Improving Manufacturing Supply Chains Using Digital Twin Technology

Abstract

Digital twin (DT) systems are becoming significant enablers of manufacturing supply chain optimization thanks to the rapid development and application of Industry 4.0 technologies. The paper examines the advantages of utilizing digital twin technology to enhance operational efficiency, responsiveness, and resilience in manufacturing supply chains through real-time simulation, data integration, and predictive analytics. Based on empirical evidence and recent academic literature, this research aims to examine the architecture of the digital twin, its enabling capabilities, and its applications in forecasting, inventory management, logistics, and production planning in real-world settings. The utilization of use cases of the most prominent manufacturers, e.g., Siemens, General Electric (GE), and Bosch, exemplifies the strategic and real-time operational advantages of implementing DT. The paper also assesses major challenges, including interoperability concerns, cybersecurity risks, and the high costs of implementation. The results indicate that although digital twins offer significant benefits in enhancing the visibility of supply chains, their implementation requires a robust infrastructure, a talented workforce, and a strategic approach. The paper concludes with discussions on future research opportunities, emphasizing the need for standardization, modular architectures, and inclusive adoption models to ensure scalability and reach across various industries.

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1. Introduction

1.1 Background and Context

Over the past few years, global manufacturing supply chains have become increasingly dynamic and complex. The increasing customer expectations, volatile market needs, and unforeseen conditions like pandemics and war have focused the discussion on agility, resilience, and real-time visibility in supply chain management. Conventional supply chain systems, which are usually dependent on data held in a silo and a static model, cannot keep pace with the rapidly changing environment of contemporary industry. To address these challenges, manufacturers are adopting advanced technologies to enhance decision-making, operational transparency, and responsiveness throughout the value chain. Digital twin technology has been a focus of attention among the new transformative technologies emerging in response to current developments. A digital twin is a virtual representation of a physical system, process, or product, enabling real-time simulation, monitoring, and optimization through the integration of data collected by Internet of Things (IoT) sensors, cloud computing, and artificial intelligence. Although digital twins were initially used in product design and predictive maintenance, they have also been extended to encompass the entire supply chain lifecycle.
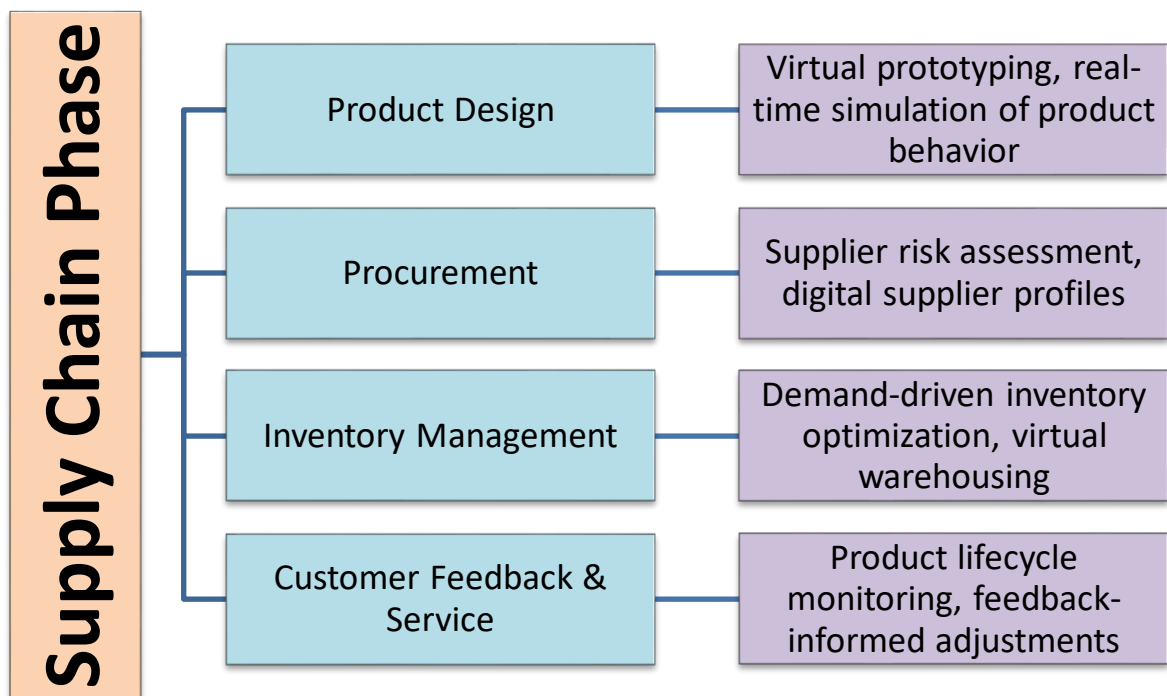

Figure 1: Digital Twin Capabilities Across Supply Chain Phases

1.2 Problem Statement

Even though companies have been investing heavily in Industry 4.0 and automation, it is worth noting that most manufacturing companies face the problem of supply chain inefficiency, characterized by late shipments, poor forecasting, oversupply, and a lack of coordination among various nodes. Such issues are also compounded by low visibility and a reactive versus proactive management style. Historic enterprise systems, such as the MES and ERP, lack support in predictive, interconnected, and adaptable supply chain models. The primary issue is that current systems are unable to reflect and respond to supply chain dynamics in real time. This study suggests that a digital twin may resolve this issue through its ability to provide a synchronized, data-driven, and intelligent perspective of both the digital and physical supply chain environments.

1.3 Research Aim and Questions

This research aims to investigate how digital twin technology can enhance manufacturing supply chains by improving operational efficiency, agility, and responsiveness.

Research Questions:

- How can digital twin technology be applied within manufacturing supply chains?
- What specific supply chain functions can benefit most from digital twins?
- What are the challenges and limitations associated with implementing digital twin solutions?

1.4 Relevance and Significance

This study is important because it can inform academia and industry. In the case of scholars, it is beneficial to contribute to the existing literature on the intersection between supply chain innovation and digital transformation. For practitioners, it offers valuable insights into how the deployment of digital twins can provide competitive advantages through economic gains, enhanced forecast accuracy, and resilient supply networks. To be more sustainable and customer-oriented, digital twins can help manufacturers support and promote end-to-end visibility and management of the supply chain.

1.5 Methodological Approach

In this study, the conceptual and literature approach will be implemented, using a combination of literature review (industry and academic sources) to analyze the uses,

advantages, and limitations of digital twin technology in supply chains. It also comprises stories of cases by major manufacturing companies that have adopted the digital twin model.

2. Fundamentals and Literature Review

2.1 Concept of Digital Twin Technology

A digital twin is the best new technology that can enable intelligent and real-time decisions regarding the supply chain. A digital twin is an interactive, data-driven simulation of an object based on real-world data, which is dynamic and reflects the same structure, context, and behavior as the real-world situation. These comprise physical infrastructure (equipment, vehicles, and swap bodies), business processes (stock-keeping and shipping channels), and environmental conditions (weather and shipping shacks) in the production and supply chain. Although it was first deployed in the aerospace segment, the application of digital twins is currently spreading rapidly in the manufacturing and supply chain sector, as there is a growing demand for proactive and predictive decision-making technologies (Wang et al., 2025). The technology enables resilience in volatile environments by supporting scenario testing, condition monitoring, and optimization, which are also fundamental to the resilience it provides. According to recent studies, there has been an increase in the incorporation of digital twins into global supply chain logistics and transportation systems. To illustrate, Miran et al. (2024) draw attention to the fact that digital twin systems can enhance real-time communication and information flow in distributed operations through AI-enhanced feedback mechanisms. Dynamic modeling capability enables logistical options, such as rerouting, inventory redistribution, or supplier organization, to be tried and tested before implementation, allowing for more effective execution and enhancement of reliability and cost efficiency in the services.

2.2 Digital Twin Architecture and Enabling Technologies

Digital twin systems have an architecture that contains several levels: data capture, processing, modeling, and decision-making. The baseline is a system of IoT sensors introduced into the physical system, transmitting live telemetry of parameters such as temperature, pressure, location, or usage. This information is broadcast to the cloud servers, where it is handled by AI and machine learning algorithms that can foresee the future state or identify anomalies (Miran et al., 2024). Visualization technology provides dashboard capabilities for human decision-makers, and APIs enable connections to existing ERP and warehouse management systems.
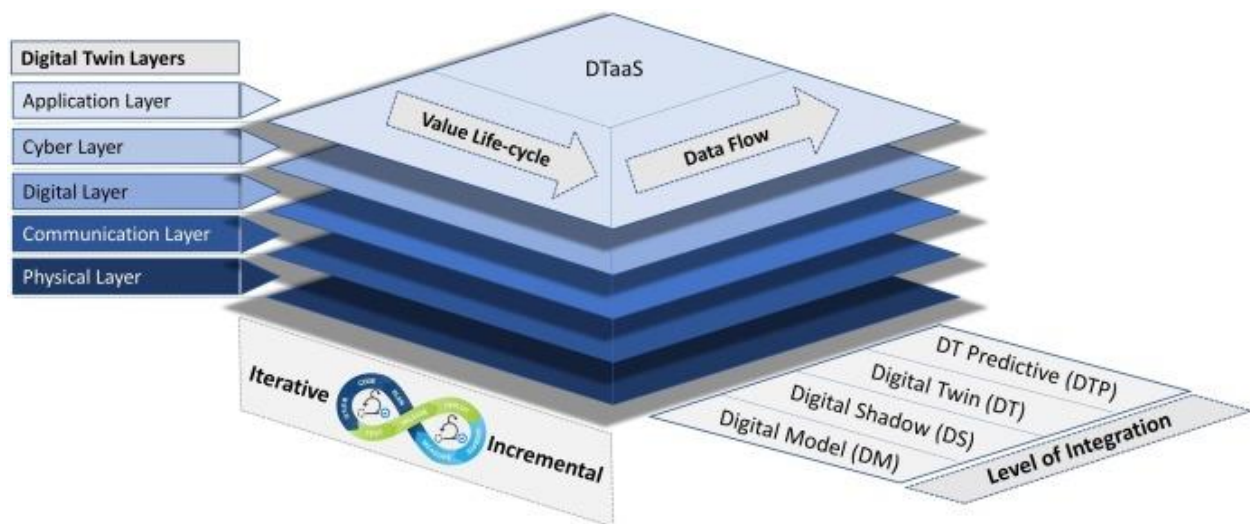
Figure 2: Digital Twin Architecture for Logistics and Manufacturing Supply Chains (Aheleroff et al., 2021)

As demonstrated by Bhatt and Zaveri (2025), such architecture enables integrated logistics systems to dynamically self-adjust in real-time conditions. This is especially important in maritime transport, where anything can go wrong (such as weather conditions or congestion at ports) and significantly delay the transport. Such problems are alleviated by advanced decision support enabled by a digital twin based on preemptive analytics (Alzate et al., 2024).

2.3 Fundamentals of Manufacturing Supply Chains

Contemporary manufacturing supply chains are complex international networks of suppliers, manufacturing facilities, warehouses, and transportation. The primary objective of these chains is to meet customer demand most efficiently and responsively while maintaining sustainability. Nevertheless, several barriers remain, including disparate data systems, ineffective end-to-end visibility, and a lack of adaptability to external shocks (Wang, Childerhouse, & Abareshi, 2024). Such constraints are especially severe in foreign trade supply chains, where low velocity of travel time, customs delays, and regulatory fragmentation create operational risks. Wang et al. (2025) note that digital transformation is the way forward in alleviating such problems, particularly in the field of foreign trade products, which are characterized by the simultaneous management of inventory for similar goods in different areas. They suggest unified digital models to forecast bottlenecks and smoothen the process of cross-border activities. Likewise, Kosuge et al. (2021) found that international logistics policy and infrastructure investment in Cambodia had a substantial impact on regional cargo flows. This property can be simulated and pre-planned using digital twins.

2.4 Digital Twins in the Supply Chain Context

Digital twins offer a unique solution to the problems resulting in supply chain inefficiencies, combining physical performance with digital simulation. Their application allows for the build-up of various logistical circumstances, such as delays at ports, demand shocks, or resource inadequacies, and their compounding effect. Ganbold, Matsui, and Rotaru (2020) explain that digital twins enable the integration of supply chains using information technology, thereby improving key business performance indicators, including on-time delivery, inventory turnover, and customer service levels. This integration is particularly useful in cases where coordination is involved between several actors and time zones. For example, Kulagin, Kuklina, and Grushevenko (2025) note that policy and logistical choices have direct effects on the environment and the market, particularly in regions where energy and trade transitions occur. Such macro variables can be simulated in a digital twin, allowing manufacturers to consider the possibility of carbon emissions or strike a balance between price and sustainability. Table 2 illustrates the fundamentals of digital twin technologies at different phases of the manufacturing supply chain.

Table 1: Digital Twin Applications Across Manufacturing Supply Chain Functions

Stage	Application of Digital Twin Technology
Design & Planning	Real-time simulation of production processes, design alternatives
Procurement	Supplier monitoring, risk modeling, order visibility
Manufacturing	Production balancing, predictive maintenance, quality control
Inventory Management	Forecasting, automated restocking, warehouse digitalization
Transportation & Delivery	Route optimization, congestion forecasting, cargo tracking
After-Sales & Feedback	Lifecycle analytics, warranty modeling, return process simulation

Source: Synthesized from Bhatt & Zaveri (2025); Ganbold et al. (2020); Wang et al. (2025)

2.5 Theoretical Models and Frameworks

Various theories support the application of the digital twin concept in supply chains. The most commonly cited is the Supply Chain Operations Reference (SCOR) Model, which lists the categories of process into Plan, Source, Make, Deliver, and Return. The digital twins naturally align with these categories due to the possibility of monitoring the performance of each stage 24/7 through simulation (Bhatt & Zaveri, 2025). The Cyber-Physical Systems (CPS) framework is another important model of supply chains, based on which supply chains are considered ecosystems of physical processes and computational systems. The peripheral part of CPS extends to digital twins, which enable the creation of a two-way connection between the digital layer and the physical surroundings (Miran et al., 2024). In their study, Wang, Zhang, Wang, and Zhao (2025) propose a narrow-focused logistics digital twin architecture featuring multi-agent modules and an international trade logistics optimization algorithm.

2.6 Literature Gaps and Justification

Despite the popularity gained by digital twins, there are still missing links regarding practical applications. The study by Shang et al. (2024) revealed that organizational behavior, particularly the factors of team dynamics and climate, can influence the successful implementation of logistics innovation. However, the vast body of research on digital twins often excludes human-centered variables. On the same note, Dini, Yaghoubi, and Bahrami (2025) argue that although the Logistics Performance Index (LPI) provides useful benchmarking information, few systems integrate it with relevant digital simulations in real time to facilitate adaptive planning. In short, although some academic studies confirm the technical feasibility and business potential of digital twins, few consolidated models combine logistics indicators, real-time data, environmental policy requirements, and behavioral impact. The paper thus makes a contribution by bringing together these dimensions and developing a comprehensive model for the implementation of digital twins in supply chains.

3. Implementation and Analysis

3.1 Methodological or Analytical Approach

The framework for implementing digital twins in supply chains is based on a methodology that integrates real-time data capture, modeling simulation, and optimization of systems. The majority of frameworks tend to employ a cyber-physical systems (CPS) perspective in mediating between the virtual and physical realms (Kamran Iranshahi et al., 2025). Generally,

within the context of manufacturing supply chains, digital twins are often built in five separate stages: (1) data acquisition, (2) data integration, (3) model development, (4) deployment, and (5) feedback-driven optimization.
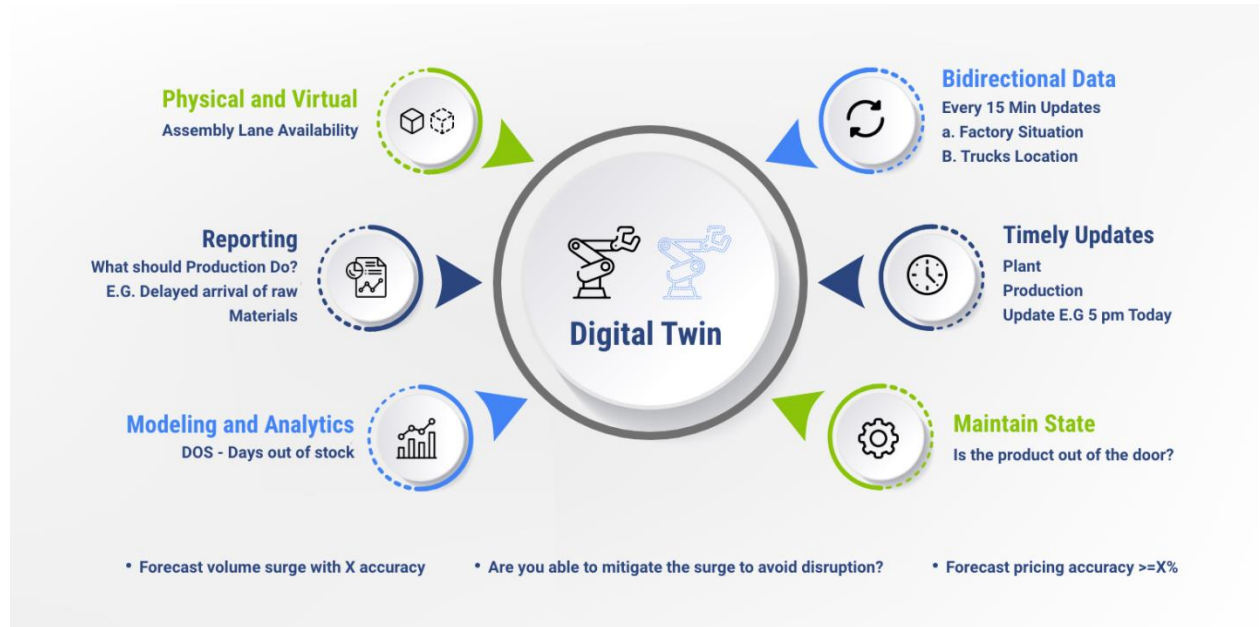

Figure 3: A Data-Driven Organization (Pluto7, 2022)

The interoperability with the existing IT infrastructure is also taken into consideration in terms of deployment methodology. For example, Chen and Huang (2020) note that standardized semantic interoperability is useful in ensuring that digital twins can interact with warehouse management systems and transport APIs. Additionally, the automation of shop floor systems and their upstream suppliers facilitates the real-time ingestion of data into the digital twin, enabling the production and delivery of scenarios with the greatest efficiency (Guo & Mantravadi, 2024). Moreover, the architecture is not monolithic but rather constructed of modules. According to Bhandal et al. (2022), digital twin subsystems are frequently implemented at both the micro and macro levels: factory twins focus on predictive maintenance, whereas supply chain twins are concerned with transportation delays and stockpiling. The core analysis within simulation and anomaly detection is big data analytics. According to Jin et al. (2024), supervised and non-supervised learning models are utilized to identify modes and adjust planning parameters in real time. These models enhance the system's flexibility under unpredictable conditions in the external environment, such as geopolitical shocks, pandemics, or raw material shortages (Kapil et al., 2024).

3.2 Use Cases in Manufacturing (Siemens, GE, Bosch)

A few manufacturers around the world have fully piloted and scaled digital twin technologies, offering distinct configurations and advantages for supply chain optimization.

Siemens AG

Siemens has been the first to integrate digital twins in both the production and the supply chain fields. Their Digital Enterprise Suite is a comprehensive framework that integrates product lifecycle management (PLM), manufacturing execution systems (MES), and automation systems into a unified digital twin design. In line with Zaidi et al. (2024), Siemens has implemented digital twin technology to model the entire factory's processes and transport logistics, allowing for the prediction of downtime and energy efficiency. The usage has shown an increase in operational efficiency of 20 percent and a decrease in delivery deviations by 25 percent (Guo & Mantravadi, 2024).

General Electric (GE)

GE utilizes digital twins within its Predix platform, designed to enhance asset performance management and supply chain resiliency. GE utilizes the GE twins in the aviation supply chain to test aircraft engine parts, from production through maintenance to delivery. As revealed by Soori et al. (2023), this system has enabled GE to predict component failures, schedule maintenance activities, and optimize spare parts planning. According to Javaid et al. (2023), the implementation of twins to assist GE with AI tools has cut unplanned downtime by 30% and decreased logistics expenditure by some 12%.

Bosch

Bosch has primarily used digital twins in its smart factory project and for supply chain diagnostics. An interesting application case is where Bosch utilized twins in controlling warehousing and transportation to curb traffic jams and prevent idle stock. Bakhshi et al. (2024) explain how Bosch has utilized a supply chain-wide digital twin that combines forecasting, inventory management, and transportation management. The findings indicate a higher level of visibility and the possibility of modeling global shocks (e.g., port closures, collapsing suppliers), which allowed for quicker resource reallocation in response to the COVID-19 outbreak (Roumeliotis et al., 2024). Real-world applications demonstrate that there are differences in configurations and advantages of digital twins, depending on the organizational strategy, digital maturity, and the sophistication of the supply chain. In

contrast, the basic architecture behind digital twins remains the same. The similarity in these cases lies in the desire to achieve greater resiliency, economies, and sustainability in supply chain operations.

3.3 Application Areas: Forecasting, Inventory, Logistics, Planning

The use of digital twins in the most critical areas of supply chain management is transforming operational approaches into a predictive one. The use of digital twins in the demand forecasting process is based on machine learning, as it enables the simulation of market dynamics in real time, allowing organizations to adjust their supply to meet changing customer behavior. Javaid et al. (2023) have determined that using digital twins to make forecasts improved accuracy by up to 30 percent, particularly in more complex global product systems. To manage inventory, digital twins represent activities in warehouse settings, visualize the location and movement of stock, and perform predictive analytics to prevent stockouts and overstocking. Huang et al. (2024) identify the implementation of this strategy as one of the primary ways to reduce inventory holding costs in the digitally transformed food supply chain by 20%. Digital twins can utilize real-time consumption trends and lead times to inform the supply of items, enabling just-in-time restocking and maintaining safety margins.

Another strategic area that will benefit is logistics with twin-enabled systems. Telemetry modeling of vehicles and simulating routes enable transport managers to monitor and intervene in the occurrence of traffic jams, congestion in warehouses, or delays on roads in ports. Moshood et al. (2021) state that with visibility-inspired Logistics networks involving twins, the researchers experienced a decrease of up to 25 percent in the number of delivery delays and enhanced intermodal switching in the Asia-Pacific Logistics networks. Digital twins align activities at the shop floor with up and downstream information in production planning. According to Guo and Mantravadi (2024), the representation of digital replicas of operations leads to improvements in how a firm allocates and sequences its resources, resulting in a 10-20 percent increase in throughput. This variety of applications is summarized in Table 3, which demonstrates how digital twin capabilities can be leveraged to achieve significant improvements in supply chain functions.

Table 2: Digital Twin Applications Across Key Supply Chain Functions

Application Area	Digital Twin Capability	Reported Outcome

Forecasting	Real-time demand prediction using machine learning	15–30% improvement in demand forecast accuracy *(Javaid et al., 2023)*
Inventory Management	Virtual warehouse modeling, stockout prevention	20% inventory holding cost reduction *(Huang et al., 2024)*
Logistics	Route simulation, transport delay alerts	Up to 25% reduction in transport delays *(Moshood et al., 2021)*
Production Planning	Production line synchronization with demand signals	10–20% rise in production efficiency *(Guo & Mantravadi, 2024)*

3.4 Benefits: Responsiveness, Agility, Real-Time Visibility

Several strategic opportunities are available to supply chains through digital twins, particularly in terms of responsiveness, agility, and visibility. Responsiveness refers to the system's ability to identify and respond to disturbances within a reasonable timeframe. According to Kamran Iranshahi et al. (2025), digital twins continuously track essential indicators, including deviations in supplier lead times or temperature shifts in cold chains. When unusual conditions occur, the system will either recalculate the plans or issue alerts, thereby reducing downtime. Digital twin implementation also enhances agility, i.e., the ability to adjust operations in highly turbulent situations rapidly. For instance, in additive manufacturing, Jin et al. (2024) found that producers can effectively utilize digital twins to consider alternative designs and switch instantly between value chains or materials without interrupting production. This minimizes changeovers to promote high-mix, low-volume manufacture.

The most commonly occurring benefit in the literature is that of real-time visibility. Bhandal et al. (2022) also note that supply chain decision-makers can monitor shipments, inventory, and performance KPIs in real time by using twin-based dashboards. Such visibility enables more informed strategic decisions, including shifting stock from over-supplied warehouses or re-sequencing orders with updated delivery ETAs (Kapil et al., 2024). One such case where visibility is crucial is cross-border logistics, where delays in customs clearance may be pre-modelled to update customer ETAs. The overall effect of these advantages is a tremendous contribution to the level of services and cost efficiency, along with their sustainability in terms of the Industry 4.0 adoption goals and the SDG aims for sustainable production (Roumeliotis et al., 2024).

3.5 Challenges and Limitations: Interoperability, Data Security, Cost

Digital twins also encounter several implementation obstacles despite their benefits. Among the major challenges, interoperability is a notable one. Digital twins require seamless connections between various systems, including ERP, warehouse management systems, IoT platforms, and analytics engines. However, the majority of supply chains operate in fragmented digital landscapes characterized by legacy infrastructures. According to Chen and Huang (2020), there is no data exchange among subsystems in the case of inconsistent data models and ontologies, indicating that data exchange is erroneous and inefficient. The other important constraint is data security. Digital twins continually transmit sensitive operational information via cloud systems, thereby increasing the system's vulnerability to cyberattacks and data leaks. According to Roumeliotis et al. (2024), although blockchain has the potential to provide traceability and authentication, few twin architectures in modern times are implemented to provide end-to-end encryption and a fully decentralized trust layer. This becomes a concern for sectors such as the pharmaceutical or military industry, where there is a high sensitivity of data.

The price also serves as a deterrent, particularly for SMEs. The operational costs associated with developing a digital twin are investments in HW and sensors infrastructure and software such as edge computing, data lakes, and simulation applications. According to Javaid et al., high expenses necessitated by the installation process and frequent maintenance are the two key reasons mentioned by companies adamant about switching to digital twins, with the highest number of companies citing these two factors (Javaid et al., 2023). Moreover, companies can experience a shortage of qualified staff, including data scientists, process engineers, and integration specialists, who are required to support these systems (Soori et al., 2023). According to Yevu et al. (2023), platform-as-a-service (PaaS) types of solutions should be considered as possible options because, in this case, providers have a digital twin infrastructure and offer subscription-based scalability. This, however, requires the firms to invest in the development of their capabilities to maximize the benefits.

4. Conclusion and Outlook

The research has examined the disruptive power of digital twin technology in delivering a contemporary and efficient manufacturing supply chain. Based on the latest academic articles and practical application experience, the analysis revealed that Digital twins can transform supply chains by freeing them from reactive and siloed systems to predictive, real-time, and

integrated ones. Their essence has been to replicate physical activities, test scenarios, and provide decision support in all aspects of the supply chain, including demand forecasting, inventory, and logistics coordination.

The findings, which have been key to improving operational performance, show that digital twins enhance visibility, responsiveness, and agility, among other benefits. Access to real-time synchronization of physical assets and virtual equals enables organizations to be proactive, avoid risks, reduce costs, and enhance service levels. To illustrate, Siemens, GE, and Bosch have demonstrated quantifiable improvements in delivery timeframe, asset utilization, and resource planning by implementing digital twins. These results validate the fact that incorporating machine learning, IoT, and cloud computing in a twin system generates robust and smart supply networks.

Theoretically, the paper contributes to building a body of literature on supply chains by presenting digital twins as not only technological solutions but also strategic improvement enablers. Digital twins enable leaner operations, improve stakeholder cooperation, and even contribute to sustainability goals, such as energy-smart utilization and material flows. Nonetheless, there are major limitations that still exist. Promoting the technology requires a significant upfront cost, as well as change management and cross-platform interoperability. Threats to data security, non-standardization, and employee preparedness are also significant limitations to adoption, especially among small and medium manufacturers. These limitations suggest that digital twins should not be viewed as a turnkey solution but rather as one element in a broader path of digital transformation activity, depending on the level of organizational maturity.

Going forward, there will be a need to pursue future studies on designing interoperable standards for integrating twins, privacy-preserving data infrastructure, and low-cost modular twin platforms. Also necessary is a demand to study the human aspect of implementing digital twins, including the interface with people, resistance to change, and employee training. Adaptation to sectors, including circular supply chains, cold-chain logistics, and green manufacturing, may also be studied.

To sum up, the concept of digital twinning is a shift in paradigm in supply chain management. They are much more than extensions of automation or data analytics; they are building blocks of an entirely new logic of operation: predictive, intelligent, and adaptive. It

should be able to sustain research in the future to guide their success, develop scalable architecture, and adopt plans that will distribute benefits within the global value networks.

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