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Exploring the Role of Digital Twin Technologies in Transforming Modern Supply Chain Management

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Abstract

The advent of digital twins (DTs) has improved operational efficiency, sustainability, and predictive analytics, hence transforming the field of supply chain management. This study explores the role of DTs in optimizing supply chain processes, distinguishing them from digital models and shadows by emphasizing bidirectional data flow and real-time synchronization. The study showcases DT applications across a range of sectors, elucidating their revolutionary influence: manufacturing, healthcare, smart cities, education, and next-generation networks. Key supply chain use cases such as demand forecasting, predictive maintenance, supplier performance monitoring, and smart warehousing are analyzed, showcasing the potential of DTs to drive digital transformation. DTs save costs and enhance decision-making by combining state-of-the-art technologies like automation, the Internet of Things (IoT), and AI to offer real-time monitoring, predictive analytics, and operational efficiency. The integration of DT into Supply Chain Management is thoroughly examined in this article.

Keywords: Digital Twin Technology; Supply Chain Management; Smart Warehousing; Predictive Maintenance; Supply Chain Digitalization

1. Introduction

The term "supply chain" (SC) is used to describe the extensive system of interdependent businesses that work together to provide goods and services to consumers. An SC contains all of the components that belong to different stakeholders and covers each stage that goes into providing the client with a final product or service. An SC consists of six main processes: enable, deliver, source, make, plan, and return [1]. The protocols outlined here facilitate the sharing of information, data, and other resources throughout the SC and touch on a variety of business stakeholders' functional areas. Multiple operational levels, numerous stakeholders, and high interoperability make up the SC's intrinsically complicated hierarchical structure [2].

Companies depend significantly on digital transformation to maximize performance in SCs because of their interconnected and complicated nature. " An enterprise-wide plan to integrate digital technology " is the definition given for digital transformation. Within this framework, businesses are looking at new SCM-related technologies to help them compete on a global scale. As a result, supply networks are embracing Industry 4.0, the next wave of industrial change. A plethora of new technologies are coming together to form Industry 4.0. These encompass a wide range of technologies, such as RFID, cloud computing, CPS, big data, AI, smart sensors, and the IoT [3].

Industry 4.0 relies heavily on digital twins (DTs). Virtually everything may be represented digitally by a DT. The original idea of DTs came from the National Aeronautics and Space Administration (NASA) to simulate actual spaceship scenarios [3]. Digital Twins, Digital Models, and Digital The term "shadow" is one example of how industrial jargon can

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change depending on how much information is shared between a product's physical and digital versions. A DT normally consists of 3 parts: (1) a physical entity; (2) a virtual entity, which is often a physical thing's digital counterpart; and (3) a bridge that enables bidirectional communication between the virtual and physical things. The creation of digital twins—which enable the real-time virtual depiction of physical assets, processes, and systems—is crucial for sustainable supply chain mobility [4]. The supply chain can now be better monitored, analyzed, and optimized due to this innovation. Organizations can utilize digital twins to enhance commodity flow efficiency and decrease waste by modeling and forecasting the outcomes of various scenarios. Their assistance with route planning, energy savings, and emission reductions allows for more efficient and ecologically friendly transportation across the supply chain. The exclusive emphasis of this research is on DTs, or digital twins, in which data flows in both directions between digital and physical components.

1.1. Research Motivation and Contribution

The motivation behind this study is to explore how Digital Twin technology can revolutionize modern supply chain management by reducing operational risks, enhancing sustainability, and driving innovation in an increasingly complex global market. The key contribution of the study is the following:

- Distinguishes Digital Twins from digital models and shadows, explaining bidirectional data flow and real-time synchronization.
- Highlights their impact on manufacturing, healthcare, smart cities, education, and next-gen networks.
- Explores their role in demand forecasting, predictive maintenance, supplier monitoring, and smart warehousing.
- Links Digital Twins with AI, IoT, and automation to drive digital transformation.
- Emphasizes real-time monitoring, predictive analytics, and operational efficiency for cost reduction.

1.2. Structure of the Study

This paper explores DT technology in supply chain management. Section II introduces DT fundamentals, Section III discusses benefits like real-time monitoring and predictive maintenance, Section IV examines applications in various sectors, Section V focuses on DTs in supply chain management, Section VI highlights operational benefits, and Section VII reviews related literature.

2. Understanding Digital Twin Technology

The phrase "DT" describes a data-connected digital copy of a real-world system and its related operations that may be used to seamlessly transition from the real to the virtual world while maintaining full conformity [5]. The format and direction of data transfer between real and virtual systems is where DT diverges by digital models or shadows of systems [6]. In contrast to digital models/shadows, which do not incorporate the complete data cycle, digital twins allow for the automatic and bidirectional integration of data flows among physical and digital systems, allowing for the synchronization of digital objects with the current status of physical ones and the transmission of control information to them[7][8]. Data flow direction and kind are the primary differentiators between DT, digital models, and shadows of systems [9]. Digital twins rely on this data to provide complete, up-to-the-minute information on the physical system [10].

Many advantages may be gained by deploying digital twins. The following are only a few of these benefits [11]:

- Real-time monitoring, control and data acquisition: DT allows for the transmission of real-time updates between digital and physical systems, which in turn allows for the control of the physical system as required, the monitoring of all changes, and the collecting of all data required for business decisions.
- Business continuity through remote access: The DT, which can be accessed by remote users all over the globe, guarantees that all parties involved participate and cooperate even when the real system is down.
- Increased efficiency: Digital twins provide a platform for proactive experimentation with solutions by allowing their assessment in various settings and instances prior to being implemented in physical systems. This approach allows for the selection and deployment of the most effective solutions, thereby enhancing the overall efficiency of the system.
- Highly-informed decision support: Business decisions may be made more quickly, with more accurate information, and with less effort when all real-time data is collected in one place and readily input into data analytics tools.

- Predictive maintenance and optimized scheduling: Digital twin forecasts may be enhanced with the use of ML and AI methods to assess the best times to do maintenance in order to minimize interruptions. Scheduling business operations may also be optimized for greater efficiency using AI approaches.
- Enhanced risk assessment: Virtual testing of alternative solutions is made possible using a digital twin, enabling for what-if analysis to be carried out without affecting the actual system.

2.1. Digital Twin Applications

Digital twins have been used in many fields because of their many benefits, as mentioned above, and their tremendous potential for correctly simulating physical systems. These domains include, for example:

2.1.1. Manufacturing

Industry 4.0 describes the most recent developments in manufacturing as part of the fourth industrial revolution. Digital twins can provide all nine technologies that make up Industry 4.0, according to a BCG analysis [12]. The following technological advancements have been made in recent years: additive manufacturing, sophisticated robotics, cloud computing, cybersecurity, industrial IoT, simulation, and augmented reality.

2.1.2. Healthcare

It has been claimed that the healthcare industry would be one of the most important users of digital twins [13]. Wearable sensors and data collection devices are becoming increasingly commonplace, opening the door to the possibility of human digital twins that can foresee and prevent potential health problems, such as alerting a healthcare provider or dispatching an ambulance to the patient's location in the event of an emergency.

2.1.3. Smart Cities

Digital twins have the potential to be a game-changer in smart city development as it create a digital copy of the city, making it possible to see all of its resources and the interactions among people and cars [14]. Additionally, it enables the tracking of infrastructure, utilities, and companies, in addition to managing future improvements.

2.1.4. Education

Educators and students across the globe have been scrambling to find ways to keep learning in the face of lockdown limitations caused by the COVID-19 outbreak. The problem was initially significant since not all schools had the resources to implement a fully digital curriculum. But in the end, a lot of them used the concept of digital twins in the classroom, opening up a new way of teaching and learning to students all around the globe.

2.1.5. Next Generation

There is growing complexity in the testing and optimization of next-generation networks on settings prior to their actual deployment as networks undergo continuous evolution from fourth to fifth and soon sixth generation [15]. This difficulty may be addressed in part by using digital twins of network installations, which can demonstrate whether next-generation networks can meet needs like security, latency, and efficiency.

3. Digital Twin Applications in Supply Chain Management

The main goals of integrating DTs into SCs are optimization, simulation, visibility and monitoring, and prediction [16]. A heuristic optimization system running in a DT warehouse, for instance, might improve material handling [17]. Further, order-picking systems that make use of DTs for operational control have had their functional and architectural frameworks laid out. An analysis of worker tiredness during material handling movements has been conducted using a DT framework inside the material handling process [18]. Although there are several methods for simulating AS/RSs, many models fail to include real-time data, which restricts the extent of digitization. For the purpose of validating the simulation model, a DT-based technique was used to construct a discrete event simulation model that included both the physical system and the IT architecture.

3.1. Demand Forecasting and Inventory Optimization

Inventory planning is also affected by the domino effect of inaccurate forecasts [19]. The ability to effectively manage inventory should be considered an enabling competency, and the best way to make use of the company's forecasting tools is to merge the two processes [20]. The reality is that many SMEs lose ground in the market due to sloppy inventory management [21]. SMEs often struggle with inventory management due to a lack of well-defined planning processes, poor communication between sales, supply chain, and production, and, most importantly, staff members' inadequate knowledge and skills [22][23].

3.2. Predictive Maintenance

Predictive maintenance driven by AI is transforming many industries, particularly those that heavily depend on machinery and equipment. It addresses a critical aspect of company continuity by reducing operational interruptions and preventing unplanned downtime. This approach allows companies to plan maintenance ahead of time by using complex artificial intelligence algorithms and data analytics to predict when machinery or equipment may break down [24].

3.3. Supplier and Vendor Performance Monitoring

Supply chain operations need a sustained collaboration between suppliers and purchasers. Building such a connection requires that buyers keep an eye on suppliers' performance in a variety of areas and provide suggestions for improvement [25]. Soon after the supplier selection process, there is an additional, separate, but connected step called supplier monitoring.

3.4. Smart Warehousing and Automation

The key to smart warehousing's success is for its adopters to understand their own objectives and goals in order to discover and take advantage of value drivers [26]. Smart warehousing's primary value drivers are listed in Figure 1.

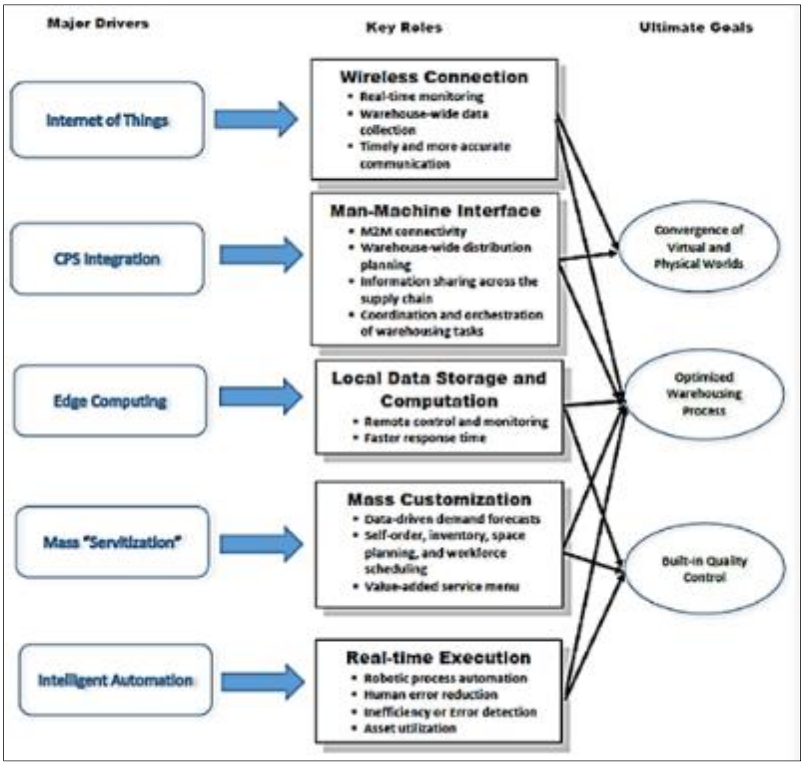

Figure 1 Key Drivers of Smart Warehousing

These include: (1) Quality inspection, space planning, cross-docking, cycle counting, and slotting are just a few of the common warehousing processes that can be managed and monitored in real-time with the help of the IoT embedded with sensors. (2) The IoT connected to physical things via CPS-driven integration improves M2M connection, which in turn speeds up replies to fulfillment error messages, inventory restocking requests, and safety alarms [27]. (3) Edge computing allows data processing to go to the periphery of the warehouse's computer network, allowing for local storage and computation regardless of the location. By using edge computing, data loss may be prevented even in areas with spotty internet service, and response times to customers can be reduced without any major disruptions. (4) The development of individualized self-warehousing and order processing based on business intelligence tools like AI is facilitated by mass "sterilization" offers, such as value-added services (VAS). (5) Intelligent automation that might imitate human behavior to diagnose anomalies or flaws in the warehousing process, detect inefficiencies in the warehouse in real time, and coordinate material flows within the warehouse[28]. Such a feature encourages rapid remedial action using the recommended appropriate methods or resources to assist in resolving issues immediately.

4. Benefits and Applications of Digital Twin Technology in Supply Chains

Digital twins (DTs) have many applications in supply chains (SCs), but some of the more common ones are visibility and monitoring, optimization, prediction, and simulation [16][29]. A heuristic optimization algorithm running in a warehouse's DT, for instance, might enhance material handling. They have also provided functional and architectural frameworks for order-picking systems that use DTs to aid operational control. An analysis of worker tiredness during material handling movements has been conducted using a DT framework inside the material handling process. Even though there are a number of simulation methods that deal with the intricacy of AS/RSs, a lot of models don't use real-time data, which restricts the amount of data that can be digitalized [30]. An approach to DT-based model validation was developed, which entails constructing an integrated physical-and-information-technological discrete-event simulation model. DT-based human-robot interfaces can direct and manoeuvre autonomous robots to discrete workstations inside a warehouse. Data is retrieved from industrial processes via DT-based AS/RS systems, which then process the digital model based on simulation and transmit the results back to the AS/RS systems [31]. The process has made AS/RSs more reliable and scalable.

There are some common Benefits of Digital Twin Technology in supply chain [32]:

- Real-time monitoring for better decision-making.
- Predictive analytics to prevent disruptions and optimize performance.
- Simulation capabilities to test and validate supply chain strategies.
- Risk assessment & security features to improve resilience.
- Cost reduction & sustainability improvements.
- End-to-end visibility & collaboration across supply chain networks.

4.1. Industry-Specific Applications of Digital Twins

DT technology has become a disruptive force in many different sectors, providing creative answers to difficult problems. Below are key applications of Digital Twins in specific sectors:

4.1.1. Digital Twins in Manufacturing Supply Chains

A new breed of digital solutions for automating business challenges has emerged in response to the flurry of activity around SCM system improvement. Companies nowadays are faced with the constant challenge of adjusting to new circumstances in the management of their supply chain [33].

4.1.2. Role of Digital Twins in Automotive Supply Chains

Digital Twins' (DTs') revolutionary potential in the automobile industry, especially in light of the fourth industrial revolution. It explores the history of DTs from their inception to their present uses in order to demonstrate the speed at which technology is developing and the growing impact that DTs have on a range of sectors, settings, and locales [34].

4.1.3. Digital Twin Technology in Healthcare Logistics

A DT, or digital representation of an object, is becoming popular in many industries. Huge strides are being made in healthcare because of this technology. "DT" are exact digital reproductions of physical objects or people. The linked application's IoT sensors must collect massive amounts of data before a testable and simulated digital model can be created [35]. This technology lets patients stay informed about medications, dietary modifications, medical consultations, and more based on their lifestyle, frequent eating habits, and blood sugar readings. Data from several IoT devices is used by Digital Twin, which employs models driven by AI[36]. The patient's own digital twin may aid in pharmaceutical selection, operation outcome prediction, and chronic disease management by drawing on insights from past data [37].

4.1.4. Application of Digital Twins in Food Supply Chains

Security, safety, waste, and quality are four major issues confronting the food business throughout the world. A lack of customer confidence, financial losses, and potential health risks have resulted from food safety incidents in recent years [38].

5. Literature review

This study highlights the literature review based on Digital Twin Technology in Transforming Modern Supply Chain Management, along with significant findings. Also, provide summary in Table 1:

Iliuţă et al. (2024) this extensive examination digs into the history of Digital Twin (DT) technology, charting it from its conceptual roots to modern technical applications. The paper includes extensive definitions, classifications of several kinds of DT, and a comparison of their designs. Additionally, it explores the use of technology across a range of industries, with a focus on manufacturing and medicine, as shown by use cases like personalized medicine [39].

Singh et al. (2021) the goal of this work is to compile the many forms of DT and definitions found in the literature so that DT can be easily distinguished from other related concepts like "Product Avatar," "Digital Thread," "Digital Model," and "Digital Shadow." From its origin to its anticipated future, the idea of DT has been used to realize the value it can provide to certain industries. Before investing in DT, any researcher, company, or industry must comprehend its features and types while assessing its benefits and drawbacks [40].

Stroumpoulis, Kopanaki and Chountalas (2024) this research delves into how digital transformation and information systems play a pivotal role in promoting sustainable SCM. In an effort to save the environment, improve society, and propel economic progress, more and more companies are embracing sustainable strategies. The company's operational efficiency and productivity are both enhanced by the digitization of its procedures. With the rise of information systems, supply chains have become indispensable for a wide range of tasks, including digital transformation, sustainable development, and process support [41].

Table 1 The Table Highlights their Important Areas of Research Along with Significant Findings and Problems and their Impact on DT Technology and Modern Supply Chain Management

References	Focus Area	Key Findings	Challenges	Key Contribution
Iliuţă et al. (2024)	Evolution of DT technology	Traces DT from conceptual origins to modern implementations; provides classification and comparative analysis of architectures; explores applications in medicine and manufacturing	Lacks specific focus on supply chain applications	Offers a broad understanding of DT evolution and its interdisciplinary applications
Singh et al. (2021)	Definitions and classification of DT	Consolidates various DT definitions and differentiates it from related terms (e.g., digital thread, product avatar)	Does not focus on DT in supply chains	Establishes a clear taxonomy of DT, helping industries distinguish it from complementary concepts
Stroumpoulis, Kopanaki and Chountalas, (2024)	Digital transformation in Sustainable Supply Chain Management (SSCM)	Highlights how digitalization enhances efficiency, environmental sustainability, and business performance	Limited direct reference to DT technology in SCM	Shows how digital transformation improves SSCM, laying the groundwork for DT integration
Kumar et al. (2023)	Literature review on SSCM and digitalization	Identifies research gaps in SSCM, emphasizing the lack of standardized sustainability frameworks and measurement indices	Absence of concrete SSCM frameworks and clear sustainability metrics	Provides a comprehensive review of digital SSCM research, identifying future research directions
Bandara and Buics, (2024)	DT applications in supply chains (SCs)	Explore sustainable inbound and outbound logistics and key enablers for DT adoption in SCs	Lacks empirical case studies or real-world implementations	Establishes key enablers for successful DT integration in SCM

				using systematic literature analysis
Douaioui, Benmoussa and Ahlaqqach, (2024)	Optimization in SCM using digital models	Proposes an optimization model incorporating goal programming (GP), dependent chance constraints (DCC), and hunger games search algorithm (HGSA) for improved efficiency	Does not explicitly mention Digital Twin applications	Introduces an advanced SCM optimization model that can be enhanced with DT for predictive analytics and decision-making

Kumar et al. (2023) this research aimed to examine the role of TA in supply chain management systems that rely on digital platforms by conducting a comprehensive literature review. By analyzing relevant research publications using bibliometric and content analytic approaches, this review aimed to provide a comprehensive understanding of the current state of the issue, pinpoint any gaps in the literature, and offer recommendations for further study. Literature reviews revealed a lack of SSCM frameworks and an urgent need for more transparent and practical sustainability monitoring indices [42].

Bandara and Buics (2024) investigate the present state of DT applications in SCs, with an emphasis on environmentally friendly incoming and outgoing logistics, and pinpoint the critical enablers that will pave the way for the effective implementation of DTs in SCs. This research aimed to examine the current knowledge on this issue by screening articles from the Scopus database using the PRISMA framework and the PEO model. Articles about DTs have increased dramatically over the last decade, suggesting that more and more people are interested in learning about and finding ways to use this technology. The successful implementation of DTs is largely influenced by knowledge workers, standardized processes, advanced technological infrastructure, technologies like IoT, IIoT, AR/VR, and managerial assistance [16].

Douaioui, Benmoussa and Ahlaqqach (2024) this study introduce a strategy for optimizing SCM that combines HGSA, dependent chance restrictions, and goal programming. By including unknown factors that boost efficiency and robustness, the model takes uncertainty into account. Maximizing on-time deliveries while minimizing costs is achieved by optimizing key decision criteria such as production setups, volumes, inventory levels, and back orders. The model outperforms traditional models in delivering strong solutions to supply chain challenges that are subject to constant change, according to numerical findings and extensive simulations [43].

6. Conclusion and Future Work

The advent of DT technology has been a game-changer in many sectors, such as manufacturing, healthcare, education, smart cities, and next-gen networks. By making data-driven decisions, predictive maintenance, and real-time monitoring easier, digital twins boost performance, optimize operations, and decrease dangers. Digital twins contribute to supply chain management in several ways, including smart warehousing, improvement of demand forecasting, optimization of inventory, and monitoring of supplier performance. The integration of AI and IoT further strengthens their capabilities, making supply chains more agile and resilient. As organizations continue to adopt Digital Twin technology, its impact on operational efficiency and strategic planning will become increasingly significant.

Future research on Digital Twin technology should focus on improving interoperability, scalability, and security, particularly in large-scale industrial and supply chain environments. Data security, traceability, and the capacity to do real-time analysis stand to benefit greatly from the integration of new technologies like blockchain and edge computing.

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