Digital Twins for Supply Chains: Current Outlook and Future Challenges

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ABSTRACT

The growing complexity of worldwide supply chain networks, together with the increased occurrence of disruptive events stress the need for a focused introduction of digital support tools. Digital twins have encountered an increased interest from both industry and research for their capability to provide useful services in the short term. The number of contributions on digital twin-based methodologies for system design and production planning and control experienced a significant increase, while applications to supply chain management remain scarce. However, the recent investments in digitization and the concrete need for short-term planning capabilities mean digital twins can effectively aid enterprises in the management of their value chains. This paper provides an overview of the existing contributions regarding digital twins for supply chains, and gathers useful insights on both the current level of development and the future research challenges.

KEYWORDS

Digital twins; supply chains; inventory management; literature review.

I. INTRODUCTION

Global supply chains recently experienced major disruptions due to both internal and external drivers. Pressure on prices and customized products demand pushed toward more flexible production systems and logistic networks. Meanwhile, unpredictable events such as and pandemic lockdowns increased the need for stress tests and risk averse planning approaches [22]. As a result, production and logistic enterprises became interested in investing in digital support tools, backed by significant investments in digitization [5].

In this context, the *supply chain digital twin* matured as tool to be incorporated into business operations. This concept is based on the idea of creating a *digital twin* (DT) of a supply chain, which is a virtual representation of the physical supply chain or a section of its related material and information flows. One of the most inclusive DT definitions itentifies it as *"a set of adaptive models that emulate the behaviour of a physical system in a virtual system getting real time data to update itself along its life cycle. The DT replicates the physical system to predict failures and opportunities for changing, to prescribe real time actions for optimizing and/or mitigating unexpected events observing and evaluating the operating profile system"* [20].

The application of DTs to supply chains can be used to optimize and improve customer service, as well as to reduce costs and increase profits. Also, it can be used to identify and eliminate inefficiencies, reduce risks, monitor and track the performance of the supply chain to identify opportunities for improvement.

Figure 1 compares the number of publications on DTs in manufacturing with respect to logistics and supply chains. The papers have been obtained as a result of two separate queries which have been done on 2023-01-10 on the Scopus database, respectively: (1) "Digital Twin" AND ("Logistics" OR "Supply Chain"), resulting in 528 papers, and (2) "Digital Twin" AND ("Manufacturing" OR "Production"), which provides 3687 results. The figure shows that while in manufacturing there has been a significant increase in publications following 2017, the number of publications on DTs for supply chains has not experienced the same increase. Indeed, supply chains often include complex networks that involve multiple stakeholders and processes that need to be accurately modeled. The complexity may also increase if the value chain is more global and with various transportation modes. Also, supply chains are highly dynamic and subject to frequent disruptions such as pressures on prices, customer and supplier disruptions, as well as transportation delays, which imply structural changes in both material and information flows. Such changes are hardly reflected in digital models, which are often conceived for lower frequency uses. Moreover, structural changes imply that the sources of data are continuously adjusted, and this can result in a challenging generation and update of accurate digital representations.

This paper aims to gather insights from the available literature and summarize the main features that must be provided by DTs applied to whole value chains. Existing literature reviews are listed and exploited to gather useful insights on the technological enablers, barriers, and research challenges. The rest of the paper is organized as follows: Section II summarizes the existing literature reviews on DTs for supply chains; Section III gathers insighs on the current trends in the literature; Section IV discusses on the common features and functions of DTs, while the main technological enablers and barriers are summarized in Section V. Section VI lists the research challenges. Final remarks can be found in Section VII.

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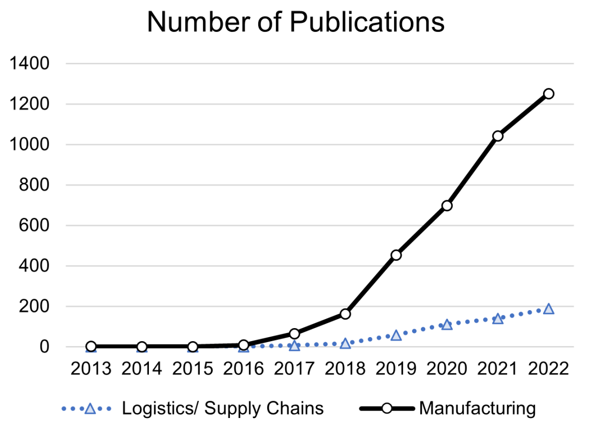

Fig. 1. Comparison in the number of publications on digital twins in manufacturing with respect to logistics and supply chains in the last ten years.

II. LITERATURE REVIEWS

In this section, we gather insights from existing literature reviews on DTs for supply chains. The papers have been selected by executing the query *"Digital Twin" AND ("Logistics" OR "Supply Chain")* on the SCOPUS database without date restrictions. From the 528 results, a subset of papers has been selected based on the following criteria applied to the title and the abstract: (1) the publication must be in English, (2) the publication must regard the application of DTs to provide benefits to supply chains, (3) the publication aims to provide a comprehensive literature review on the subject. As as result, 15 papers have been selected and their contributions are summarized in the following.

Agalianos et al. [2] investigated the literature on the integration of discrete event simulation and DTs in the management of warehouse systems. The work highlighted the trend of including real-time capabilities in simulation experiments, for instance for scheduling capabilities. Barykin et al. [4] attempted to address the link between DTs and risk management. The authors concluded that there are no available approaches to build the conceptual model of a supply chain DT. Krajcovic et al. [14] used a case study to demonstrate the phases with which an enterprice can adopt intelligent logistic planning methodology, and identified how different technologies can aid in specific inventory strategies. Marcucci et al. [18] explored the DT concept and its potential role in urban freight transport policy-making and planning. The authors emphasized the importance of having a thorough understanding of the connections between real-world context and choice/behavior. The paper claims that the use of both behavioral and simulation models is crucial in creating a DT that can facilitate effective participatory planning processes and forecast both behavior and responses to structural changes and policy implementations. Vilas-Boas et al. [28] provided an overview of the use of DTs in food logistics, outlining the key requirements for technologies to be applied in each stage of the logistics process. The paper also discussed potential research opportunities in the fresh food supply chain and highlighted the challenges that must be addressed when integrating these technologies. Taghipour et al. [23] emphasized the impact of digital enablers in enhancing the performance of various entities within a supply chain, and investigated how digitization can influence the profitability of these activities both individually and collectively. The authors underlined the importance of collaboratively managing supply chain processes that are autonomous and decentralized. Kamble et al. [13] conducted a systematic literature review to examine the relationship between various dimensions of supply chain DT and sustainable objectives. The authors concluded that technological advancements in Internet-of-Things (IoT), cloud computing, and blockchain have expanded the potential applications of DT in supply chain management. Also, they suggested that a comprehensive supply chain DT should encompass all entities, including people and things, throughout the entire supply chain, rather than solely local manufacturing systems. Further, the paper proposes a sustainable DT implementation framework for supply chain management to assist future practitioners and researchers. Bhandal et al. [6] identified four clusters of values and one cluster of enablers for DTs in operations and supply chain management. The value clusters include articles that demonstrate how DT implementation can improve supply chain activities at the level of business processes and supply chain capabilities. The authors identified the supply chain resilience and risk management value cluster as a newly emerging cluster and situated on the periphery of the primary literature network. Van der Valk et al. [27] did a liteature review by classifying papers on the basis of use cases, purposes, and technological readiness. The authors highlighted the challenges for DTs development and identified five main research directions: (1) the integration of different information system tasks within a single digital object, (2) the derivation of further DT-driven services, (3) the development of of industrial use cases, (4) the extension of DT capabilities toward additional domains besides classical production, and (5) the direct control of supply chains. Abdul Zahra et al. [1] highlighted the role of digitization in supply chains and the enabling technologies to achieve DT capabilities. Dy et al. [8] examined the uses of DTs in different industrial sectors. Their literature review also focuses on the application of DTs for supply chain risks. The authors revealed the current advancements of DTs in the mentioned industries and their application to risk management. Its purpose is to aid supply chain practitioners and researchers in recognizing challenges and areas of potential research related to DTs. Kulac et al. [15] presented enabling technologies and application sectors of DTs for supply chain operations. The authors suggested the value of DTs can be divided in three main functions: (1) descriptive, which means providing end-to-end visibility of the supply chain status; (2) analytical and predictive, which exploits capabilities of simulation models for scenario analysis; (3) diagnostic,

TABLE I: Existing literature reviews on digital twins for supply chains: • = full coverage, (•) = partial coverage.

Reference	Domains	Framework	Barriers	Enablers	Challenges
Agalianos et al. [2]	Unspecific	-	-	-	-
Barykin et al. [4]	Unspecific	•	-	(•)	-
Krajcovic et al. [14]	Automotive	•	-	-	-
Marcucci et al. [18]	Urban Logistics	-	(•)	-	-
Vilas-Boas et al. [28]	Food	-	-	(•)	•
Taghipour et al. [23]	Supply Chain Management	-	-	•	-
Kamble et al. [13]	Sustainability	(•)	-	(•)	-
Bhandal et al. [6]	Risk Management	-	-	•	-
Van der Valk et al. [27]	Unspecific	-	-	-	-
Abdul Zahra et al. [1]	IoT	-	-	-	-
Dy et al. [8]	Unspecific	-	-	-	•
Kulac et al. [15]	Unspecific	-	-	(•)	-
Uhlenkamp et al. [25]	Unspecific	(•)	-	-	-
Jeong et al. [12]	Unspecific	(•)	-	-	-
Aguilar-Ramirez et al. [3]	Blockchain, IoT	-	-	-	-

which exploits big data analytics and machine learning algorithms to detect patterns, hidden relationships, and abnormalities. Uhlenkamp et al. [25] developed a maturity model of DTs that includes seven categories: context, data, computing capabilities, model, integration, control, human-machine interface. The goal is to assess the effectiveness of existing solutions and identify opportunities for improvement or adaptation to new use-cases. The method provides a comprehensive framework for evaluating DTs and represents the first step towards a systematic evaluation and a structured development of new applications. Jeong et al. [12] provided a comprehensive overview of the evolution of DTs since the introduction of the term in 2002. The authors presented implementation layers to guide the practical application of DTs, and suggested technology elements for each layer that can efficiently facilitate the creation of new DT models. The technology elements are also defined and applicable across various domains. Last but not least, Aguilar-Ramirez et al. [3] identified how DTs and blockchain technologies can collaborate to meet the requirements of supply chains. The authors identified the advantages and disadvantages that should be thoroughly evaluated before implementing blockchain-based DTs in any business.

Table I summarises the aforementioned contributions that reviewed the literature on DTs for supply chains. It is possible to highlight that there are no works that comprehensively address barriers, enablers, and research challenges for the development of DTs in supply chains. Also, proposals of specific DT frameworks as a result of a literature survey are scarce.

III. CURRENT TRENDS

Van der Valk et al. [27] conducted a literature review using the same query of Figure 1. The authors classified papers published until the end of 2021 according to the use cases, purposes, and technological readiness. After this study, other 189 papers have been published. Therefore, it is relevant to identify current trends by analysing how the newly published papers would classify within the same categories, namely (1) the supply chain operations reference model (SCOR) dimensions, (2) the DT purpose categories, and (3) the DT use cases.

Figures 2a, 2b, and 2c show the results of the aforementioned trend analysis. From the figures we may gather useful insights on current research trends. Figure 2a shows the trends on the SCOR processes dimensions. The figure shows the papers published until 2022 had a tendency to focus on the *make* phases. Coherently with Figure 1, DTs for production phases anticipated the development of DTs for supply chain processes. We also notice a significant increase in papers focusing on planning (mostly risk assessment) and delivery phases (resilience, recovery phases). This is a signal of a focus shift from the factory level toward the entire supply chain. Figure 2b shows the arrangement of DT functionalities. Until 2022, there has been a relatively even quota among the DT functions, while more recently a significant increase in the visibility and monitoring applications is noticeable. This trend is supported by the fact that system state mirroring is one of the first step of DT development, both in terms of implementation and application interests [12]. Despite an evident focus on a particular service, the existing contributions remain at a general, conceptual level, without proposing practical insights on DT architecture building nor diving deeper in the quantitative methodologies. Figure 2c compares the existing literature trends with respect to the DT use cases. A significant increase in the number of literature reviews indicates a growing maturity of the topic.

IV. DIGITAL TWIN FEATURES

By leveraging the data provided by the DT, enterprises can make more informed decisions and optimize their value chain for greater operational and economical efficiency. DTs can contribute with a comprehensive view of the entire supply chain, allowing manufacturers to optimize their value chain processes. DTs can provide specific functions to supply chains, which include:

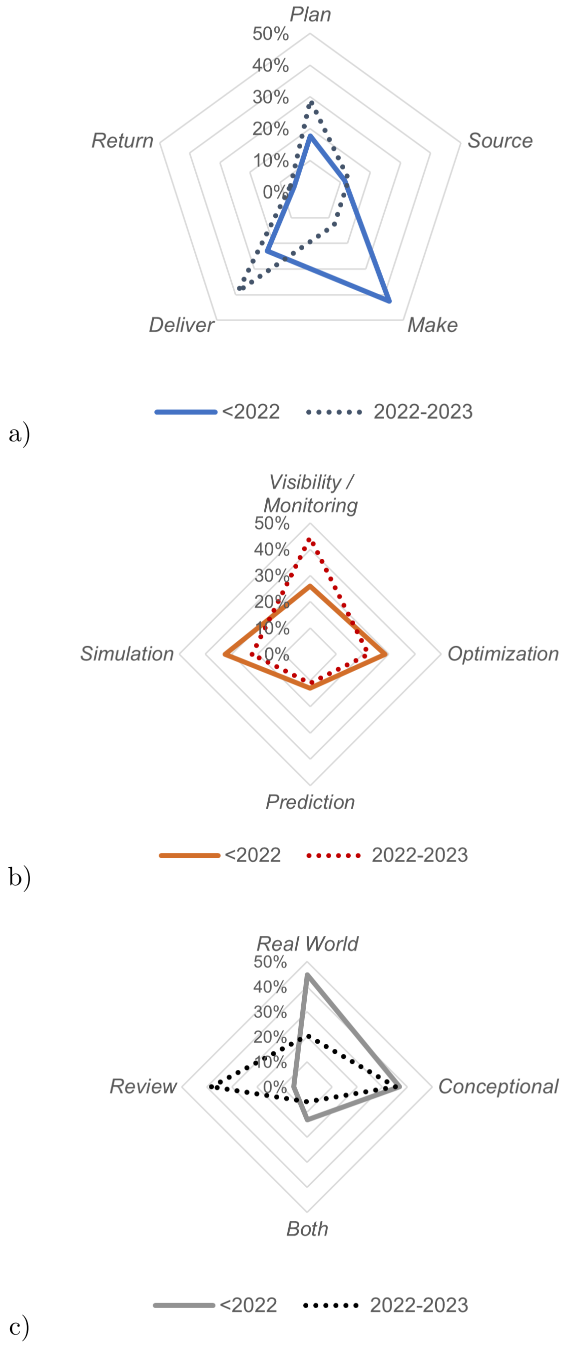

Fig. 2. Trends identification based on the classification proposed in [27]: a) SCOR model dimensions, b) digital twin purpose, c) digital twin use cases. The indicators are expressing the relative number of papers that fall into each category.

• *Visualization and Monitoring.* A DT is based on a real-time representation of the supply chain. Hence, it allows organizations to monitor the status of assets, inventory, and products in real-time. This capability grant the needed information to make on-time and undistorted judgements.
• *Predictive Analytics.* Using data from both the physical systems and the DTs, predictive analytics can be used to identify issues such as potential bottlenecks or inventory deviations, as well as to forecast both demand and supply. Differently from the traditional approaches, DTs can provide the capability to perform predictions based on data that do not represent any historical situation.
• *Simulation and Optimization.* A DT can be used to analyse different scenarios and optimize the supply chain performance. For instance, the impact of changes to transportation routes, inventory levels, or suppliers can be tested and optimized in the virtual world before designing operational procedures.
• *Risk Management.* By exploiting DTs, organizations can mitigate potential risks in the supply chain, such as disruptions in the transportation network or quality issues with suppliers. For instance, a scenario analysis can be used to design contingency actions before they are effectively needed [11].
• *Cross-Organizational Collaboration.* A DT can be used to facilitate collaboration and coordination between different stakeholders in the value chain (i.e., suppliers, manufacturers, and logistics providers).
• *Continuous Improvement.* Organizations can collect and analyse data from both the physical and digital systems in order to identify opportunities for continuous improvement such as reducing costs, improving delivery times, or enhancing product quality.

V. TECHNOLOGICAL ENABLERS AND BARRIERS

Based on the literature review of section II a set of technological enablers and barriers to DTs in supply chains can be identified.

A. Technological Enablers

The main enablers are identified and defined as the elements that can effectively help organizations in creating an accurate and comprehensive DT of their value chain. The enablers are listed as follows:
• *Data and Information Technology Infrastructure.* A robust information system and data management infrastructure is crucial for DTs in supply chains. Indeed, the multiple actors network implies that data from multiple sources must be refined, integrated, and harmonized to provide a comprehensive and accurate representation of the supply chain. Further, newly developed technologies such as 5G represent enablers of higher frequency data exchanges [7], which aid the physical-digital alignment.
• *IoT Devices.* Recently introduced devices such as sensors and RFID tags can be exploited to collect data on assets and products throughout the value chain. This data can be used to create a digital shadow that mirrors the real-world system, enabling the construction of a DT architecture. Also, the sensorized physical assets can aid in the analysis of alternative scenarios that are initialized on the real system status.
• *Cloud Computing and Advanced Analytics.* Despite sometime controversial, the introduction of cloud computing can aid to achieve scalability, flexibility, and cost-effectiveness, since it allows organizations to store and process large amounts of data in real-time. Also, the cloud-based information systems allow the existence of multiple owners and users of the same DT ar-

chitecture. Further, the cloud can facilitate the access to advanced analytics capabilities and machine learning can be applied to analyze the vast amounts of data collected along the supply chain processes to identify patterns, detect anomalies, and make predictions.

- *Standardization.* Standardization of data and technology interfaces across the supply chain can facilitate the sharing of information between different systems, which is essential in a complex network value chain. Further, architectural standards such as the recent ISO23247 [21] can assist the development and management processes of DTs.

B. Technological Barriers

While DTs can bring many benefits to supply chains, there are also several technological barriers. Addressing these barriers will necessitate a combination of technology, standards, and investment to create an accurate and effective DT of the supply chain. The barriers are listed as follows:

- *Data Quality.* One of the biggest challenges in creating a DT for supply chains is ensuring the quality and integration of data [18]. This is emphasized by the fact that in supply chains data streams come from different sources. To be effectively used, data must be accurate, consistent, and standardized before being used. Also, the proper level of detail must be guaranteed by the data to ensure the alignment of the digital models with the real value chain.
- *Functional Interoperability.* Supply chains are normally composed by different systems and technologies that not always belong to the same family (e.g., different software providers, data owners, confidentiality constraints). As a result, it can be problematic to integrate functional elements within the same digital representation. To this end, standards for architectural interfaces and data exchange are essential to guarantee the interoperability between different components.
- *Computing Power.* Given the inherent complexity of a value chain network, a DT for a supply chain certainly requires significant computing power and storage capacity. Despite specific technologies such as cloud computing have proved successful in addressing these challenges, it remains important to prepare the necessary infrastructure in place to support the future specific needs of DTs.
- *Economical Sustainability.* The creation of DTs supply chains can require consistent investments [17]. The required investments in the development, the infrastructure, as well as the data management may constitute a barrier for some organizations, especially if small and medium enterprises.
- *Data Security and Privacy.* Since the amount of data involved in creating a DT can be considerable, data security and privacy are major concerns [9]. In order to ensure trust among all players of the value chain, sensitive data must be protected from unauthorized access.

VI. RESEARCH CHALLENGES

On the basis of the aforementioned literature review and discussion, the authors have identified three main types of research challenges: (1) architecture challenges are related to the development of a common, comprehensive DT architecture that can aid both researchers and practitioners, (2) interaction challenges indicate the complexity of managing existing DTs once they are in operational phases, and (3) application challenges are specific to the deployment of DTs to supply chains.

Architecture Challenges. To increase the performance of the whole supply chain, the management processes needs to be autonomous, decentralized and handled collaboratively which allows each constituent to achieve its own desired plan and constraints autonomously and at the same time to pursue the optimum as a whole [23]. As a result, it is fundamental to design and agree upon a functional DT architecture that can aid the development of both general components such as data exchange interfaces and application specific services. The structural development should also take into account the operational phases of DTs (i.e., life cycle management) [19].

Interaction Challenges. While DTs require both on- and off-line interaction between the physical and digital world, a small part of existing studies specifically considers it. The development of specific techniques for the physical-digital alignment is essential to overcome this challenge [24]. Further, it is not clear how DTs will be built and managed at the federated level, for reaching level 5 of the DT evolution framework [12, 10].

Application Challenges. In general, DTs have been implemented sparsely for the improvement of different supply chain functions (e.g., procurement, logistics, distribution, retail). As a result, existing DTs usually regard only one or few echelons of the supply chain, missing holistic opportunities of whole DT approach [26]. The multi-structural composition of SC networks and the implications for the DT still need to be addressed (e.g., organizational, financial, informational changes). Most existing implementations focus on an asset-centric perspective (e.g., hyper-connected objects, virtual representation). A perspective to enhance sensing and adjusting capabilities of the entire supply chain environment is scarcely studied. While supply chain DTs can offer planning and controlling capabilities at both the tactical and operational levels, the advantages on the strategic decision-making level to provide business intelligence and enhance the business ecosystem need to be further exploited. Last but not least, value chains typically include organizations of different sizes. However, there are many challenges in devising and integrating DTs for small and medium enterprises.

VII. CONCLUSIONS

The existing literature reviews highlighted significant contributions in specific aspects of DTs for supply chains. Specific functions of DTs can be applied to different processes within a supply chain. Future research should highlight the requirements, the similarities and implementation challenges for each process. Also, the relationships between the DT functionalities and requirements must be studied further. Future research should also consider the dependence between the requirements and the applications. For instance, inventory control functions might have strict requirements in high rotation industries such as food, while they might be more unconstrained in less critical markets (e.g., automotive spare parts). It is worth to notice that some research directions remain completely unexplored in the supply chain domain. For instance, none of the analyzed papers mention the model generation problem, which has been identified as essential for the alignment between physical and digital objects [16]; similarly, specific methodologies for the management of operational phases of DTs will need to be developed. Last but not least, it is promising to investigate applications in closed-loop supply chains with the aim to foster sustainability and circular economy objectives, which can be achieved using DTs.

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