Impacts of Digital Technologies on Supply Chain Performance: A System Dynamics Approach

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Abstract
The advent of Industry 4.0 and associated digital technologies makes it possible to share information and access data real-time. Such a capability needs to be investigated in the Supply Chain Management (SCM) to study the joint impacts of digital technologies on transforming SC members' behavior. In this paper, Cloud Computing, Internet of Things, and Big Data Analytics have been selected due to their relevant effects on real-time information sharing within different SC echelons rather than inside one echelon. Moreover, the implementation of these technologies in real SC requires high investments. Also, due to the increased complexity of the SC after applying these technologies, their impacts on SC behavior and performance should be determined precisely. This paper proposes simulation as a cost-effective and comprehensive method to investigate how digital technologies affect SC performance. A three echelon manufacturing SC has been simulated by using System Dynamics (SD) modeling under different scenarios in both traditional and digital SCM. The results reveal a significant improvement of SC performance, in terms of inventory level and cost as well as order fulfillment ratio, in digital SCs compared to traditional SCs. Future research will further develop the model by validating the simulation results with real cases from the industry.

Keywords
Digital technologies, Supply Chain, performance, System Dynamics, simulation.

Biographies

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1. Introduction

In recent years, technological improvement changes customer expectations in all aspects, from the transparency of originality and quality of raw materials to the availability and timely delivery of final products. In this regard, the superiority of each product could depend on its SC competitiveness. Therefore, SCs need to be more connected and integrated to be able to retain their market share in the current competitive era. In this regard, developing new technologies, like for example Cloud Computing (CC), Big Data Analytics (BDA), and the Internet of Things (IoT) could help SCs to have real-time data and information. These digital technologies are considered as key potential solutions in order to pave the way for companies for having more integrated SCs (Büyüközkan and Göçer 2018; Queiroz et al. 2019; Raut et al. 2018; Shee et al. 2018; Sundarakani et al. 2019). Moreover, digital technologies could have potential effects and some advantages for SC members. For instance, improving transparency and collaboration stems from using Industry 4.0 technologies to enhance the trust level and make a stronger relationship among SC members (Ghadge et al. 2020). Additionally, by applying these new technologies it could be possible to set the prices based on the dynamic conditions and benefit all the members of the SC as well as increase the service level to customers (Schmidt and Wagner 2019).

This paper aims to investigate the impacts of applying digital technologies on the behavior of different members of a SC. In fact, the current literature on Industry 4.0 technologies in Supply Chain Management (SCM) asks for a comprehensive investigation on the effects of these different technologies in combination with each other on the SC in order to have a better understanding of their impacts. Novais et.al (2019) suggested studying the impact of CC on the integration of SC in combination with the other Industry 4.0 technologies to investigate their joint effects on SC connections and integration. Addo-Tenkorang & Helo (2016) reported that CC and BDA are dependent technologies: BDA relies on CC as storage for processing and sharing data. Moreover, according to the report from HP by the year 2030 IoT data will be identified as the most influential data for BDA (Addo-Tenkorang and Helo 2016). In this way, it could be concluded that CC, IoT, and BDA have a strong influence on changing the structure of information sharing throughout the SC. Therefore, given the interconnection between such three technologies and their importance to SCM, this paper studies the impact of simultaneously applying CC, IoT, and BDA on the performance of a three echelon manufacturing SC. The focus is on the following research questions:

1. How academicians and practitioners can study and assess the impacts of the selected Industry 4.0 technologies on the SC?
2. What are the effects of applying the selected Industry 4.0 technologies on SC performance?

Implementation of new technologies in SC is costly, and makes the system complex; therefore, simulation is used to analyze SC in a cost effective and accurate manner. In this regard, Systems Dynamics (SD) models are recognized as a potential simulation tool for studying different scenarios to analyze the possible behaviors of the systems under introduced conditions. Hence, the present paper will develop SD models to investigate the effects of Industry 4.0 technologies on the different parts and members of a SC as an integrated system and compared that with the performance of traditional SCs.

The rest of the paper is organized as follows: In section 2, the literature on the related background has been presented in two sections. In section 3, the main structure of the proposed SD model has been described. Then, in section 4 the results of the SD model and findings have been discussed. Finally, In the last section conclusion and limitation with some directions for future research has been presented.

2. Literature Review

In the present section to illustrate the background of the research, a brief discussion is presented in two-fold. First of all, the impact of Industry 4.0 technologies on the digitalization of the SCM is investigated. Afterward, different possible methods to study the impact of Industry 4.0 on SCM are discussed. The benefits and limitations of each methodology are identified and the best one to achieve the goal of this research is selected.

2.1 Impact of Industry 4.0 on digitalization of SCM

Nowadays, in the current competitive era, one of the major concerns of companies is improving the customer service level to retain the market share. To this end, companies highly rely on having an integrated and flexible SC. Therefore, companies need to make collaboration with the other members of their SCs. As a matter of fact, collaboration not only includes information sharing between different SC partners but also makes efficient connections throughout the SC to overcome difficulties and obtain common goals (Yu, Cao, and Schniederjans 2017). As a result, making collaboration between SC members leads to a greater impact on improving the total value of SC compared with such SC value without collaboration (Jiang 2019). Thus, collaboration brings about significant improvements in SC competitiveness (Jiang 2019) and service level to customers (Yu et al. 2017). In this regard, according to Singh, Kumar, and Chand (2019) many pieces of research have addressed the impact of collaboration on the traditional SC. However, with the advent of Industry 4.0 technologies, it is possible to have a more connected and flexible SC by digitalizing its main processes (Büyüközkan and Göçer 2018; Ghadge et al. 2020).

To this end, Industry 4.0 technologies like CC, IoT, and BDA by making cross-functional collaboration among SC partners provide real-time data, transparency, and visibility throughout the SC that lead to significant impacts on performance (Shee et al. 2018; de Vass, Shee, and Miah 2020; Wamba et al. 2020; Wilkin et al. 2020).

Similarly, Industry 4.0 technologies can make a great improvement to the different areas and issues of SCM. In revenue and cost-sharing BDA has been considered as one of the potential technologies to affect different SC echelons. Xiang & Xu (2020) showed the impact of information sharing and BDA on cost-sharing between three echelon SC under different conditions. Tsao (2017) by considering revenue sharing tried to figure out who is responsible to invest in BDA and what is its effect on the behavior of other SC members.

Besides, many pieces of research have been focused on studying the impacts of digital technologies on the sustainability of SC. Singh and El-Kassar (2019) indicated the integration of BDA technologies, green SC management, and green human resource management practices to enhance firms' sustainable performance. Also, Mishra et al. (2020) reported the important influence of BDA on corporate social performance and corporate green performance. Shee et al. (2018) investigated the role of CC to enhance the firms' sustainability by improving the SC performance. Jede and Teuteberg (2016) discovered the relation between CC and SC by a systematic literature review and suggested the possible effect of CC on enhancing the attention of firms to sustainability issues. Also, de Vass et al. (2020) indicated the positive effect of IoT on the triple bottom lines of sustainability by enhancing the SC performance. Li et al.(2020) enhanced the sustainable production management of SC by using IoT, Blockchain, and BDA to design a production capability evaluation system.

Aside from these points, to have a coordinated SC using these technologies by all its members is suggested. In fact, applying single Industry 4.0 technologies just by one SC echelon gives rise to sub-optimality of using resources (Singh et al., 2019). However, most of the researches in the field of digital SCM has studied the impact of individual technologies on the SC partners' behavior and structure of SC. However, there is a need to study these technologies in combination with each other (Novais et al. 2019; Pournader et al. 2020; Zelbst et al. 2019) to better understand their integrated effect on the whole SC. To this end, Lee (2019) designed a dynamic control solution to overcome the issues of production by using CC, IoT, and BDA. Additionally, Jiang (2019) used the combination of BDA and IoT to investigate the key factors that affect the Bullwhip Effect in the SCM. Also, they considered CC as a solution to the complexity of data collecting by IoT. In a study to investigate the application of BDA on SCM, Addo-Tenkorang and Helo (2016) concluded that the success of IoT is highly dependent on making the efficient connection between IoT, BDA, and CC.

2.2 Methods for studying digital SCM

Industry 4.0 is a newborn concept. Therefore, the research on the impact of Industry 4.0 technologies is in its infant stage (Menon, Shah, and Coutroubis 2018). By considering this fact, it is important to pay special attention to know how different methods can assist academicians and practitioners to investigate the influence of digital technologies on the SCM. The novelty of these technologies and limited or sometimes no access to real cases of their implementation have led many researchers to the development of hypotheses and surveys to illustrate the roles and effects of Industry 4.0 technologies on SCM processes and issues (Gawankar, Gunasekaran, and Kamble 2020; Manuel Maqueira, Moyano-Fuentes, and Bruque 2019; Wamba et al. 2020). To identify the benefits and challenges in adopting Industry 4.0 technologies many researchers provided conceptual works or presented frameworks for analysis. To this end, some papers used a survey to develop the concept or framework (Jha et al., 2020; Sodero et al., 2019). Other papers tried to construct their concept or framework based on the literature reviews on the relevant background (Arunachalam, Kumar, and Kawalek 2018; Büyüközkan and Göçer 2018; Kamble and Gunasekaran 2020).

It is worth mentioning that the inherent differences between these technologies lead to the distribution of using various methods to be not the same. For instance, the use of optimization with mathematical modeling and game theory in BDA (Lamba, Singh, and Mishra 2019; Ma and Hu 2020) has been more debated compared to CC. On the other hand, developing tools, platforms, and constructing architectures are more prevalent in CC (Akbaripour, Houshmand, and Valilai 2015; Dahbi and Mouftah 2016) in comparison with BDA (Giannakis and Louis 2016; Mani et al. 2017). This difference stems from the fact that CC revolutionizes IT architecture. Nevertheless, BDA is used to optimize the process of operational decision making (Addo-Tenkorang and Helo 2016).

In addition, connecting different SC echelons and partners by using Industry 4.0 technologies results in having a more complex system (Ghadge et al. 2020). Moreover, the cost of implementing these technologies in the real world is high. Therefore, it is risky to investigate the influence of these technologies and new strategies on the market dynamics in the real-world (Groves et al. 2014). SD modeling has been introduced as one of the capable methods to assist in analyzing complex systems under different scenarios (Cagliano et al. 2011; Ghadge et al. 2020).There is a paucity of research in the field of digital SCM that has been used the SD simulation. Gonul Kochan et al. (2018) studied the impact of CC on the performance of hospital SCs by SD simulation. Hofmann (2017) analyzed the influence of BDA on SCM activities and processes to reduce the Bullwhip Effect. Ghadge et al. (2020), by identifying barriers and drivers for applying Industry 4.0 in SCM based on literature, constructed a SD simulation model focuses on CC and IoT.

To sum up, CC, IoT, and BDA have been identified as the most promising Industry 4.0 technologies to make SC members more connected. Therefore, there is a need to study the impacts of the combination of these technologies on the SC behavior. Also, the joint application of such technologies increases SC complexity. Hence, there is a further need to simulate different scenarios by SD models to investigate the associated outcomes and predict their effects on the SC performance.

3. Methodology and model development

The investigative research followed a two-step research approach. Firstly, an extensive literature review was conducted to define the reference SC, potential digital technologies and their impacts on the SC management context. Secondly, data sources were used to assess the digital transformation of SCs, e.g. scientific papers, academic articles, magazines, white paper articles, business reports. The potential digital technologies which can be implemented in SC were identified including the main echelon's of SC(Ghadge et al. 2020). CC, IoT and BDA were selected as possible set of technologies in digital SC. In the second step, a SD approach was applied to model SC through integrating the impacts of drivers for this digital transformation(Gonul Kochan et al. 2018).

3.1 Traditional vs digital supply chain

Figure 1 shows the structure of a traditional SC. In this traditional SC, each member has been connected with the previous echelon and the next one with both physical and information flows. Therefore, each echelon only relies on the information received from the previous and next echelon to make the decision about its activities. Therefore, each echelon makes its own decisions and forecasts on different parameters without access to the other echelons' information.

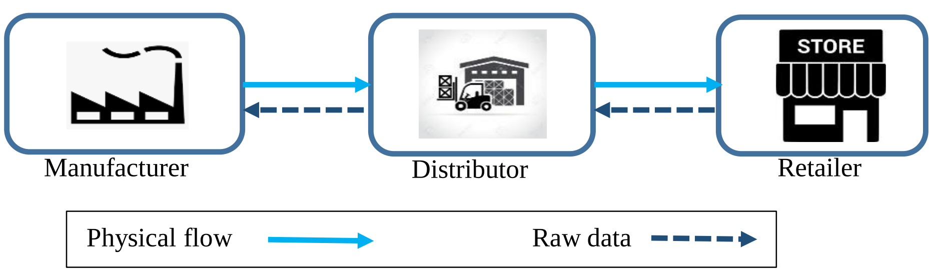

Figure 1. Traditional SC

On the other hand, figure 2 depicts the new SC configuration by applying new technologies including CC, BDA, and IoT. These technologies are used in different parts of the SC to change the structure of connections among echelons. In this regard, by using IoT raw data (like inventory levels, retail price, demands, lead times) are collected from Manufacturers, Distributors, and Retailers. Then, data are sent to a BDA system for analyzing the patterns and forecasting the demands and information from IoT data. Afterward, the analyzed data are available for all members (Manufacturer, Distributor, Retailer) on a CC platform. The access to such analyzed data in all the echelons leads to having the same information and forecasts for the different variables throughout the SC. Therefore, different echelons can make collaborative decisions to reduce the Bullwhip Effect (Hofmann 2017; Jiang 2019) and have a better perception of their SC activities. Additionally, by constructing a new structure based on these technologies all the echelons send feedbacks and share their decisions about different parameters by using IoT and BDA to the CC platform and share them throughout all SCM members.

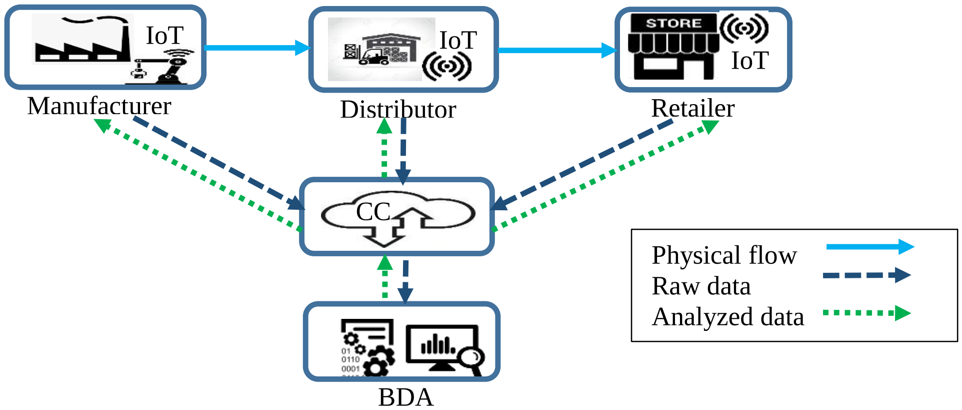

Figure 2. Digital SC

3.2 System Dynamic model

The suggested System Dynamics model has been developed based on by previous research works such as (Cagliano et al. 2017; Ghadge et al. 2020; Gonul Kochan et al. 2018) as well as by the System Dynamic modelling of SC and inventory management (Sterman 2000).The model is structured as integrated parts of each echelon of the SC including Manufacturer, Distributor and Retailer. Every echelon will include multiple companies in a real SC, thus the behavior of a representative company in each echelon is here modelled. Moreover, it has been constructed the TO-BE system which indicates the impact of digital technologies such as CC, IoT and BDA in SC. Figure 3 illustrates digital SD model which is developed on the basis of traditional form of the SC as traditional SD model. Black font variables with blue arrows are fundamental representation of traditional SC, whereas the colored ones with dash line arrows are integrated by authors to develop the transformation to the digital SC SD model.

Table 1 shows the notation authors use to represent the general structure of 3-echelon SC with the main parameters and variables of the simulation model of the traditional SC as well as the application of the digital technologies in SC.. In addition, these notations were used to develop the stock&flow diagram and its associated Systems Dynamics (SD) models for comparing traditional and digital SC. This work uses parameters and variables that have been widely studied and recommended for SD models to establish proper means for simulating SC behavior(Sterman 2000). Inventory level, inventory gap, order fulfillment ratio and inventory cost were selected as the potential criteria to understand the behavior digital technologies in SC. Inventory level for each echelon was computed based on the following equation:

$$\text{Inventory level}_\text{i} = \text{INTEG}(\text{Shipment rate}_{\text{i}-1} + \text{Shipment rate}_\text{i}, \text{Desired inventory}_\text{i}) \qquad (1)$$

where "i' indicates supply chain echelon and its order respectively Manufacturer, Distributor and Retailer.

Inventory gap appears when there is not enough inventory coverage as well as there is a difference desired inventory level and inventory level within a given inventory adjustment time. The following equation was used to define the inventory gap:

$$\text{Inventory gap}_\text{i} = \text{MAX}\left\{0, \frac{(\text{Desired inventory level}_\text{i} - \text{Inventory level}_\text{i})}{\text{Inventory adjustment time}_\text{i}}\right\} \qquad (2)$$

Order fulfillment ratio is the ratio of Maximum shipment rate and Desired shipment rate of each echelon and it was calculated based on the following equation (Sterman 2000):

$$\text{Order fulfullment ratio}_\text{i} = \text{Table for fulfullment}\left(\frac{\text{Maximum shipment rate}_\text{i}}{\text{Desired shipment rate}_\text{i}}\right) \qquad (3)$$

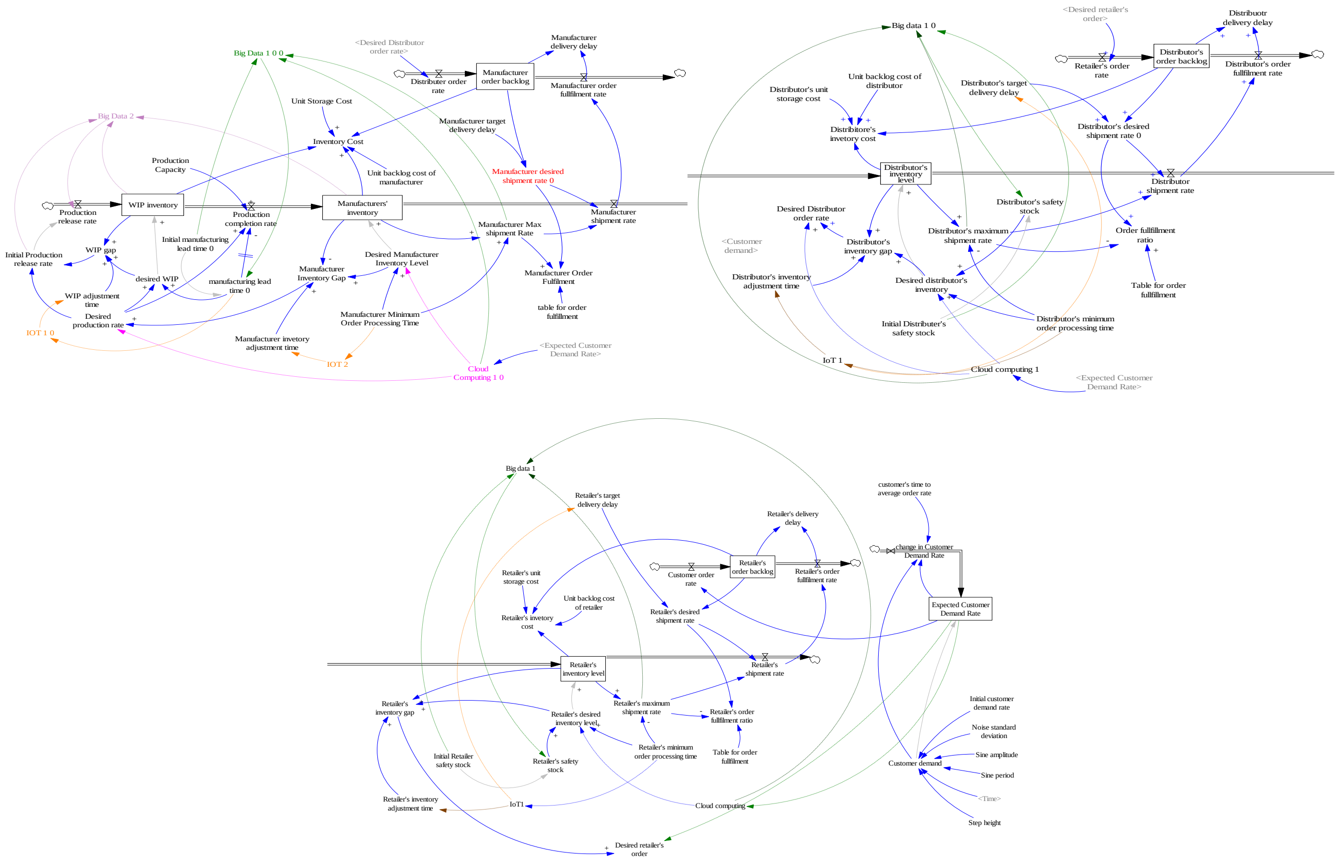

Figure 3. Digital SC SD model

Inventory cost is defined as sum of the inventory and backlog cost of each echelon. Detailed equation for inventory cost is given as following:

$$\text{Inventory cost}_i = \text{Inventory level} * \text{Unit cost of inventory} + \text{Order backlog} * \text{Unit cost of backlog} \qquad (4)$$

All the previous four variables are very important SC performance metrics (Ghadge et al.2020b). In this study "Inventory cost" is taken into account to the exclusion of investment cost of digital technologies. The most potential relations are evaluated and illustrated in the Figure 3 based on previous contributions (Ghadge et al. 2020; Gonul Kochan et al. 2018). Impacts of CC, IoT, BDA are represented with green, orange, light violet arrows, respectively; other relations are represented with blue arrows. Positive and negative relationships between different variables are depicted by "+" and "-" signs, respectively. Integration of the digital technologies to SD model of supply chain is described by the following equations:

$$\text{Big data 1} = \text{IF THEN ELSE (Cloud computing} > \text{Retialer's maximum shipment,} \\ \text{initial retailer safety stock} * 2, \text{Initial retialer safety stock} * 1) \qquad (5)$$

$$\text{Big data 1 0} = \text{IF THEN ELSE (Cloud computing 1} > \text{Distributor's maximum shipment rate,} \\ \text{Initial Distributer's safety stock} * 2, \text{Initial Distributer's safety stock} * 1)$$

$$\text{Big Data 1 0 0} = \text{IF THEN ELSE (Cloud Computing 1} > \text{Manufacturer Max shipment Rate,} \\ \text{Initial manufacturing lead time 0} / 2, \text{Initial manufacturing lead time 0} * 1)$$

$$\text{Big Data 2} = \text{ IF THEN ELSE (WIP inventory} > (2 * \text{Manufacturers' inventory}), \text{Initial Production release rate} /2, \text{Initial Production release rate} * 1)$$

$$\text{Cloud computing} = \text{ Expected Customer Demand Rate} \quad (9)$$

$$\text{IoT 1} = \text{Distributor's minimum order processing time} \quad (10)$$

To provide better representation of real supply chain environment, defined mathematical equations and parameters to this technological adoptation. The one of the main difference of digital supply chain model is an implementation of CC to support data sharing between different echelons. Whenever, each member of supply chain has an access to the real time information, they are more flexible and stable on forecasting their demands. Once, CC delivers qualitative data for predicting the demand, BDA plays a key role on controlling the inventory level by using this information to change parameters of each member of the supply chain. Safety stock is used as control action in Distributor's and Retailer's inventory level, whereas Initial lead time and Initial production release rate utilized for managing Manufacturer's inventory. The model was built by means of the Vensim® PLE software package. The simulations have been performed with half-day time intervals and a simulation horizon of 100 days.

Table 1. Notation for the general supply chain models

Parameters	**Variables**		
DD_i = target delivery delay	I_i = inventory level	DO_i = desired orders	GW_i = adjustment for WIP
D_i = customer demand	OB_i = order backlog	O_i = order rate	DP_i=desired production
PT_i = minimum order processing time	$E[D_i]$ = expected demand	DS_i = desired shipment rate	CC = Cloud computing
T_i = time to average order rate	W_i = WIP inventory level	DD_i = actual delivery delay	BD = Big data
SS_i = safety stock	PR_i = Production release rate	F_i = order fulfillment ratio	IoT = Internet of things
L_i = manufacturing lead time	S_i = shipment rate	MS_i = maximum shipment rate	IC_i = Inventory cost
IJ_i = inventory adjustment time	P_i = production completion rate	DI_i = desired inventory	
WJ_i = WIP adjustment time	CD_i = change in customer demand	GI_i = inventory gap	
PC = Production capacity	OR_i = order fullfilment ratio	DW_i = desired quantity of work in process inventory	
** index "i" – indicates echelon in the SC (Manufacturer, Distributor and Retailer)			

3.3 Model calibration

The numerical values of the input variables to carry out simulations have been gathered from a variety of sources as follows. Table 2 represents the values of input parameters. Because of not accessing customer demand directly, Demand for Manufacturer and Distributor were not any numerical values, however it was computed based on the Retailer's order rate.

Table 2. Numerical values of parameters in model calibration (Kochan, et al. 2018)

Parameters	Parameter values in traditional SC model			Parameter values in digital SC model		
	Manufacturer	Distributor	Retailer	Manufacturer	Distributor	Retailer
DDi	3 days	3 days	3 days	3 days	3 days	3 days
Di	N/A	N/A	12 items/week	12 items/week	12 items/week	12 items/week

PTi	2 days	2 days	2 days	2 days	2 days	2 days
Ti	8 days	8 days	8 days	8 days	8 days	8 days
SSi	500 items	500 items	500 items	500 items	500 items	500 items
Li =	2 days	2 days	2 days	1 day	1 day	1 day
IJi =	1 day	1 day	1 day	1 day	1 day	1 day

4. Simulation results

4.1 Base case

Vensim PLE was used to simulate the models of both the traditional and digital technologies adopted SC. Inventory level, inventory cost, inventory gap 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 4. As it can be seen from Figure 4, the results show improved inventory levels and reduction in inventory cost with digital inventory management practices and the use of IoT, CC, BDA tools compared to the traditional system.

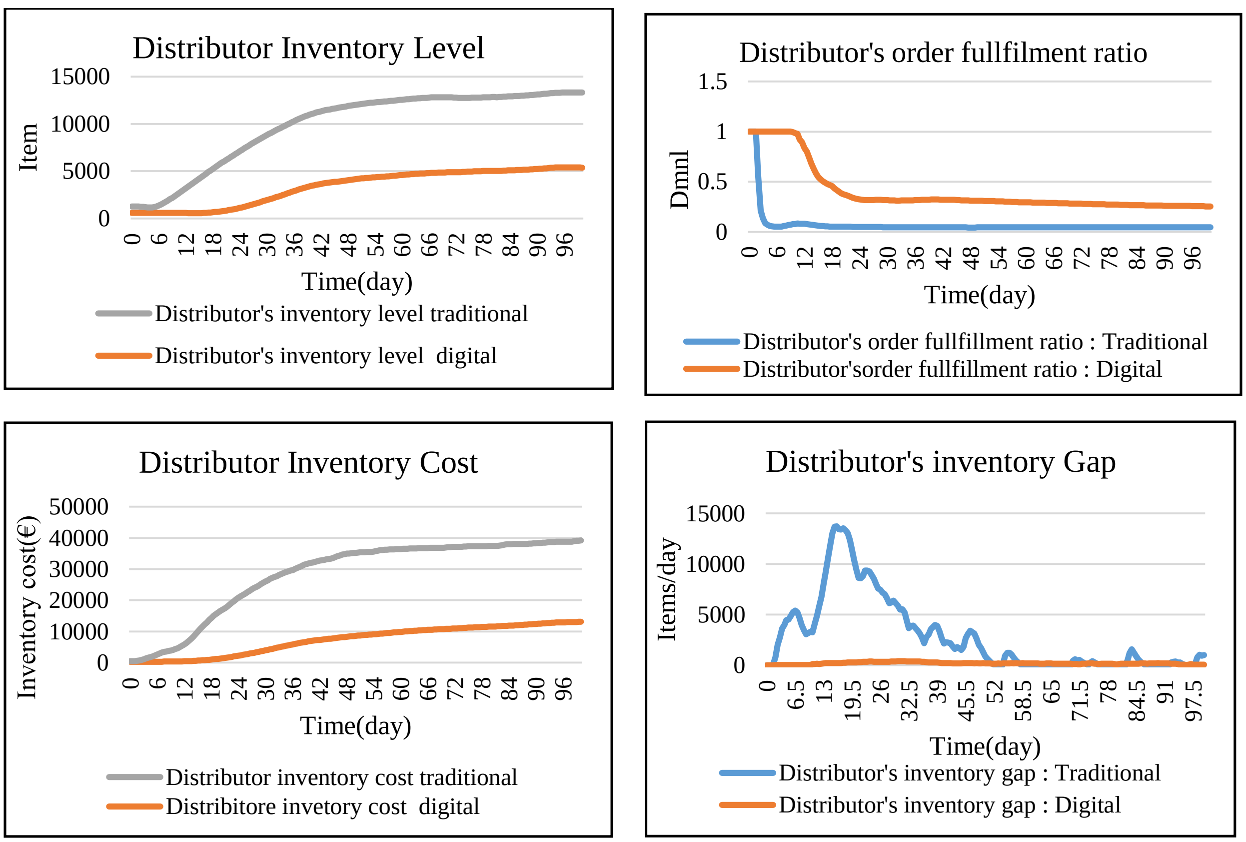

Figure 4. Simulation results for the output variable “Inventory level”

4.2 Sensitivity analysis

The SD models developed in this work are based on literature and since the previous contributions do not offer a complete database of numerical values to allow validation through past data, sensitivity analysis is here applied. The sensitivity analysis helps to check the robustness of the SD model (Sterman 2000). Figures 5 shows the variation of the output values with respect to the input parameters. Input values are changed by -50, -25, 25 and 50 percent compared to their base case values Sensitivity analysis was performed with all output variables. However, authors represent only manufacturing inventory cost and order fulfillment ratio. Production capacity has a little impact on Digital inventory cost in Figure 5 with -50 percent change, nevertheless it does not influence on overall sensitivity of

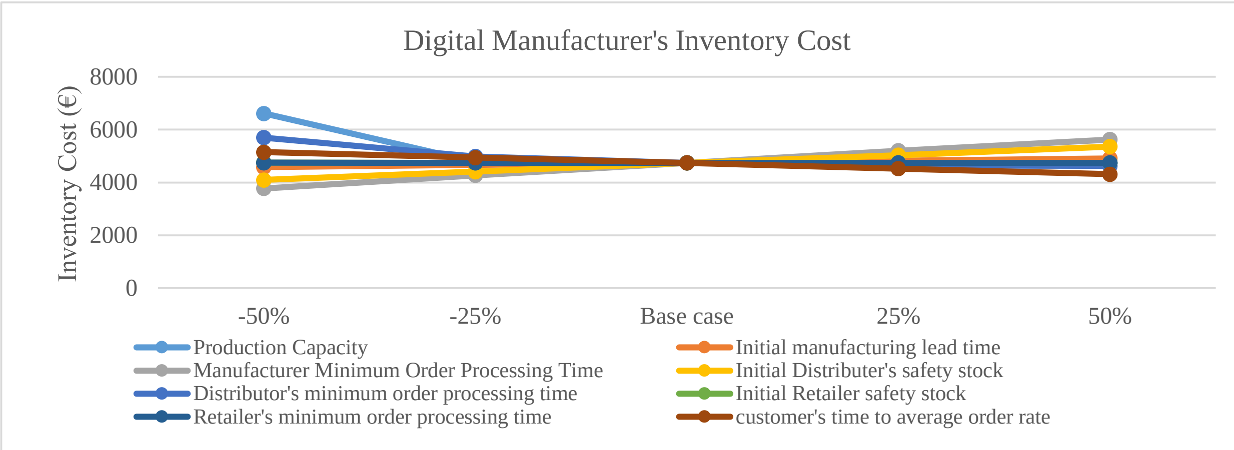

Figure 5. Sensitivity analysis of "Inventory cost"

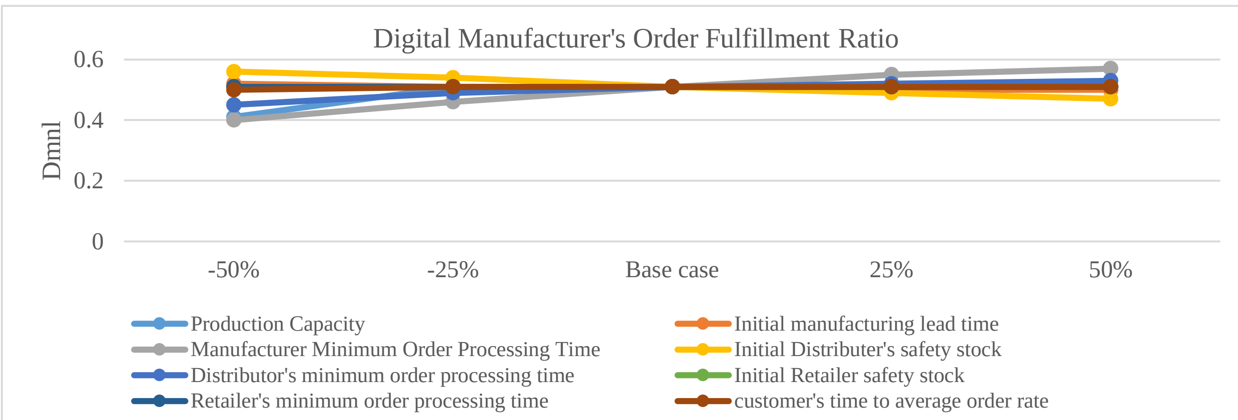

Figure 6. Sensitivity analysis of "Order fulfillment ratio"

other parameters of model. As is shown in Figure 6, changing the parameters does not affect significantly on Distributor's order fulfillment ratio. Moreover, all the other output variables have the same result as order fulfillment ratio and it does not change an overall performance of robustness of the model. To this end, it can be proved that proposed digital SC simulation model is robust enough.

4.3 Discussion of findings

As it can be seen in Figure 4, CC, IoT and BDA based supply chain has reduced inventory level fairly, which is consistent with the results obtained in previous studies (Gonul Kochan et al. 2018). However, the present study indicates that implementation of CC, IoT, BDA technologies as an integration significantly improves overall operational performance of supply chain. Comparing traditional and digital supply chain System Dynamics models, CC and IoT play a key role in real-time data sharing and smoothing expected demand among each echelon of supply chain. Inventory cost of each echelon in digital supply chain is considerably lower than traditional model. Moreover, the inventory gap is consistent with these results and it is reduced in the proposed model of digitalized supply chain. Contrary to inventory cost, the service level (order fulfillment ratio) is significantly higher than in the traditional supply chain (Ghadge et al. 2020; Gonul Kochan et al. 2018).

The digital supply chain model notices significant reduction in unfilled orders in comparison to the traditional model. The reduction points out an increase in the service levels of each supply chain echelon. In the traditional supply chain model, the inventory gap of each echelon represents an oscillating curve (Figure 4) due to instability in the process driven by poor inventory management. Whereas, with the introduction of IoT, BDA, CC in the system, the inventory gap is stabilized because of constant data sharing of demand, orders, shipments and production output in the whole supply network. All of these technologies allow better utilization of information to optimize operational performance.

5. Conclusions

Industry 4.0 is a significant revolution that covers a wide range of digital technologies such as Artificial Intelligence, Cyber-Physical Systems, RFID technology, IoT, CC, BDA, and Advanced Robotics. The concept of Industry 4.0 transforms digital businesses in all industries and sectors. In this context, SC is one of the emphasized fields of research. The traditional SCs need to metamorphose quickly by implementing digital technologies to survive in rapidly changing markets. However, a limited number of papers have been focused on the importance of assessing the Industry 4.0 transition within an SC network perspective, and the impact of different digital technologies on each partner of the SC. Therefore, the present study contributes to close such a gap by discussing the key effects of CC, IoT, and BDA technologies within the SC network on a dynamic basis. The complexity of SC is increased significantly by applying CC, IoT, and BDA. Moreover, the implementation of these technologies needs a considerable amount of investment. Hence, simulation methods might assist the evaluation of these changes in a cost-effective and efficient manner. In this regard, to find the answer to the first research question posed in the present work, SD modeling helps academicians and practitioners to analyze the possible impacts of the new complex SC structure resulting from the adoption of digital technologies under different scenarios. In particular, academicians can study the advantages of a digitalized SC on its members and how it changes their behavior, as well as the criteria that could be adopted to improve SC performance. For practitioners, this work offers a valuable approach to evaluate the above mentioned impacts and to assist them in making decisions about the investment in SC digitalization. To answer the second research question, the main outcomes of this study are as follows. The proposed digital SC model has shown improved service level, inventory cost, inventory level, and inventory gap for all the members of the SC compared to traditional configuration. Thus, it can be concluded that implementing digital technologies in SCs has a great impact on making them more integrated. Additionally, it increases transparency and collaboration among chain members leading to more strong relationships.

Like all research, this paper has some limitations. First of all, in the present SD model only the operational costs have been considered, and the impact of the initial investment of these technologies has not been addressed. Additionally, there is no real data from industries to validate the results of the SD model. Moreover, in this paper, just the three Industry 4.0 technologies more promising to stimulate real time information sharing and connection among SC members have been considered. Finally, in the current SD model the impact of combination of these technologies on the sustainability issues throughout the SC has not been focused on.

Hence, future research can use real data to validate the results and assess the performance of the present model. Moreover, by the development of other technologies such as Blockchain and Additive Manufacturing, it could be possible to add those technologies to the investigated ones and study their impacts in combination with each other on SCM s. Also, future research can study the amount of initial investment for each technology to investigate its impact on the behavior of SC members. Besides, the evaluation of the influence of the present model on the sustainability issues can be one of the interesting directions for the development of the current work. For instance, some criteria could be added for the effect of the present model on human resources as the social dimension for sustainability issues.

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