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A REVIEW OF THE CONCEPT OF 'SUPPLY CHAIN DIGITAL TWIN' IN THE ERA OF INDUSTRY 4.0

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ABSTRACT

Today's supply chain is different from what we had a decade ago. The direct result of the impact of technology on supply chains includes increasing its complexity and dynamism while adopting an agile approach has never been so important. With the COVID-19 challenge, real-time data availability is an important competitive advantage. Industry 4.0 includes a technology framework that focuses on digitalization and analytics capabilities for real-time event detection. This is where digital twins come in. The digital twin is essentially a virtual copy of the supply chain, which consists of hundreds of assets, warehouses, logistics, and inventory positions. It has attracted more attention in the industry by improving its technical and computational capabilities in operations technology. In this article, we examine the concept and importance of the digital twin and its benefits as well as its applications in the supply chain. After reviewing the recent trends in digital supply chains and the impact of smart digital technologies on Industry 4.0, we will examine the transformative role of one of the most influential digital technologies in the supply chain, namely the supply chain digital twin.

Keywords: Digital Supply Chain, Industry 4.0, Digitalization, Digital Twin, Digital Supply Chain Twin

1. INTRODUCTION

Creating a sustainable supply chain means balancing reliability and flexibility. Both supply chain features can act as airbags against uncertainty and should be considered in planning. While old-fashioned logistics solutions have not improved in the digital age, decentralized communication gives way to more accurate and modern solutions.

A combination of simulation, optimization, and data analysis makes a basic technology that helps to create a relatively accurate model of the real supply chain - its digital twin. Based on Gartner's definition, a digital twin is a digital representation of a real-world entity or system (Gartner, 2021). Here are some other definitions of DT:

- An integrated multiphysics, multiscale, probabilistic simulation of an as-built vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding flying twin (Shafto et al., 2012)
- A coupled model of the real machine that operates in the cloud platform and simulates the health condition with integrated knowledge from both data-driven analytical algorithms as well as other available physical knowledge (Lee et al., 2013)

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- A dynamic virtual representation of a physical object or system across its lifecycle, using real-time data to enable understanding, learning, and reasoning (Bolton, 2018)

The idea behind creating a digital twin comes from risk management in supply chains, so in the case of a failure, it makes the supply chain more reliable and stable. Simulation and optimization are the basic technologies used primarily as strategic planning tools. However, the quality of decision-making when risks occur depends greatly on the timely availability of relevant data, because most decisions must be made immediately.

Modern technologies make it possible to collect large amounts of data (such as supply failure probability and supplier data like financial status and production capabilities) on online supply chains. The management technologies used in supply chains allow important critical points to be identified and enable timely warnings of events that could have a significant impact on the supply chain.

All these real-time data on failures along with natural, financial, or political risks can be incorporated into the simulation model. Integration of simulation and optimization with online or live data allows the simulation to be used for strategic planning. According to several scientific studies (Ivanov et al., 2019; Ivanov and Dolgi, a2019; Ivanov et Dolgi, b2019; Popkov et al., 2019) this type of strategic supply chain simulation, which includes optimization and data analysis models, is the digital twin of the supply chain. In our opinion, this view reflects the common practice of supply chain planning and modeling, but it is not the result of a scientific understanding of the concept of digital supply chain twins (Klochkov et al., 2021).

The combination of simulation, optimization, and data analytics constitutes the full stack of technologies needed to create a model for a supply chain digital twin. A supply chain digital twin is a detailed simulation model of an actual supply chain which uses real-time data/snapshots to forecast supply chain dynamics. From this, analysts can understand a supply chain's behavior (understanding), predict abnormal situations (learning), and work out an action plan (reasoning). A supply chain digital twin includes computerized supply chain models in real-time which at each point of time represents the physical supply chain with the actual transportation, inventory, demand, and capacity data. This digital supply chain model can be used for planning and real-time control decisions.

Barykin et al. (2020) posed questions that should be answered by supply chain digital twins. First, what combination of modeling, simulation, optimization, and data analysis creates the wide range of technologies required to create a digital twin model of the supply chain? Second, how accurate or detailed must the simulation model be to be called a supply chain digital twin, and what questions do we need to answer in the modeling process? Third, which supply chain digital twin concept is more efficient? What is the optimal combination of analytical optimization and dynamic simulation? Two main approaches are considered:

A) Analytical optimization which is complementary to dynamic simulation
B) Dynamic simulation which is complementary to analytical optimization

The intelligent digital technologies of Industry 4.0 will greatly affect and completely transform supply chain planning. The present paper seeks to introduce a new concept called digital twin in the supply chain and expresses the role, impact, importance, and application of this intelligent technology in digital supply chain planning. This paper is organized as follows. First, the digital twin literature is reviewed in section 2. Then, new trends and the role of smart digital technologies in supply chain management in researchers' studies are presented in sections 3 and 4. Section 5 is an overview of studies that investigated the impact of Industry 4.0 smart technologies in supply chain management. The concept of supply chain digital twin and its vital role in supply chain planning are described in sections 6 and 7. Section 8 concludes the paper.

2. Literature Review

The concept of the digital twin was first introduced by Grieves in 2003 (Graves, 2014). Digital twin refers to having a digital replica of real entities, such as people, processes, physical assets, systems, and devices (EI, 2018). Digital Twin has opened a new way to synchronize physical activity with the virtual world. With the rapid development of the Internet of Things, the digital twin has become a hot research topic. The digital twin has been used recently in various industries, including product design (Tao et al., 2019), production line design (Zhang et al., 2017), digital twin workshop (Tao & Zhang, 2017), production process optimization (Ullman et al., 2017), preventive maintenance and performance status management (Tao et al., 2018). Digital Twin helps improve system performance, reduce costs, monitor status and trends, and predict future status using big data and machine learning techniques. General Electric (USA), Siemens AG (Germany), Parametric Technology (USA), Dassault Systèmes (France), Tesla (USA), DHL (USA), Unilever (UK), etc. have also utilized digital twins in their industrial operations (Schleich et al., 2017; Emily, 2020; Sharma et al., 2020). These companies use digital twins to increase product performance, production flexibility, and competition.

In general, when using the concept of the digital twin in research and industry the focus might be limited or broad (Zheng et al., 2019). The distinction refers to integration with the whole system. Features of Digital Twin include data-driven, intelligent comprehension, virtual reality mapping (Tao et al. 2019), and interactive collaboration. The limited concept of the digital twin consists of three main components, which include physical space, cyberspace, and the processing of information that is interconnected (Graves, 2014). After collecting product data in the physical space and transferring it to the virtual model in the virtual space, the received data information is processed and sent to the physical space to achieve data mapping, which is usually real-time mapping. Features include personalization, high performance, and very quasi-realism. Researchers have briefly pointed out that this type of twin has five main components: physical space, cyberspace, connectivity, data, and services (Tao et al., 2018b). These five components are equally important. The physical part is the basis to produce the virtual part. The virtual part is used to support the decision and management of the physical part through simulation. Data is at the heart of the digital twin because data is a prerequisite for all functions. Digital Twin creates new services to increase the convenience, reliability, and efficiency of an engineered system. The connection acts as a bridge to connect the other parts, creating an efficient interaction between the different parts.

The broad concept of the digital twin is an integrated system that can simulate, monitor, calculate, adjust, and control the status and process of the system, which is the functional extension of the limited concept of the digital twin. Considering the application of digital twins in the manufacturing industry, for example, the limited concept of digital twins focuses only on product visualization, that is, how to fully describe a potential or actual physical product dynamically.

Santos et al. (2020) investigated an internal supply chain digital twin in a pharmaceutical company. Their proposed digital twin provides accurate estimates of capacity needs for supply chain managers and develops the ability to easily visualize the resources required from different involved areas in the 24 months. Lee & Lee (2021) addressed digital twin applications for supply chain coordination in modular construction. Burgos & Ivanov (2021) proposed several directions and practical implementation guidelines to improve the food retail supply chain resilience. They stressed the importance of supply chain digital twins and end-to-end visibility along with resilient demand, inventory, and capacity management. The outcomes of their study can be instructive for enhancing the resilience of food retail supply chains in reaction to future pandemics and pandemic-like crises. Kenett & Bortman (2021) provided a review of digital twins with an emphasis on Industry 4.0 applications.

Pia Ciano et al. (2020) investigated the body of literature on digital twins, exploring, in particular, their role in enabling smart industrial systems. Shen et al. (2021) surveyed the literature on digital twins and showed that operation research and digital twin can contribute to each other in the areas of real-time decisions, digital models, and data integration. Yang et al. (2021) focused on the major research and application areas of digital twins. Their survey analyzed the recent developments of digital twins and summarized the theoretical underpinnings of the technology. Finally, they concluded with specific developments in various application areas of digital twins. They also discussed the challenges that may be encountered in the future. Gerlach et al. (2021) did a systematic literature review of the digital twin concept in supply chain management and logistics and presented conceptual clarification, use cases, and benefits of digital supply chain twins.

3. NEW TRENDS IN SUPPLY CHAIN MANAGEMENT

Supply Chain Management (SCM) is an essential part of any business entity. It includes planning, designing, implementing, and controlling the logistics activities of a company, including purchasing, warehousing, inventory control, production, distribution, and order fulfillment (Attaran, 2017).

The endless cycle of increasing supply chain costs affects the result of all actors involved. Reducing supply chain costs, such as transportation costs, inventory costs, etc., affect the efficiency of the entire chain. Cost reduction is a key factor in today's global supply chain competitiveness. Manufacturers, retailers, and distributors have identified reducing supply chain costs as an important issue to address. In addition, excellent supply chain performance has a strategic value that can lead to rapid financial repayment, improved productivity, and profitability, and improved global competitive advantage (Attaran, 2012).

4. DIGITAL TECHNOLOGIES IN SUPPLY CHAIN

It is interesting to examine which technologies can play a pivotal role in achieving the digital transformation of supply chain processes. Much literature has emerged in recent years and several lists of digital supply chain technologies have been proposed (Idris, 2018; Meier, 2016), both in terms of the number of technologies studied and sometimes in terms of the terminology used. They are different from each other. Digital supply chain technologies can be classified into six groups based on the similarity of their features, which include big data and cloud computing, the Internet of Things, intelligent manufacturing, collaborative robots (Cobots), augmented reality, artificial intelligence, and finally, blockchain. These six technologies represent a group of technologies, so they are not a single technology. Table 1 summarizes the most important digital supply chain technologies in the literature. The reported references are a selection from a wider set of academic and professional literature in the digital supply chain technologies context which can be classified into the six aforementioned categories based on the similarity of their characteristics.

5. UTILIZING THE INDUSTRY 4.0 SOLUTIONS IN SUPPLY CHAIN MANAGEMENT

In 2011, the concept of Industry 4.0 came into scientific terms with the prospect of merging objects and services into a global business network. On a broader scale, Industry 4.0 defines the current development trend of automation and data exchange. This is a new level of manufacturing organization and value chain management throughout the product life cycle.

Recent literature concerning various dimensions and factors is presented in Table 2. This table highlights the adoption of smart technologies in various industries and supply chains.

6. THE CONCEPT OF SUPPLY CHAIN DIGITAL TWIN

Traditional supply chains may no longer be enough in the digital age. Modern markets benefit not only from supply chain efficiency but also from its agility and flexibility. Today, the supply chain is evolving from a traditional model of linear, individual, and asynchronous relationships to a more connected and coordinated network of business partners. The supply chain is expected to be refurbished, digital, and able to provide the required services. Therefore, it must evolve through interconnected digital devices and complex networks. This digital supply chain connects different stakeholders (including customers) more effectively and enables them to respond faster and adapt to a rapidly changing market. The transition from the traditional supply chain to the digital supply chain was first proposed by Desousa (Desousa et al., 2017).

Capgemini Consulting (Rob & Griffin-Krian, 2011) explains the five dimensions of change as follows:

1) Digital supply chain strategy: The goal is to integrate digital innovations into the overall supply chain strategy.
2) Supply Chain Governance and Operational Model: A specific digital operating model in which data no longer depends on location. Large corporations operating globally will consider internal coordination committees in more detail.
3) Integrated implementation: Implementing different supply chain functions is very important. The main goal is to provide processes that provide all the information needed by employees.

Table 1. The main technologies of the digital supply chain

Group	Technologies	Definition	References
Big data	Big data	A very large volume of data characterized by high speed and great variety is used in decision-making and is managed through innovative analytical techniques.	Choi, Wallace, and Wang, 2018
	Cloud computing	An Internet-based model for easy, accessible, and on-demand access to a common, customizable set of computing resources (such as servers, software applications, etc.) that is easily accessible and released.	Fosso Wamba et al., 2015 Mell and Grance; Ryan and Loeffler, 2010
	Cloud manufacturing	A customer-oriented production model based on demand-based access to a common set of distinct and distributed production resources	Ren et al., 2017; Wu et al., 2013
Internet of Things (IoT)	Industrial Internet of Things	Integration of interconnected physical objects based on the Internet to enhance the value of products and processes	Boyes et al., 2018; Jeschke et al., 2017; Wang et al., 2016; Wortmann & Flüchter, 2015
Intelligent manufacturing	Additive manufacturing	A set of manufacturing technologies and processes that allow users to create tangible objects from 3D digital models which provides the possibility of mass customization of different types of products according to customer needs.	Gibson et al., 2015; Lipson & Kurman, 2013; Meier, 2016
	Advanced manufacturing automation	Refers to the latest automated production and logistics support systems, including unmanned aerial vehicles (UAVs), commonly referred to as UAVs.	Murray & Chu, 2015; Olivares, et al., 2017
Collaborative Robots (Cobots)	-	Robots that can process information and work with humans in shared work environments without any security barriers.	Djuric et al., 2016; Shravani and Rao, 2018
Augmented reality and artificial intelligence	Augmented reality	Integrates the real environment through mobile devices with the generated virtual information. Includes a set of wearable devices and human-machine interfaces for acquiring or transmitting audio, video, and tactile information.	Masood and Egger, 2019
	Artificial intelligence	Information technologies that are used in conjunction with machine learning to produce intelligent sensors, edge computing, and intelligent manufacturing systems.	Herz & Rauschnabel, 2019
Blockchain	-	A digitally distributed database to record transactions in several so-called blocks. The information in the blockchain is automatically updated without the need for any central agency responsible for data manipulation.	Michelman, 2017; Saberi et al., 2019

4) Integrated supply chain performance measurement: This feature makes it possible to track any order or transaction through a digital operating model. When using barcodes or RFID tags, the use of tagging technologies opens the way to receiving real-time data on physical displacement.

A digital twin can be defined as a dynamic virtual representation of an object or physical system, using real-time data to understand, learn, and reason (Bolton, 2018). Although its definition varies from source to source, the main idea is to provide a digital representation of an asset (tangible [existence] or intangible [system]), which uses the Internet of Things to receive meaningful data in real time. And based on the developed model, how it worked in the past and how it works now, concludes.

Table 2. Review recent literature on Industry 4.0 and digital supply chain

Reference	Research goal	Analysis level	methodology	Research field	Findings
Manavalan and Jayakrishna (2019)	Looking for IoT Sustainable Supply Chain Opportunities for Industry 4.0	Supply chain	Review of literature	Sustainable supply chain management under Generation 4.0 industry	A sustainable supply chain can be driven by five elements: smart products based on technology, collaboration, strategy and organization, smart operations, and sustainable development.
Moghtader et al. (2018)	Identify the challenges of using Industry 4.0	Supply chain	The best worst method	Bangladesh Leather Industry	The infrastructure technology frontier is the most important concern of companies. Existing challenges need to be addressed before bringing smart operations to companies.
Rajput and Singh (2018)	Identify and review IoT basics enablers for Industry 4.0	Supply chain	multi-criteria decision making	Manufacturing industries, from automobiles to aerospace	The emergence of IoT data and the IoT ecosystem as the most effective enablers as well as facilitating Industry 4.0 as a strong pillar. In addition, the IoT interface, robustness, interchangeability, and network capability are also essential elements for the successful implementation of Industry 4.0.
Lane et al. (2018b)	Developing a framework for examining and identifying elements of Industry 4.0 for its positive application	Agency	Interpretive structural modeling	Chinese manufacturing agencies	Company size and work environment do not necessarily affect the adoption of advanced technologies in production and other supply chain activities, while other factors have a positive effect on the adoption of Industry 4.0 technologies.
Ghobakhloo et al. (2018)	Develop a strategic framework for the transition to Industry 4.0 from the traditional situation	Supply chain	literature Review	Design trends and principles followed in industry 4.0	Dozens of principles and 14 industry trends of Industry 4.0 have been identified. These principles and processes have great potential to affect the operational capacity and efficiency of the company ecosystem.
Boyukozkan and Gucher (2018)	Development of digital supply chain framework	Supply chain	literature Review	A framework that is value-driven and efficient with new and technological methods	The three main elements of technology implementation, SCM and digitalization, drive the digital supply chain. Infrastructure, enablers, human-user interface, and technology are highlighted in technology implementation, while SCM covers process automation, analysis, and integration.

Table 2. *Continued*

Zhong et al. (2017b)	Distinguish between IoT-based, and cloud-based products	Supply chain	Case study	Case studies of government and large corporations from the United States, Europe, China, and Japan	In many cases, it has been observed from different dimensions that the economy and industry can be advanced through intelligent production systems. Product service systems are useful in advancing digital initiatives and Industry 4.0.
Dubi et al. (2018)	Investigating the role of institutional pressure in performance management	Agency	Survey	Indian manufacturing agencies	NP and CP have a positive effect on the performance management system (PMS), but MP does not. PMS can be formed through organizational culture to set new standards in relevant fields.
Lu (2017)	Investigating the motivations behind the selection of companies to accept IoT in logistics and supply chain	supply chain	Mixed methodology approach	Various industries in Taiwan	Instead of internal factors, some elements are outside the company. External factors contribute to the implementation of emerging technologies in supply chain logistics operations. Elements such as uncertainty, cost, and trust are rare.
Wu, Ding, and Chen (2012)	Investigating the relationship between green supply practices and its management	Supply chain	Regression analysis	Taiwan manufacturing enterprises	Organizational support affects the improvement of investment. Market pressure from different stakeholders does not affect this relationship, while the legal framework modifies the relationship between practices and management.
Liu et al. (2013)	See the power of institutional pressure on companies to implement the electronic supply chain	Supply chain	Survey	Chinese service and manufacturing companies	MP has no direct power to implement the electronic supply chain. On the other hand, CP and NP potentially have a positive impact on e-supply chain management due to their characteristics.

Digital twins are often confused with monitoring tools and simulation models. Digital twins combine both concepts and provide an effective visualization tool with improved simulation models (Madani et al., 2019). Digital twins differ from simulation models in that they receive real-time data for better prediction. Regularly, simulation models have a complete description of the object or system being studied, but they often lack its historical function and almost always lack its current state. In both cases, the generated simulations can be validated and improved by simulating past data and predictions that the model can make based on the current situation, providing more accurate and data-driven responses. Digital twins are also replacing surveillance tools; This means that all the data that these tools have, and the display is also available by digital twins. In addition, digital twins have access to prediction data generated by their simulation models.

A combination of simulation and optimization constitutes a full stack of technologies to create a supply chain digital twin, a model that always represents the state of the network in the present. A supply chain digital twin is a detailed simulation model of an actual supply chain which predicts the behavior and dynamics of a supply chain to make mid-term/short-term decisions:

- Mid-term decisions are mostly related to how a supply chain should work i.e., supply chain processes/resources/logic. It may require you to simulate a few months of operations.

- Short-term decisions are mostly related to the identification of problems and the analysis of solutions. It may require the simulation for a few days or weeks.

7. The Importance of Digital Twin in Supply Chain Planning

The digital twin was developed with three main components including physical product (PP), virtual product (VP), and data exchange. Digital Twin has three important features: synchronization between physical products and virtual products, comprehensive and dynamic data collection, and high-quality virtual modeling. These three characteristics play an important role in dealing with planning challenges.

By synchronizing the physical product and the virtual product, the digital twin improves the speed of operation and responsiveness to reduce procurement time. Planning is based on information retrieved from historical items and each unit in the supply chain. Usually, there is a significant time lag between target identification, data collection, data exchange, and performance. Synchronization between the physical product and the virtual product allows information to be shared between each unit and each engineer in the supply chain in real time, which significantly reduces procurement time. In addition, synchronization between the physical product and the virtual product enhances the human-machine interaction between the supply chain and engineers. So, engineers can quickly manage the supply chain by changing virtual products.

By dynamically and comprehensively collecting data, Digital Twin significantly improves forecast accuracy. Usually, data collected from historical cases are often not comprehensive enough to fully describe the environments they include and the status of supply chain units or products. In contrast, Digital Twin dynamically collects data from multiple sources. In the physical product, the digital twin records real-time data of physical products, environments, similar products, and operators. In the virtual product, the digital twin extracts data from virtual models and simulations. Historical case data is also stored. In addition, different digital twins can interact and exchange data with each other, allowing the digital twin to retrieve data from other systems. Therefore, this huge data makes forecasting and planning more accurate over a longer period. With high-quality modeling, Digital Twin enhances planning validation. A key approach to verifying planning is simulation. Conventional software and tools often include inadequate environmental factors, rules, mechanisms, and behaviors. In contrast, the digital twin models all of this in the virtual product. Therefore, the simulation quality will be improved, and the planning verification will have fewer deviations.

8. CONCLUSION

The supply chain digital twin is an accurate simulation model of a real supply chain that uses real-time data and snapshots to predict supply chain dynamics. Thus, analysts can understand supply chain behavior, anticipate unusual situations, and formulate an action plan. The supply chain digital twin can be used to understand the dynamics and behavior of the supply chain, identify bottlenecks, test changes and development of supply chain design, monitor risk and test possible scenarios, conduct transportation planning, optimize inventory, provide cash for services and the cost to offer services and forecast and test operations over the coming days and weeks. The digital twin of the supply chain is detailed enough to analyze supply chain interactions, from large changes in demand to the facility framework. The digital twin should enable functions such as forecasting cash flows and inventory flow, identifying demand variability, and testing scenarios.

The impact of Industry 4.0 and digital transformation on supply chain management has not yet been fully explored, as these concepts are mainly focused on production. As a result, companies need to prepare for potential challenges. Therefore, there are still areas that need attention for future research. This study can be a starting point that can be considered on a larger scale and perspective. In addition, experts with different industry backgrounds may have differing views that should be considered in future research. Little has been said about the impact of Industry 4.0 and digital transformation on the legal aspects across the supply chain. The financial aspects were also largely ignored. Future research should therefore examine these potential areas of conflict.

Future research may also examine upstream and downstream actors to understand the acceptance status of Industry 4.0 and the digital supply chain. Future research can also consider traditional elements that can facilitate new and dynamic elements in a changing business scenario. Automatic renewal of supply chain contracts and automated maintenance and call records may be new solutions for future research. Industry 4.0 optimization and digital supply chain from central firm to supplier or customer side can be compared and analyzed. The balance between customer satisfaction, waste reduction, revenue, and employee satisfaction can be traced back to companies that have started or implemented digital initiatives. In addition, factors such as the firm's position in the supply chain and the firm's impact on the supply chain can also be considered.

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