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The impact of Industry 4.0 implementation on supply chains

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Abstract

Purpose – The research aims to analyse the impact of *Industry 4.0* implementation on supply chains and develop an implementation framework by considering potential drivers and barriers for Industry 4.0 paradigm.

Design/methodology/approach –A critical literature review is performed to explore key drivers and barriers for *Industry 4.0* implementation under four business dimensions: strategic, organizational, technological, and legal & ethical. A system dynamics model is later developed to understand the impact of *Industry 4.0* implementation on supply chain parameters, by including both the identified driving forces and barriers for this technological transformation. The results of the simulation model are utilised to develop a conceptual model for a successful implementation and acceleration of *Industry 4.0* in supply chains.

Findings – *Industry 4.0* is predicted to bring new challenges and opportunities for future supply chains. The study discussed several implementation challenges and proposed a framework for an effective adaption and transition of *Industry 4.0* concept into supply chains.

Practical implications – The study is expected to benefit supply chain managers in understanding the challenges for implementing *Industry 4.0* in their network.

Originality/value- Simulation analysis provides examination of Industry 4.0 adoption in terms of its impact on SC performance and allows incorporation of both the drivers and barriers of this technological transformation into the analysis. Besides providing an empirical basis for this relationship, a new conceptual framework is proposed for *Industry 4.0* implementation in supply chains.

Keywords Industry 4.0, Digital supply chains, System dynamics, Digitization, Implementation

Paper type: Conceptual paper

1. Introduction

Over the past few years, the rapid evolution of information and communication technologies and their integration into supply chains have led to the advent of the fourth industrial revolution - "*Industry 4.0*" (Dalenogare et al., 2018; Frank et al., 2019). There is increased competition within business, resulting from technological innovations and changing customer requirements. This transformational change in business ecosystems will profoundly influence operational models/frameworks and management strategies in order to adapt and integrate with new challenges in an evolving ecosystem (Barreto et al., 2017). Since the beginning of Industry 4.0, an increasing number of companies have adopted principles and technologies of the new industrial revolution to improve performance and productivity (Barreto et al., 2017; Rachinger et al., 2018). The key strength of Industry 4.0 is its high impact on many facets of society. From a typical user perspective, there is clearer visibility of the influence of Industry 4.0 on both the professional, domestic and social fields. Smart homes, smart cities and offices, and e-health systems are only a few examples of the probable scenarios of how the new paradigm will revolutionise the world (Bandyopadhyay and Sen, 2011). Similarly, the most apparent impact of Industry 4.0 is expected in industrial manufacturing and management, logistics, and business process management areas (Strange and Zucchella, 2017). Digitalization is a must for supply chain (SC) systems to survive in today's highly dynamic and competitive business environment (Wu et al., 2016; Pereira and Romero, 2017). Companies need to adopt emerging technologies in their business processes and manage the increasing data flow in their value chain for effective management of next generation digital SCs.

Following the Industry 4.0 trend, there is a growing need for researches on *Industry 4.0* implementation in supply chain networks. Although some researches exist on frameworks and roadmaps for the Industry *4.0* transformation (e.g. Sarvari et al., 2018; Ghobakhloo, 2018), an overall system approach is lacking including complex systems such as SCs. In order to contribute to this evident research gap, the study examines the adaption and transformation to Industry 4.0 in the SC context. A good starting point is to identify the potential drivers, success factors and barriers for this technological transformation (Kamble et al., 2018). Therefore, first, main drivers and barriers for adoption of the Industry 4.0 paradigm are identified with the help of literature, and then categorised under four business dimensions namely: Strategic, Organizational, Technological, and Legal & Ethical (Luthra and Mangla, 2018). The relationship between these factors are also assessed and figured with the help of two practitioners. An analytical perspective is required to provide a well-developed and comprehensive understanding on how these factors impact Industry 4.0 implementation as well as critical SC variables. Hence, secondly, a Systems Dynamics (SD) approach is utilised to model an Industry 4.0 adopted SC by including the effects of different barriers and drivers of Industry 4.0 on SC dynamics. The results are interpreted by comparing traditional SCs versus Industry 4.0-adapted SCs. Radio-Frequency Identification Device (RFID) and cloud technology are incorporated to examine the behaviour of SC performance. Besides providing theoretical background knowledge and several practical insights, review of the literature from a SC perspective and quantifiable results of the model led to development of a general multi-phased framework for successful implementation of Industry 4.0 in SC networks.

The remainder of the paper is structured as follows. Section 2 presents the relevant literature and background of the research under three sub-sections; i) overview of Industry 4.0 concept and relevant technologies, ii) the impact of Industry 4.0 on SCs, and iii) key drivers and barriers for the implementation of Industry 4.0. Section 3 explains the research methodology. Section 4 discusses the proposed SD model to capture the impact of Industry 4.0 adoption on supply chains by also considering different drivers and barriers of this paradigm. Section 5 presents the results of the simulation model and proposes a conceptual framework for Industry 4.0 implementation in SC level. Finally, the contribution of the study to theory and practice are discussed along with the limitations and possible future research directions.

2. Literature Review and Background

2.1. Overview of Industry 4.0

Industry 4.0 comprehends the development and integration of information and communication technologies into business processes (Dalenogare et al., 2018; Wagire et al., 2019). The broad vision of Industry 4.0 requires frameworks and/or architectures for connecting physical assets and digital technologies in a cyber-physical system (CPS) (Sarvari et al., 2018). The Internet of Things (IoT) plays a critical part in this fourth industrial revolution and is also referred to as the Industrial Internet of Things (IIoT) (Haddud et al., 2017; Ghobakhloo, 2018). Not just IIoT, but other significant technologies like cloud computing, artificial intelligence, Computer-Aided Design and Manufacturing (CAD/CAM), intelligent enterprise resource planning (I-ERP), programmable logic controllers (PLC), automation/industrial robots, sensors/actuators, additive manufacturing, simulation, and other innovative models of data exchange play a crucial role in digitalising supply chains (Ghobakhloo, 2018; Dalenogare et al., 2018). Industry 4.0 encompasses automated systems that allow customization, agility and speed in manufacturing and service operations by providing data from various devices, sensors and tools (Deloitte, 2014). This drives new capabilities in many areas including new product design, prototyping and development, remote control, services and diagnosis, predictive and preventive maintenance, traceability, necessary health monitoring systems, planning, innovation, agility and real-time applications (Strange and Zucchella, 2017; Sarvari et al., 2018). The capabilities realised by Industry 4.0 bring considerable benefits to companies including customization of products, real-time data analysis, increased visibility, autonomous monitoring and control, dynamic product design and development, and enhanced productivity (Dalenogare et al., 2018). The core Industry 4.0 technologies and their business applications are explained in the following:

Big Data Analytics: The use of vast volumes of data to improve efficiency and productivity is enabled by big data analytics (Wamba et al., 2017). Big data analytics helps organizations to gather value from large volumes of data to improve the efficiency and performance of processes, increase flexibility and agility, and enhance product customization (Gilchrist, 2016; Wu et al., 2016; Ghobakhloo, 2018). The collection and evaluation of data from multiple systems will become the norm to enable real-time and quick fact-based decision-making (McKendrick, 2015).

Autonomous Robots: Today robotics technology is used in a vast range of areas including manufacturing, logistics, e-commerce, education, etc. (Demetriou, 2011). Robots have finally started to interact with each other, work safely and in harmony with operators, side by side, and assist operators. In future it is expected that these robots will be more economical and will have a wider range of capabilities than those used currently.

Cloud Technology: Large amounts of data collected from a vast amount of business systems, devices, equipment and sensors are stored on remote servers known as cloud systems. Real-time access and retrieval of large chunks of data are enabled by cloud systems (Accenture consulting, 2016). There is a requirement for enhanced data-sharing across organisational departments, value chains, sites and company/organizational borders. Cloud computing environments are rapidly evolving and driving more data-driven and intelligent SC activities (Oztemel and Gursev, 2018).

Simulation: The data processed and gathered from big data and cloud systems can be used as a feed to a virtual model to analyse all possible scenarios related to the product design, development, production and SC network (Zhong et al., 2017). Simulation is used widely in business models to leverage the available real-time data and simulate the actual working world in a virtual ecosystem. Process testing and optimization through simulation allow people to reduce business changeover, risk, setup time and enhance quality control for future operations and services, even before the implementation of changes in the actual physical world (PwC, 2016).

The industrial internet of things: In Industry 4.0, the IIoT platform will be a centralized control system that communicates and interacts with different equipment and systems. The IIoT enables real-time traceability and tracking with decentralized analytics and decision-making (Gunasekaran et al., 2016). Through the IIoT, cohesive cross-company collaboration will enable entirely automated value chains, thereby enhancing companies' functional and business capabilities (Hahn, 2014; Manavalan and Jayakrishna, in press).

Additive Manufacturing: Additive manufacturing and 3D printing, are used to produce three-dimensional objects layer-by-layer. With Industry 4.0, these innovative manufacturing technologies will be widely used for the production of small batch sizes of customized tailor-made products that offer production advantages (McKendrick, 2015; Ghadge et al., 2018).

Augmented reality: A variety of services, such as designing a layout in a warehouse or a production line and communicating repair instructions through mobile or other remote-control devices, can be achieved using augmented-reality-based systems (Vaidya et al., 2018). These systems are currently in their early stages; however, in the future, organizations will make a much broader breakthrough in augmented reality to improve their business procedures and decision-making process (Bcg perspectives, 2016).

Business Intelligence (BI): Business Intelligence consists of technological platforms used to collect, analyse, store and present business data obtained from different sources (Mulcahy, 2007). It supports decision making by converting raw business data to meaningful and valuable information and insights.

Cybersecurity: With the implementation of Industry 4.0 on a wider scale, there is a likely increase in cybersecurity threats (Ghadge et al., 2019). There can be secure, reliable communication, as well as sophisticated identity and access management (Esplugues Barona, 2016). Cybersecurity is an essential requirement for the sustainability of Industry 4.0 systems; therefore, cybersecurity strategies should be integrated into the information technology systems of companies (Deloitte, 2017; Oztemel and Gursev, 2018).

The principal characteristic features of Industry 4.0 are collaboration and integration of systems, both horizontal and vertical. In vertical integration, the Information and Communication Technology (ICT) is integrated into different hierarchical levels of the organization from floor-level control to production, operations, and management levels (Dalenogare et al., 2018). This vertical integration networking enables the use of cyber-physical systems for production to respond to demand variation or the fluctuations and faults in stock levels. In horizontal integration, ICT is used to exchange information between different players (sometimes competitors) within SC network. Integration of these systems for a flawless collaboration, integration, and exchange of data with all the stakeholders is a complicated scenario (Hahn, 2014). Implementation of Industry 4.0 applications helps to reduce costs, improve productivity, efficiency and flexibility, and enhance product customization.

2.2. Impact of *Industry 4.0* on supply chains

As discussed in the previous section, Industry 4.0 uses several advanced tools and technologies, thus helping to redefine conventional industrial processes. Supply chains are taking a big stride towards becoming digitized, automated and agile in their operations. Today's digital SC networks employ many different technologies to develop efficient, transparent, adaptive and resilient systems in various stages of SCs including new product development, manufacturing, procurement, planning, logistics and marketing. The impacts of Industry 4.0 can be felt in different stages of SCs and also in supply chain management (SCM) strategies; e.g., more precise forecasting and planning through integrated flow and increased traceability of materials and products, improved supplier performance due to real-time information sharing and synchronisation with suppliers, and intelligent warehousing and vehicle routing systems (Hofmann and Rüsch, 2017; Ghobakhloo, 2018).

Disruption due to digitization demands companies to rethink the way their SC network is designed. The transparency and easy access to multiple options regarding where to shop and what and when to buy, enabled by e-commerce platforms drive the competition in supply chains. Especially, the IoT has a significant role in the transformation of SCs by providing a wide range of opportunities such as remote and real-time monitoring of the location and speed of vehicles, condition of perishable products via temperature sensors, status and performance of machines, etc. (Manavalan and Jayakrishna, 2019). Increased connectivity between SC stakeholders and growing importance of stakeholder collaboration necessitates assessing the impact of Industry 4.0 implementation on the SC network level (Tjahjono et al., 2017). Frank et al. (2019) specify *Smart Supply Chain* as a dimension of Industry 4.0 covering the digital platforms with suppliers, retailers, customers and partners. Growing information sharing and synchronisation of operations between SC partners help to decrease total costs and increase the efficiency and agility of SCs as a whole (Frank et al., 2019; Ghobakhloo and Fathi, 2019). The improved transparency and collaboration along the SC network also lead to increased trust and stronger relationships between SC members.

Industry 4.0-enabled capabilities including highly organised interconnections and real-time monitoring and control of materials, equipment and SC parameters help to improve the overall performance of the value chain and reduce risks (Luthra and Mangla, 2018). Incorporation of Industry 4.0 technologies also lead to the transformation in business models and management strategies in these networks (Arnold et al., 2016; Ghobakhloo, 2018). Besides the requirements and trends driving digital transformation in supply chains, new barriers and risks are also emerging as a result of the evolving business environment and digital transformation trend. Some of these issues include lack of data, information security risk, lack of skilled workforce, etc. (Barreto et al., 2017; BRICS Business Council, 2017; Deloitte, 2017). Consequently, there is a need for both conceptual frameworks and empirical studies to guide companies in developing successful and robust Industry 4.0-adapted supply chains and quickly adapting to the constantly evolving technology and markets.

2.3. Key drivers and barriers of Industry 4.0

Regardless of the rapid growth in Industry 4.0, studies associated with identification of potential drivers and barriers for the implementation of Industry 4.0 are lacking (Lu, 2017). A literature review was conducted to understand the drivers and barriers for the adoption and exploitation of Industry 4.0 technologies. Based the review, the main drivers for Industry 4.0 implementation are identified as follows:

Agility: Industry 4.0 implementation in supply chains enables real-time planning and control, allowing companies to be flexible and agile in responding to rapidly changing conditions; e.g. reducing planning cycles and frozen periods by faster reacting to changes in demand, supply and prices (Oztemel and Gursev, 2018). Business analytics approaches provide the capability of predicting future events and patterns such as customer behaviour, delivery time and manufacturing output. Real-time delivery routing and tracking also enables flexibility, efficiency and agility in logistics operations (Barreto et al., 2017).

Customization: Techniques like micro-segmentation, mass customization and advanced scheduling practices help companies to provide multi-choice packages for customers, achieve the last mile problems efficiently for high-value, deliver customers' orders at a faster rate by adopting innovative, digitized delivery and distribution techniques like drone delivery, and go beyond customer expectations (Zawadzki and Żywicki, 2016; Hofmann and Rüsch, 2017; Ghobakhloo, 2018).

Accuracy: Industry 4.0 technologies provide real-time, consistent and accurate data to make more informed decisions. Hence, next generation performance management systems will provide enhanced end-to-end visibility throughout the value chain (Miragliotta et al., 2018). The information spans from important top-level performance indicators, such as customer service and order fulfilment level, to in-depth process data, such as the exact location of trucks in the logistics network.

Efficiency: Supply chain efficiency is boosted by the automation of physical tasks, planning, control and information exchange process (Pereira and Romero, 2017). A high number of companies are using automated technologies especially in their logistics systems. These technologies include material handling robots and cranes, automated pallet handling systems, shipment tracking, unmanned autonomous vehicles, fully automated warehouses, etc. (Vaidya et al., 2018; Xu et al., 2018). Companies opt for cooperation and sharing of facilities through cross-company transport optimization to optimize truck utilization and increase transport flexibility. The entire SC network setup is continuously optimized to ensure an ideal fit for business requirements.

There are also some intimidating resisting forces, barriers, for implementing Industry 4.0 practices. These barriers may be classified under four business dimensions: organizational nature, legal and ethical issues, strategic perspective, and technological dimension (Luthra and Mangla, 2018). The most common barriers for Industry 4.0 adoption may be listed as follows:

Financial constraints: Financial constraint is a significant challenge in adopting Industry 4.0 regarding the development of an advanced modern infrastructure and innovations of a sustainable process (Theorin et al., 2017; Nicoletti, 2018). Technical competency of the focal organization is the primary emphasis that affect the scale of investment. However, the economic perspective remains at a nascent stage; this lack of clarity concerning cost-benefit analysis and monetary gains on digital investments is an imperative challenge for applying Industry 4.0 in the SC context (Arnold et al., 2016).

***Lack of management support**:* The Industry 4.0 transformational changes are quick and require adequate skill-development and training, which is challenging to deliver without high level of management support (Gökalp et al., 2017). The foremost requirement of initiating Industry 4.0 consists of cross-functional collaboration through the digitization of all the elements of the value chain network (Ras et al., 2017).

Resistance to change: Industries are unsure and unfamiliar with the term Industry 4.0 and are ignorant of the benefits of digital transformation due to which there is reluctance in adopting it (Müller et al., 2017b; Theorin et al., 2017). Operational and management systems are getting more complex with the global expansion of business networks and markets. Lack of competencies for managing global data as well as the latest technological innovations increase the hesitation of companies to adopt Industry 4.0 technologies (Ras et al., 2017).

***Lack of expertise**:* The literature calls for organized and highly focused researches by practitioners and scholars for understanding the implications of Industry 4.0 adoption in logistics and supply chains (Almada-Lobo, 2015; Hofmann and Rüsch, 2017). There is a need for studies on creating frameworks for developing Industry 4.0-driven supply chains and relevant new management appraoches by considering the drivers, benefits, implementation issues and barriers for Industry 4.0 adoption (Hermann et al., 2016).

Legal Issues: The vast data transaction across the value chain brings the cybersecurity risk; therefore, privacy and security issues need to be considered in the adoption of Industry 4.0 (Müller et al., 2017a; Kamble et al., 2018). Any digital transformation or adoption of poor infrastructure and internet connectivity are substantial barriers to the initiative (Bedekar, 2017).

Lack of policies and support from the government: Governments provide the necessary infrastructure for the digital world (like internet and communication systems) in most countries. However, there is lack of a roadmap in changing the industrial infrastructure, primarily due to lack of clarity (e.g. implementation of 5G network and its benefits for Industry 4.0) concerning the consequences of Industry 4.0 (BRICS Business Council 2017).

There are also other barriers faced by organizations trying to implement Industry 4.0 technologies such as insufficient research and development practices in Industry 4.0, lack of infrastructure, poor quality data, lack of digital culture and lack of trust through partners (Wang et al., 2016; Luthra and Mangla, 2018). Based on a comprehensive review of the literature concerning the implementation of Industry 4.0 at both company and SC level, and discussions with two experienced practitioners, main barriers and drivers for Industry 4.0 adoption in supply chains are tabulated as in Table I. For a flawless digital transformation of supply chains, SC executives need to revamp their understanding and attitude to Industry 4.0 by considering both their driving forces and barriers for Industry 4.0 implementation.

Table I. Drivers and barriers for the adoption of Industry 4.0 in supply chains

Business Dimensions	Drivers	Barriers
Organizational	• Increased efficiency • Cost reduction • Higher quality • Agility • Load balancing & stock reduction	• Financial constraints • Lack of management support • Resistance to change • Lack of digital vision and strategy • Lack of expertise • Complex network systems
Legal & ethical	• Reduction of monotonous work • Reduction of environmental impact	• Legal issues • Problems related with coordination and collaboration • Data privacy and security issues
Strategic	• New Business models • New value offers for enhanced competitiveness	• Profiling and complexity issues • Lack of policies and support from the government • Lack of research and development • Unclear economic benefits • Lack of digital culture
Technological	• Transparency	• Lack of digital infrastructure • Poor data quality and management

3. Research Methodology

The exploratory study followed a two-stage research approach. Firstly, a comprehensive literature review was conducted to identify driving forces and barriers of Industry 4.0 in the supply chain context. Secondary data sources were utilized to examine Industry 4.0 implementation in supply chains; e.g., scientific papers, academic articles, magazines, white paper articles, business reports, reports from consultancy firms, blogs from field experts, webinars, and technical videos. The most common drivers and barriers of Industry 4.0 adoption were identified and categorized under four business dimensions: organizational, legal and ethical, strategic, and technological (Table I). The developed table was used as a basis for the quantitative model. In the second stage, System Dynamics (SD) approach was used to model an Industry 4.0 adopted SC by incorporating the impacts of drivers and barriers for this digital transformation. SD methodology was selected because of its high capability in modelling complex and dynamic systems under different scenarios (Campuzano and Mula, 2011).

SD approach is based on systems thinking and supports developing simulation models for holistic assessment of complex systems (Ghadge et al., 2013). Development of a SD model is a stage-wise process for translating a problem into quantitative representation, followed by simulation (Akkermans and Dellaert, 2005; Golroudbary and Zahraee, 2015). In the SD approach, first the problem is defined, and the scope of the system is identified based on the available information. Then, the system is conceptualized by developing a causal loop diagram (CLD) that includes key variables of the system, interrelationships between variables and the feedback structures (Bala et al., 2017). Causal-loop diagrams exhibit the structure of the system under consideration by reflecting the link between various influencing variables (Georgiadis et al., 2005). They consist of several variables connected by arrows and influence links (lines) which form several causal loops and chains. The polarity of an influence link represents the direction of the causal effect (Qiu et al., 2015). The causal loop diagram is then converted into a stock-and-flow diagram for computer-based simulation. Stock and flow diagrams are mathematical representations of systems by using stock, flow and auxiliary variables. There are several commercial packages like Vensim, Anylogic, DYNAMO, iThink, and Powersim for developing SD models and performing simulation studies. In this research, Vensim commercial software was used for developing causal loop diagrams and stock-and-flow diagrams and performing simulation analysis.

In this study, first, a causal loop diagram was developed to conceptualize the impact of the identified barriers and drivers on the implementation of Industry 4.0 in supply chains, by including the inter-relationship between different influencing variables. These variables were represented under four different loops (strategic, legal and ethical, technological and organizational) in parallel with the categorisation in Table I.

Later, a comprehensive causal loop diagram was developed by integrating these factors into a broader SC system. This causal loop diagram was used to develop two stock and flow diagrams: i) a traditional SC, and ii) an Industry 4.0 adopted SC. These models were run to analyse the behaviour of SC dynamics and provide insights into the implementation of Industry 4.0 in supply chains. The findings of the simulation model as well as the literature review have also been used to develop a general framework for implementing Industry 4.0 in supply chains.

4. Proposed SD Model

In this section, an SD model was developed to investigate the behaviour of SC dynamics while implementing Industry 4.0. Before providing the SC model, it is essential to understand the impacts of different drivers and barriers of Industry 4.0. Therefore, a preliminary causal loop diagram was developed to represent the inter-relations between the identified factors in Section 2.3 (See Figure 1). In Figure 1, the drivers and barriers of Industry 4.0 implementation in supply chains are represented under four causal loops; strategic, legal and ethical, technological, and organizational. The most critical relations are assessed and represented on the figure based on discussions with two experienced practitioners. Impact of drivers are represented with green arrows; other relations are represented with red arrows. Positive and negative relationships between different variables are depicted by '+' and '-' signs respectively. All of the four dimensions affect the implementation of Industry 4.0 practices in supply chains.

For the strategic business dimension, enhanced competitiveness trigger the emergence of new business models, which is another driver of Industry 4.0. Lack of policies leads to lack of R&D studies, problems in calculating economic benefits and, hence, lack of digital culture which increases the complexity for Industry 4.0 implementation. For the legal and ethical dimension, increased coordination and collaboration problems leads to the emergence of data security problems and, thereby, legal issues. From the technological perspective, lack of digital infrastructure leads to difficulty in accessing high-quality data. For the organizational perspective, lack of management support and lack of digital vision directly or indirectly cause a decrease in the efficiency of Industry 4.0 adoption. Financial constraint is another factor that prevents developing high quality and successful applications of Industry 4.0 technologies.

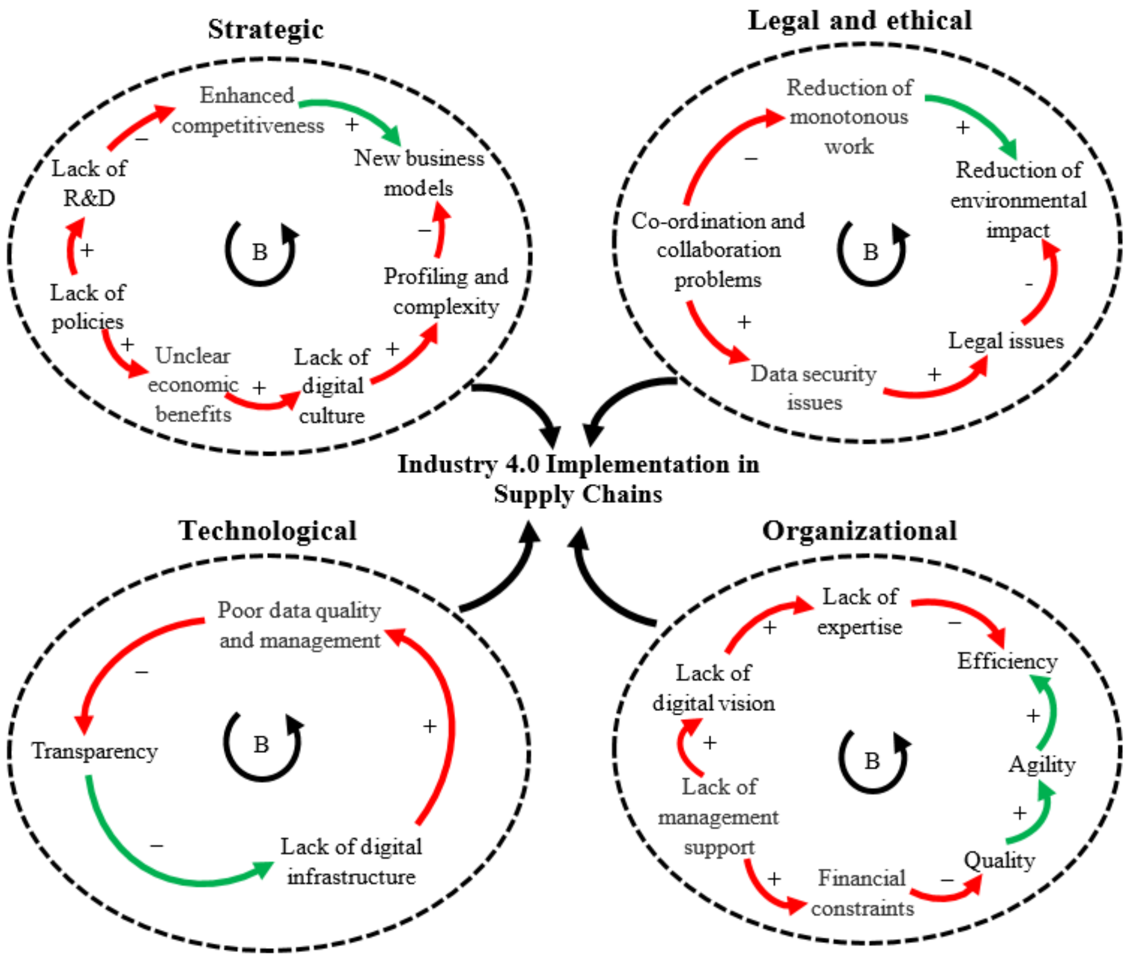

Figure 1. Preliminary causal loop diagram illustrating the potential barriers and drivers for Industry 4.0

This CLD was used to plot the relationship between supply chain variables (e.g. production rate, manufacturer's inventory level, shipment rate) and link them with critical drivers and barriers for Industry 4.0 implementation as shown in Figure 2. The relationship between SC dynamics are represented by blue arrows. The impacts of the driving forces for Industry 4.0 implementation are represented by green arrows. Barriers are represented as external factors in the causal loop. Although there may be some internal factors such as lack of digital infrastructure, there are also many external factors that may prevent companies to implement Industry 4.0 practices. Examples include lack of support from governments, unclear economic benefits, and resistance to change.

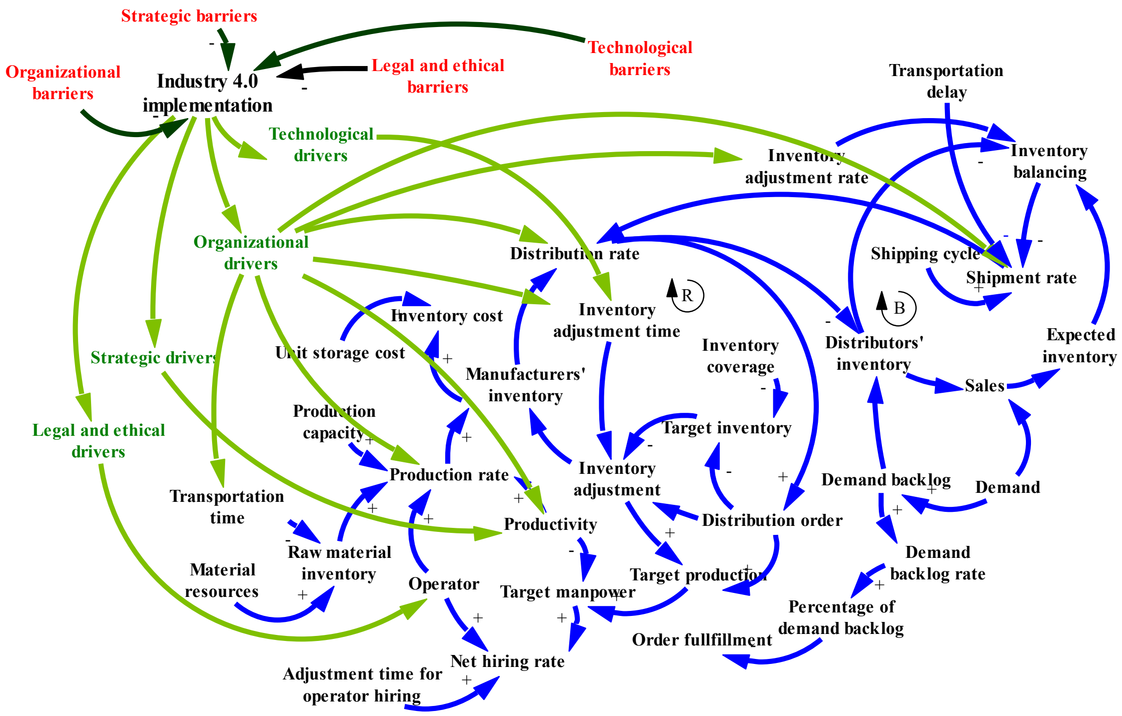

Figure 2. Causal loop diagram

Later, this diagram was converted into two different stock and flow diagrams to make a comparison between a traditional and Industry 4.0 adopted supply chains. Figure 3 represents stock and flow diagram of a traditional supply chain, and Figure 4 represents the same SC after incorporating two important Industry 4.0 technologies; Cloud computing and RFID. In Industry 4.0-enabled SCs, dynamics of supply chain is captured by assessing the improvement in SC operations based on adopted Industry 4.0 capabilities. Simulated capabilities include data utilization in inventory management via the use of cloud technology, and visibility and traceability of inventory and products provided by the RFID technology.

Real-time information sharing and improved visibility are incorporated to SC operations and included in SC variable equations such as inventory levels, distribution rate, and order fulfilment. Since the study focuses on the impact of Industry 4.0 adoption on SCs, the model is broken down into five different echelons to track the changes in critical performance metrics; raw material inventory, manufacturer's inventory, operator, distributor's inventory and demand backlog.

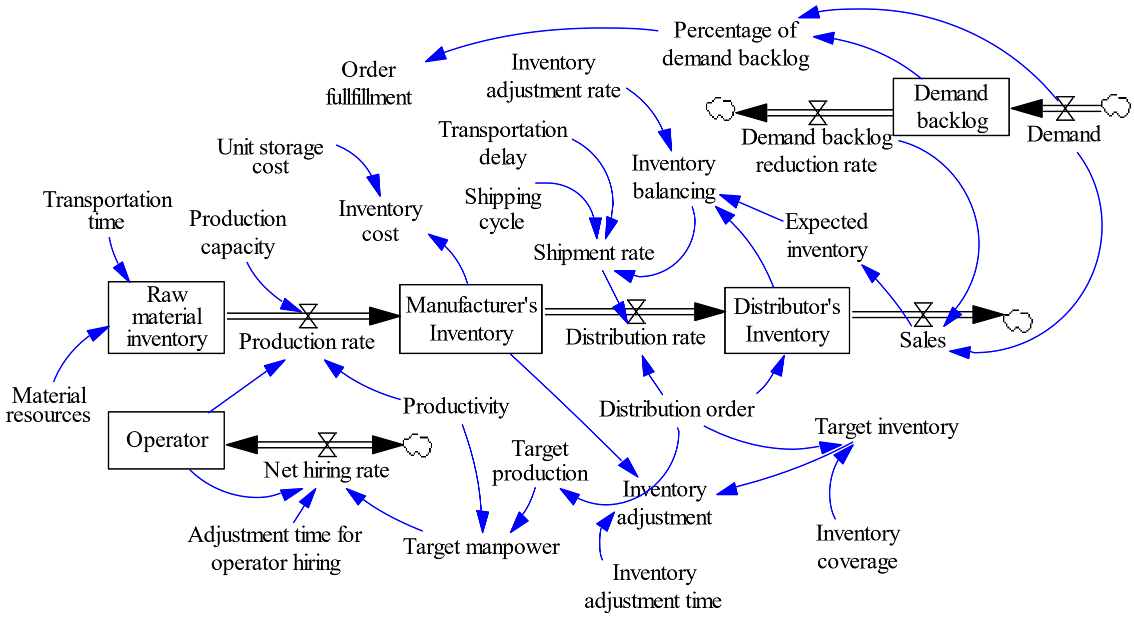

Figure 3. Stock-and-flow diagram for a conventional supply chain

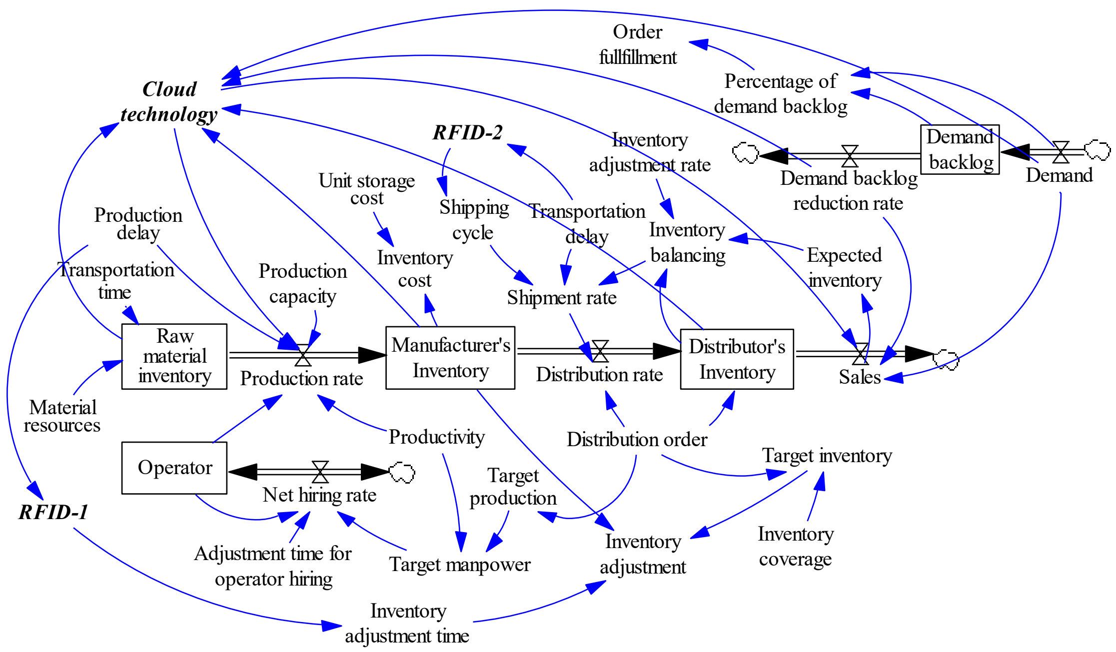

Figure 4. Stock-and-flow diagram for an Industry 4.0 adopted supply chain

In order to provide a better representation of the real business environment, defined mathematical equations and parameters in the second model also consider identified drivers and barriers of this technological adoption. Identified drivers and barriers cannot be used directly in stock and flow (accumulations and rates); however, they are modelled as part of variables considered in the modelling. For example, the *agility* driver is associated with *inventory adjustment rate*; the *financial constraint* barrier is associated with *unit storage cost*. The variables and parameters are adjusted based on driving and resisting forces for technological transformation.

5. Results and Development of Framework

Vensim PLE was used to simulate the traditional and Industry 4.0 adopted SC models. Manufacturer's inventory level, inventory cost and order fulfilment are very important SC performance metrics; therefore, these two models with different technology levels are basically compared based on these dimensions. Simulation results are provided in Figure 5 and Figure 6. As it can be seen from Figure 5, the results show improved inventory levels and reduction in inventory cost with cloud-enabled inventory management practices and the use of RFID tags compared to the traditional system. In the traditional SC model, the manufacturer's inventory shows an oscillating curve due to instability in the process driven by poor inventory management. Whereas, with the introduction of RFID and cloud technology in the system, the inventory is stabilized due to constant information sharing of demand, order, shipment, and production output in the supply chain network. Both technologies allow utilization of data to optimize operational performance. Increased visibility and agility provided by Industry 4.0 technologies have a considerable role in providing flexible, agile, robust and sustainable supply chains. With RFID (as a prerequisite for IoT), there is also transparency across the value chain. With the implementation of RFID tags to all products, real-time data can be made visible among all supply chain members for accurate forecasting, production planning, and logistics strategy development.

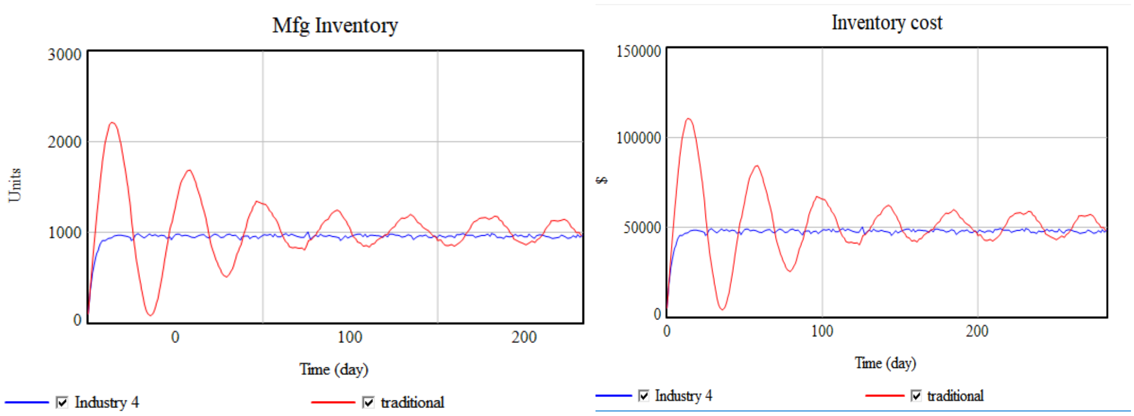

Figure 5. Manufacturer's inventory level in traditional vs Industry 4.0 adopted SC

The variation in logistics shipment and demand fluctuation with order backlog is fed to the cloud system in real time, thereby negating the bullwhip effect and creating a transparent system with all the stakeholders. Also, we can observe the change in the rate of order fulfilment in Figure 6, which clearly illustrates random-ness and low customer service due to lack of communication and feedback on demand backlog. With the introduction of information-sharing through the cloud system and tracking through RFID, there is clear communication and visibility of order flow. Data-driven decision making and responsiveness to disruptions provided by the employed Industry 4.0 technologies improve SC efficiency and hence will lead to improved customer satisfaction.

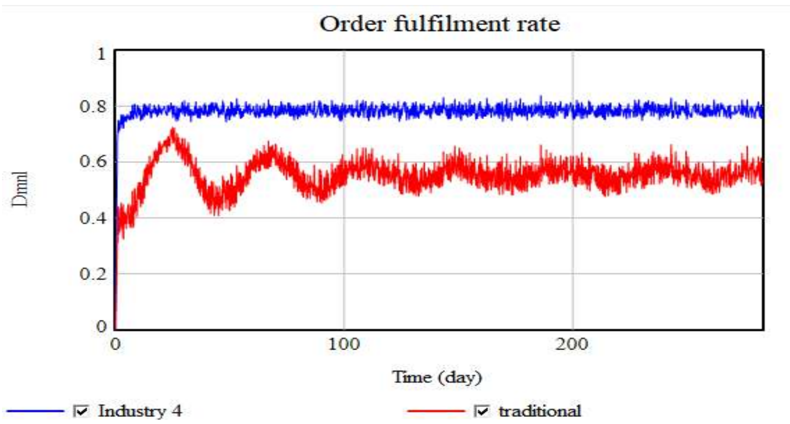

Figure 6. Order fulfilment rate in traditional vs Industry 4.0 adopted SC

Development, implementation and maintenance of Industry 4.0 platforms may be seen as a loop in which gains and costs should be assessed and balanced. As simulation results confirmed, Industry 4.0 technologies may have a huge impact on SC parameters. It is important to discuss the drivers and benefits of Industry 4.0 paradigm within SC perspective which is in immature period. Therefore, simulation results and insights gained from the relevant literature are used to develop a conceptual framework for the implementation of Industry 4.0 in a supply chain network. The proposed holistic framework is structured in two main phases: digitalization of business and transformation of business networks. The main components of these two phases are given in Figure 7. The growing implementation of Industry 4.0 technologies and digitalization of business has necessitated a transformation along the business network level. These developments lead to changes in corporate culture, management strategies and business models, as well as operations and inter- and intra-organizational relationships.

Ten critical components of Industry 4.0 implementation in supply chains are given under the digital SC triangle in Figure 7. These major issues are: i) digital culture, ii) new digital business models, iii) collaboration and data sharing, iv) optimized data management, v) connected processes and devices, vi) synchronized planning and inventory management, vii) integrated performance management, viii) SC transparency, ix) Integrated value chains, and x) connected customers and channels. These components are inevitable for developing operational excellence platforms. Re-configuration of the entire value chain network from upstream to downstream with integrated technology creates intelligent, connected, autonomous, flexible and customized networks. The results of the SD model show that incorporation of Industry 4.0 technologies to the SC network leads to a significant improvement in the performance of the SC with respect to inventory, cost and customer service. It is evident that the introduction of Industry 4.0 in SCs supports in improvement in transparency, collaboration and information-sharing. Integration of processes, data, and devices of the stakeholders in the value chain has an important effect for real-time predictive, synchronized and collaborated end-to-end planning. As businesses and supply chains transform, new drivers and barriers occur; therefore, this stage is represented with a circular loop in Figure 7.

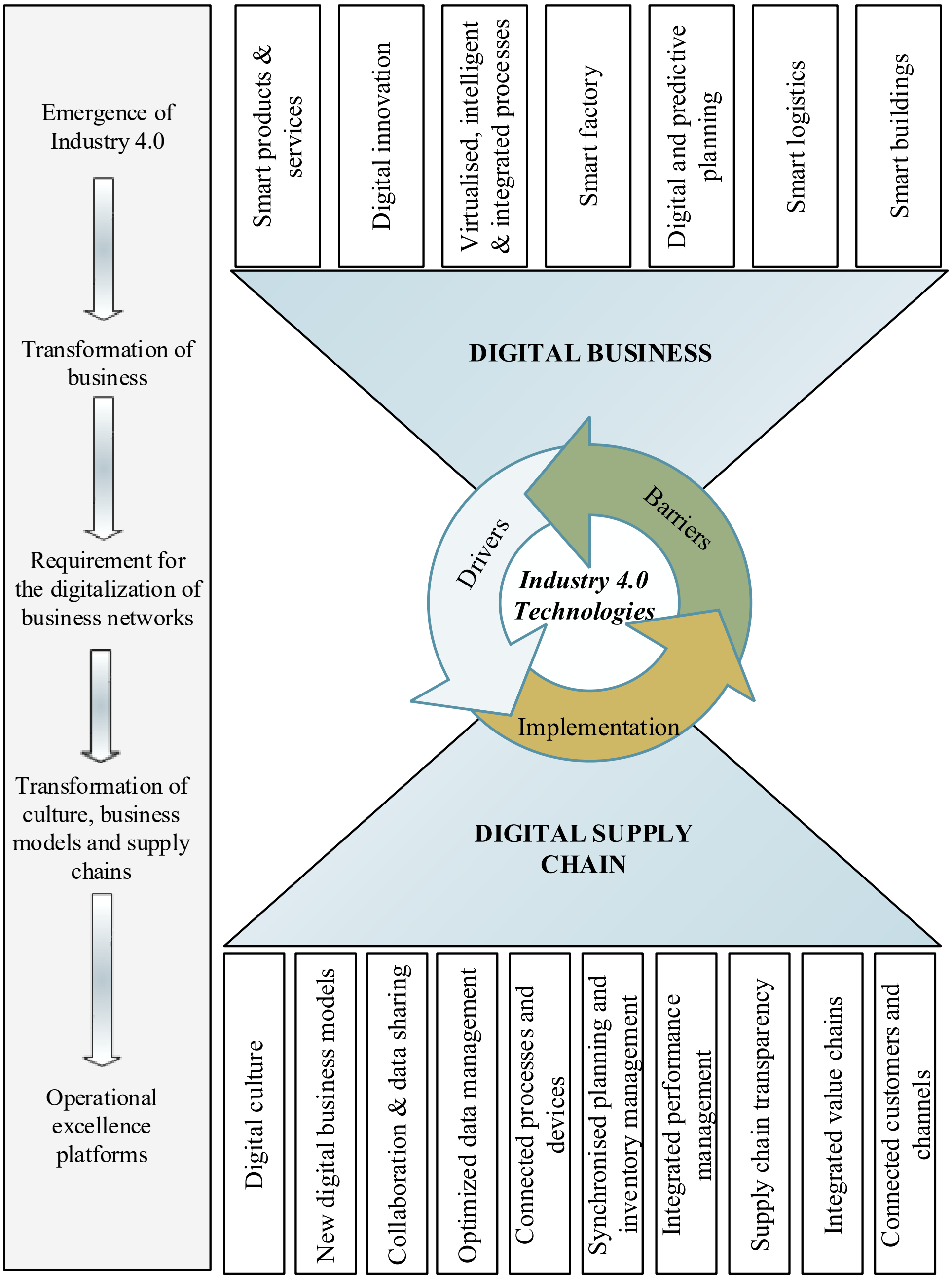

Figure 7. Framework for the implementation of Industry 4.0 in supply chains

6. Discussion

Despite the burgeoning literature in this area, it is found that, there is lack of holistic approaches, strategies and frameworks for the implementation of Industry 4.0 in supply chains. Following a systematic approach to the problem, first, key drivers and barriers of Industry 4.0 in supply chains are identified based on the relevant literature. Luthra and Mangla (2018) identified four dimensions of challenges namely: organizational, legal and ethical, strategic and technological dimensions. This categorization is adapted to analyse the impacts of identified drivers and barriers for Industry 4.0 implementation in this study. Then, an SD model is developed to evaluate the effects of the barriers and drivers of Industry 4.0 on its implementation in supply chains. The overall understanding of impact and associated learnings lead to the development of conceptual framework for successful adoption in digital supply chains.

The results of the SD model provide several important insights for the comparison of a traditional and Industry 4.0-enabled SC. The implementation of two technologies- cloud technology and RFID substantially increases the operational performance, by reducing and stabilizing inventory levels and inventory costs. The main reason for this improved inventory management level is higher visibility due to real-time inventory monitoring and information sharing among SC members. This improvement will also enhance organization's adaptability, agility and flexibility. Real time information visibility and transparency provided by the employed technologies also improve forecasting, production planning, order fulfilment and responsiveness to disruptions. Investigation of Industry 4.0 adoption in the SC level reveals the actual cumulative effect of this technological transformation on business operations. These findings are compatible with the previous studies that address advantages of Industry 4.0 paradigm (Strange and Zucchella, 2017; Zhong et al., 2017; Oztemel and Gursev, 2018; Ghobakhloo and Fathi, 2019). Nevertheless, the results obtained through the SD modelling are important to quantify the overall cumulative impact of Industry 4.0 adoption in SCs.

Several large enterprises and SMEs are moving towards the fourth industrial revolution across different industries such as automotive, defence, electrical and pharmaceutical industries (Arnold et al., 2016; Müller, 2019). Recent studies are attempting to map different Industry 4.0 technologies to various SC processes; e.g. supplier selection using multi agent technology (Ghadimi et al., 2019), IoT devices for machine-enabled decision making for real-time information sharing among SC partners (Haddud et al., 2017), cloud computing for centralized manufacturing execution systems (Almada-Lobo, 2015), RFID tags and sensors for real time vehicle tracking (Barreto et al., 2017). Digitization and automation of processes leads to the transformation of entire SC into a network of physical entities that interact and communicate with each other (Ghadimi et al., 2019). Therefore, comprehensive strategies and application of frameworks are required to realize full potential of this digital transformation in the SC level. This also requires the transformation of organizational culture, network structures and management practices of SCs in line with the Industry 4.0 vision.

7. Conclusion

Industry 4.0 is an inevitable revolution covering a wide range of innovative technologies such as cyber-physical systems, RFID technologies, IoT, cloud computing, big data analytics, advanced robotics, etc. The Industry 4.0 paradigm is transforming business in many industries; e.g. automotive, logistics, aerospace, defence and energy sectors. A growing amount of academic research is focussing on Industry 4.0 technologies and implementation issues (Ghobakhloo, 2018; Sarvari et al., 2018; Frank et al., 2019). With such a digital changeover, the supply chain is one area undergoing great metamorphism. It is evident from the study that the traditional supply chains need to transform swiftly by implementing Industry 4.0 principles to survive in rapidly changing markets. Companies are looking beyond the boundaries of the supply chain to adopt and embrace the new revolution. However, a limited number of researchers have addressed the importance of examining the Industry 4.0 transition within a SC network perspective. This study contributes to this very critical gap by discussing the key drivers, barriers and other implementation challenges of Industry 4.0 within supply chain networks.

The results of the simulation model are used to create a general, four-phased framework for the implementation of Industry 4.0 in SCs. The framework consists of four steps to coordinate successful implementation. This is a unique study that examines the dynamics of Industry 4.0 in SC systems following an SD approach. Previous studies are generally based on discussions on Industry 4.0 technologies and development of design principles for these technologies. Proposed SD based methodology provides the opportunity to quantify the relationship between Industry 4.0 technologies and SC dynamics under the effect of different barriers and drivers. The framework for implementation of Industry 4.0 in SCs is developed to accelerate successful adaptation of a new paradigm in the current digital world.

The proposed framework is a valuable contribution for adoption and acceleration of Industry 4.0 in logistics and supply chain management. The findings of the SD model and the proposed Industry 4.0 implementation framework will provide insights for companies about the benefits of Industry 4.0 adaptations and ways to implement them in supply chains successfully. This paper provides a framework for implementation which can be tested and verified by researchers in the future. The system-dynamic model developed can be used as the basis for future development and analysis of supply chains and its interaction with Industry 4.0 tools and techniques. The research provides insights for practitioners by identifying challenges for the implementation of Industry 4.0. The SD models developed can be used as a base model for companies to understand the influence of individual application of Industry 4.0.

As with other research, the study has several limitations. First, the study did not use empirical data to test the SD models. Several assumptions have been made during simulation for ease of interpretation of the results. Also, due to the complexity of the supply chain, only a few parameters of Industry 4.0 (RFID and Cloud) were considered in the model development and evaluation. In the future, the results and key findings of the model can be validated using primary data. Other performance indicators need to be evaluated by extending the model across the value chain.

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