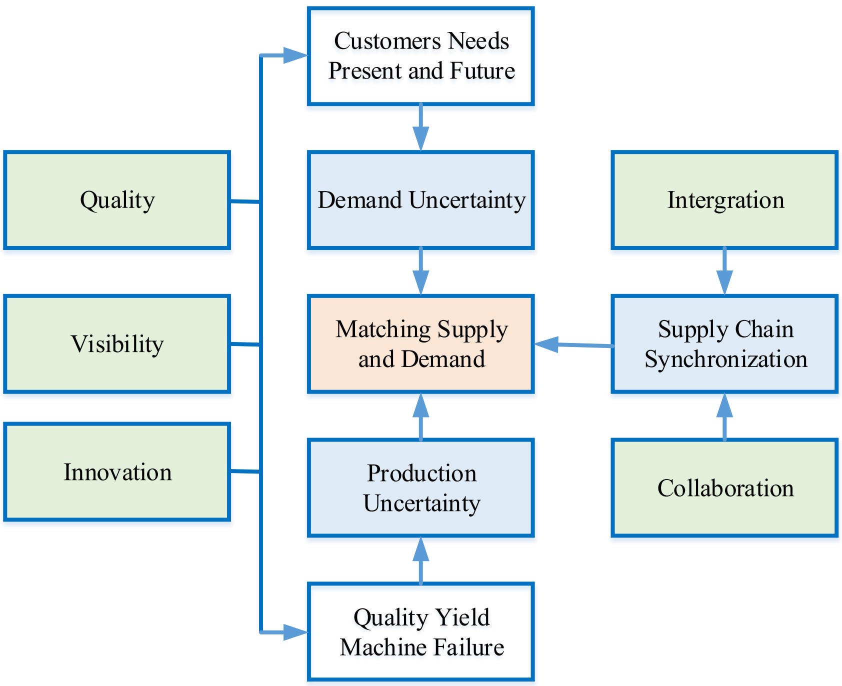

Figure 8 How Capabilities Impact SCM Challenges: Illustration with Matching Supply and Demand

As shown in **Figure 8**, supply chain synchronization is enhanced by integration and collaboration capabilities. The level of visibility provided by IoT coupled with blockchain solutions is a key enabler of synchronization in the supply chain. **Figure 8** provides an illustration of the Conceptual Framework, described in **Figure 2**, by showing how the five SCM capabilities impact the SCM challenge of "matching supply and demand" through first-level impacts (demand uncertainty, supply uncertainty and supply chain synchronization) and second-level impacts (customers' needs: present and future, and quality yield, machine failure).

10. CONCLUSIONS, LIMITATIONS, AND FUTURE RESEARCH AREAS

IoT's impact on supply chain management is a topic of great interest to both researchers and practitioners. While ICT has always been a major enabler for SCM, IoT is providing unprecedented opportunities. In this paper, we provided a conceptual framework for a better understanding of the impact of IoT on SCM. We first identified key SCM challenges and key SCM capabilities that allow supply chains to meet their challenges. We also identified key characteristics exhibited by supply chains that adequately address their challenges and will ultimately achieve the supply chain advantage in terms of financial environmental and social value.

By connecting in real-time millions of shipments, IoT is enabling more efficiency through more tracking, tracing, and visibility in the supply chain. Connecting warehouse equipment (racks, shelves, pallets, lifts, and items) is enabling smarter inventory management. Connectivity of freight also increases security and produces big data that can be used for predicting asset failures, fuel management, and scheduling maintenance. The result of these efficiencies is savings in time and costs.

IoT, in combination with other emerging technologies, has contributed to the emergence of new business models and opportunities. With the possibility of having clear visibility and traceability of the product, manufacturers can now remotely service their products and support their customers. For example, Hitachi is now able to service its heavy industry remotely in Kenya in Africa. In addition, with the power to operate remotely, companies can operate their business in different parts of the world remotely. For example, a Canadian smart grid company is managing the smart power grid in a city in Austria remotely where solar batteries are operated based on street lamps' exposure to the sun. IoT has also given rise to non-ownership models where the manufacturer leases or rents the equipment to the customer and through remote monitoring collects data on operations and manages maintenance. Airline companies are moving to this model with the availability of a complex system of sensors that allows remote control (Smith, 2013). In addition, IoT is enabling the connectivity of freight fleets with operators that facilitate the creation of collaboration platforms where competing carriers can cooperate to increase the utilization of their assets and increase customer service. Finally, internet-driven co-creation (Breidbach and Maglio, 2016) opens the door for personalized manufacturing where customers can have their own designs produced by flexible manufacturing shops such as Etsy and Quickparts, which is now part of 3D Systems on Demand Manufacturing.

The proposed framework and the insights provided will be extremely helpful to practitioners as it clarifies which capabilities are impacted by IoT and how these can address the challenges they are facing. In other words, a practitioner interested in addressing a particular SCM challenge will use the insights gained from the framework to know which competitive advantage need to be enhanced and then to which capabilities IoT should be applied to attain the desired results. One of the challenges of IoT implementation, and any other major technology investment, is to establish its operating ratio, the percent of operating expenses to operating revenue, a measure of operating efficiency and a benchmark of financial viability. Our proposed framework can be used in practice to aid in acquiring and deploying IoT technology for supply chain management and assessing its financial viability. In **Figure 9**, we present a five-stage process for doing so. We suggest starting by aligning the supply chain competitive strategy with its supply chain strategy and prioritizing the competitive advantages: which of those advantages will be emphasized by the supply chain based on the strategic alignment between the business and operations strategies. In the second stage we identify the supply chain management challenges as described in Section 4. In stage 3, we assess the supply chain capabilities. This is an important step, and we can use the metrics and objectives listed in tables 1-5. In Stage 4, we deploy IoT as per the four layers discussed in Section 3. Finally, in phase 5 we assess the financial viability by looking at the ratio between operating expenses and revenues as well as a score card for each of the supply chain capabilities.

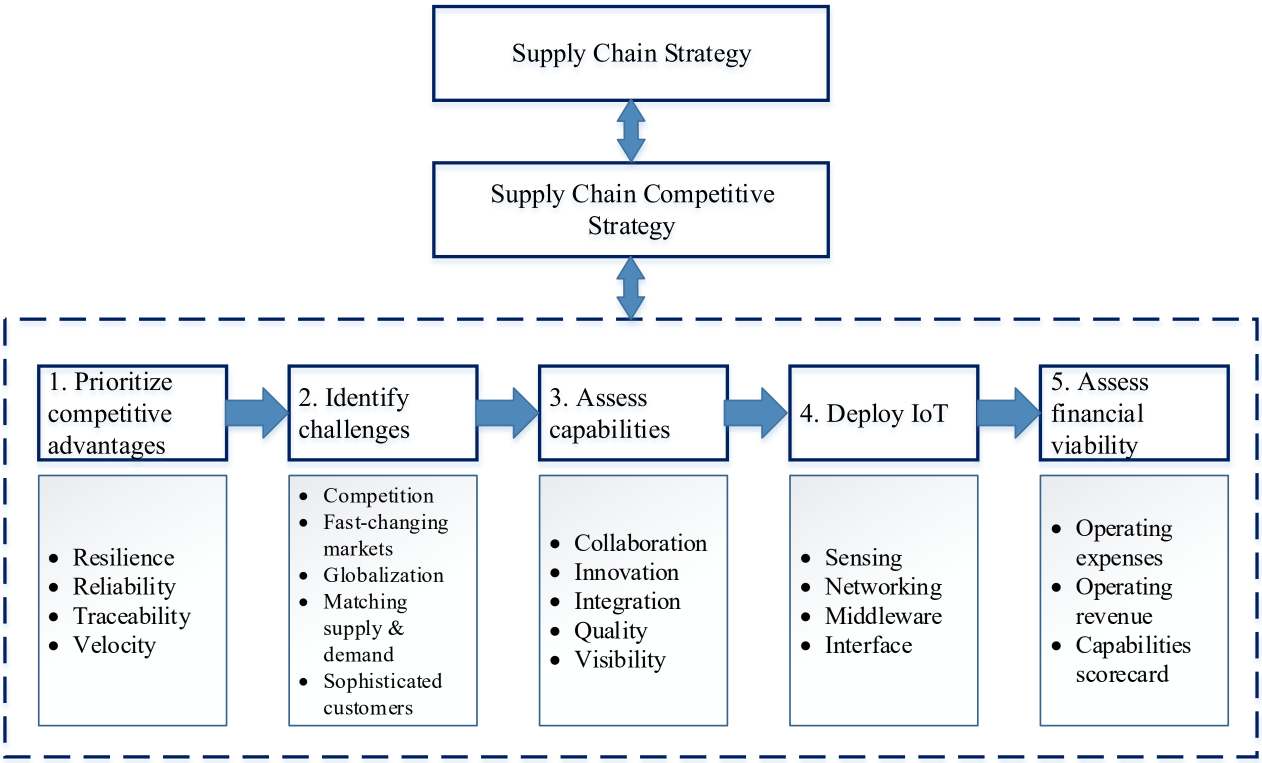

Figure 8 Suggested Approach for Practical Implementation of Framework for IoT Deployment

To achieve the benefits of IoT in the supply chain, there is a need to develop new decision-making models as well as modify existing ones. New models include the need for the *optimal design of wireless sensor networks* where IoT sensors are located along the supply chain in order to maximize the chances of uncovering quality problems while at the same time minimizing the cost of operating the networks. With after-sale active IoT devises, a vendor will have access to the retailer's point of sale data as well as the customer usage data. We believe this can facilitate the rise of *Vendor-Customer inventory management* that can be used to inform better vendor inventory decisions. IoT can also contribute to the emergence of new *sustainability* models where sharing accurate information about the provenance of items with their customers enables companies to strengthen their corporate social responsibility initiatives. This data can also be used to construct new *sustainability metrics* that are more comprehensive and include social aspects, something that has been identified as a serious gap in the literature (Hassini *et al.,* 2012; Tajbakhsh and Hassini, 2015). *Customer-centric decision making* is another modeling innovation opportunity where IoT data on customers' demand and shopping behavior allows companies to center their business operations around their customers' needs from design to after-sales. With secondary (public) data as well as common supply chain private data, that may be anonymized for confidentiality purposes, it possible to synthesize the data, perform analytics and share insight with all supply chain partners. We refer to this as "*shared analytics*" and foresee growth in this field. This is given rise to a world of *data-driven decision making* where the wide availability of big data is being used to drive all phases of decision making: exploration (e.g., visualization), prescriptive (e.g., large scale optimization) and predictive (e.g., machine learning).

New models are not restricted to operations only, there is also a need to develop new data management frameworks. IoT devices are expected to generate data across the supply chain. While this brings on many opportunities as we have discussed in this paper, it also raises several questions around *data governance and conflict resolution*: what data can be shared, in what format and when as well as how to resolve data inaccuracies and mismatches? Like with the regular internet, there are bound to be issues relating to *privacy and ethics* with IoT. For example, to what extent will customers have control over IoT devices and the data they generate in the products they purchase?

IoT is also bound to have major impacts on existing decision-making models. One such area is *supplier management* where IoT is providing more information to track suppliers' quality and delivery. This information can be used to exclude sub-par suppliers and/or renegotiate contracts based on the results of data analytics. Another area is *inventory management* where the increase in inventory accuracy and more predictability across the supply chain is expected to decrease inventory costs and safety stocks. IoT will further enable *personalized and dynamic pricing* that not only makes use of after-sales product data, but it can also use competitors' data that can be inferred using artificial intelligence algorithms based on how the product interacts with other products used by the customer. Finally, one challenge that has defied retailers is *forecasting* lost sales and product substitution (e.g., Surti *et al.,* 2013; Surti *et al.,* 2018). With IoT devices that interact with competitors' devises, it becomes possible to collect data on competitors' products and develop predictive models to infer lost sales and substitutions rates.

While we expect our study to offer an important first step in understanding the impact of novel technology, we acknowledge that it has three main limitations. The first is related to the dynamic nature of IoT. As it is the case for all other technologies, it will take some time before convergence to an industrial scale standard is reached. For this reason, we looked at IoT in a broad sense and voided to focus on any particular technology platform. The second limitation relates to our choice of the theory on which we based our conceptual framework. We acknowledge that other theories could potentially contribute to other insights. Finally, although we relied on our previous literature review, the process by which we have identified future research areas is bound by our conceptual framework. Other approached may well lead to a different potential area of future research.

Based on our proposed framework and the reviewed literature, we propose the following future research directions:

- **Data governance** across a supply chain: With the preponderance of IoT devices and their related data, the question of how to manage data across a supply chain becomes important. To benefit from IoT, supply chains have to have a clear understanding of what data will be collected and by which party, which data will be shared and in what manner. A data governance framework would outline what data will be shared, how often, data anonymization, shared analytics, and a mechanism for conflict resolution.
- **Shared analytics**: with the wide availability of IoT generated data, and to increase its value, it is critical that different supply chain partners develop a protocol for joint analytics where anonymized data can be securely shared and synthesized, and the insights shared back with partners without any self-identifiers. In this regard, there is also a need to develop algorithms that would ensure no party can infringe on other parties' confidential data.
- **Sensor network design**: depending on the application, how do we design an optimal IoT sensors' network. While one may borrow from existing network science methodologies, it is also important to consider conflict resolutions and coordination within a supply chain context.
- **Risk disruption management**: With the increase in the adoption of IoT devices, there will be more incentives for hackers to breach their security. The stakes are even higher in a supply chain as accessing one partner's data portals may provide access to all other partners. It is thus important to study the resilience of such networks to these risks as well as recovery strategies.
- **Dynamic and Personalized Pricing**: With IoT devices potentially following the customers wherever they are, like smartphones, retailers will gain both temporal and special data as well as customer preferences and consumer behavior data that can be used to construct sophisticated pricing models.
- **Investment management**. There are two critical research questions: (1) How to assess the value of an investment in IoT technology and its related big data operations and (2) how to schedule and prioritize investment in IoT technology. Many companies follow technology investment cycles and have to make a tradeoff between replacing technology that is not fully amortized with one that has a high risk of return (Kache and Seuring, 2017).
- **Data security**: Given the lack of convergence on IoT standards and the lack of protocols for inter-company data exchange, there is still a significant security risk for IoT data, as illustrated by the recent security breaches in 2016 (Perlroth, 2016; Blumenthal and Weise, 2016).

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