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Masterthesis

Applications of digital twin for Supply chain management

Ben Martens

Scriptie ingediend tot het behalen van de graad van master in de handelswetenschappen, afstudeerrichting supply chain management

PROMOTOR :
Prof. dr. Inneke VAN NIEUWENHUYSE

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Applications of Digital Twin Technology in Supply Chain Management

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Master supply chain management

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Abstract: This research delves into the multifaceted applications and implications of Digital twin (DT) technology within the realm of supply chain management. Originating from NASA's Apollo space program, the DT has evolved as a pivotal tool in the digital age, offering a real-time virtual representation of physical entities. Despite its widespread adoption across various sectors, its possibilities in supply chain management remain largely untapped. This paper provides a comprehensive overview of DT, highlighting its definitions, core concepts and foundational technologies, including the Internet of Things (IoT), Big Data Analytics and Artificial Intelligence (AI). Furthermore, a classification of DT is presented based on creation time, integration level, hierarchy, sophistication and purpose. Challenges such as data management, privacy and security are also addressed. Through a deep exploration of academic resources, this study aims to shed light on the transformative capabilities of DT technology in optimising, predicting and revolutionising supply chain operations.

Keywords: simulation, supply chain management, Digital Twin, Industry 4.0, blockchain, IoT

1 Introduction

A Digital Twin (DT) is a model or virtual representation of a physical entity connected through real-time data exchange (Tao et al., 2019). This DT conceptually mirrors its physical counterpart's condition in real-time. As industries transition into the digital age, often referred to as industry 4.0, DT emerges as a pivotal tool for gaining a competitive edge. In the ensuing decades, its use is anticipated to skyrocket (Singh et al., 2021). But why is this technology so pivotal? And what problems does it aim to address?

Historically, the "twin" concept was pioneered by NASA's Apollo space program, which developed two identical space vehicles. One remained on Earth, serving as a reference to simulate and predict the conditions of its counterpart in space (M. Liu et al., 2021). The ability to preemptively tackle problems before they escalate is invaluable in any industry, especially in supply chain management, where the stakes are high and margins are thin. Following this initiative, DT technology has been increasingly adopted across a large number of industries, from aerospace to healthcare. While traditional applications of DT have revolved around simulation, monitoring and control, the technology's scope has broadened. Today, it covers design, validation, customisation, optimisation, prediction and maintenance, offering transformative solutions for intricate supply chain networks (Singh et al., 2022).

The essence of a DT primarily lies in its ability to simulate and predict the behaviour of the system it represents, whether that system is human or otherwise, while also supporting decision-making processes (Balaji et al., 2023). This dynamic nature of DTs facilitates continuous communication and collaboration, providing supply chain managers with end-to-end visibility and traceability. Such capabilities enable the identification of complex behavioural patterns and the construction of nonlinear supply chain models. Moreover, by simulating countless what-if scenarios, DTs refine their decision-making powers over time, aiding managers in making swift, accurate and well-informed decisions that have lasting impacts. However, the fusion of DT with AI and IoT technologies introduces a set of shared challenges. These include issues related to infrastructure, data management, privacy and security (Fuller et al., 2020).

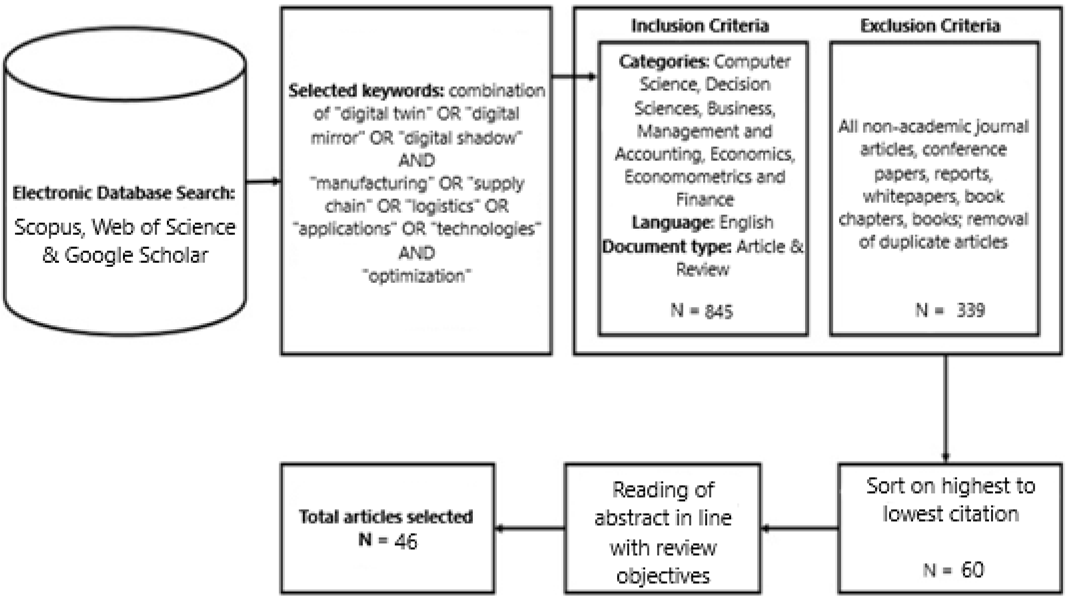
The structure of this literature review is as follows: Section 2 details the criteria for paper selection; Section 3 presents a general overview; Section 4 to 7 delve into the classification, applications, benefits and challenges respectively; Section 8 suggests future research directions and opportunities and Section 9 concludes with insights and reflections.

2 Methodology

This section provides a description of the search methods used to conduct this research. The methodology for this research study was designed to identify and review relevant literature on the topic of digital twin technology in the fields of supply chain, logistics, transportation, manufacturing, and production planning. To do this, a combination of keyword searches in Scopus, Web of Science and Google Scholar was used, and the reference lists of relevant articles were manually reviewed to find additional studies.

To guarantee the selection of a thorough and high-quality collection of papers for review, specific keyword combinations were used in the selected databases. This approach enabled the identification of articles that focused exclusively on topics relevant to the research. The search keywords used are “digital twin” OR “digital mirror” OR “digital shadow” AND “manufacturing” OR “supply chain” OR “logistics” OR “applications” OR “technologies” AND “optimization”.

The initial search resulted in 845 articles. Only categories that were relevant to the chosen area of focus were included. These categories are: Computer Science, Decision Sciences, Business, Management and Accounting, Economics, Econometrics and Finance. The results were limited to articles and reviews only written in English. Some exclusion criteria are non-academic journal articles, conference papers, reports, whitepapers, book chapters and books. Duplicate articles were removed. This resulted in a number of 339 articles. To ensure the use of quality articles, the remaining articles were ordered from high citation to low. 60 Papers were selected based on the title and after reading the abstracts of these articles, 46 remained the most suited for this research.



3 Overview

This section offers a comprehensive overview of DT technology, including its definition, concept, key technologies and some auxiliary technologies. By understanding the fundamentals of DT technology, its capabilities and its relevance in supply chain operations, valuable insights can be gained into how it can improve the way organisations manage their supply chains, optimise processes, and drive innovation.

3.1 Definitions

DT technology is a concept that has garnered significant attention in recent years, and as a result, different definitions have merged from various disciplines and industries. Broadly speaking, a DT refers to a virtual representation or simulation of a physical object, system or process. It is a digital counterpart that mirrors the characteristics, behaviour, and interactions of its real-world counterpart in real-time (Tao, Cheng, et al., 2018).

In the context of supply chain management, a DT can represent an entire supply chain network or specific components within it, such as a product, equipment, facility, or even an entire production line (L. Wang et al., 2022). The DT integrates data from various sources, including sensors, IoT devices, historical records, and external data streams, to provide a comprehensive and dynamic view of the physical entity it represents (Huang et al., 2020).

3.2 Concept

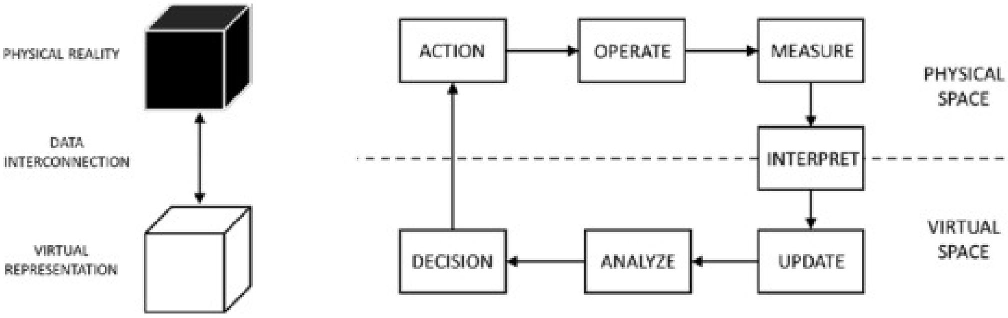
The DT concept is based on connecting the physical and digital realms to enable a symbiotic relationship between them. In this context, a 'symbiotic relationship' refers to a mutually beneficial interaction where the DT model benefits from real-time data and insights from the physical system, while the physical design can be optimised, monitored and improved based on feedback from the digital model. It leverages advanced technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), machine learning and cloud computing to create a dynamic and interactive digital representation of the physical world.

According to Tao, Zhang, et al. (2019), the DT concept involves three primary components: the physical entity, the virtual entity, and the data integration and communication infrastructure.

- **Physical entity:** The physical entity refers to the real-world object, system or process that the DT represents. It can be a single component, a complex system or even an entire supply chain network (Jones et al., 2020). The physical entity inherently produces data. Sensors, IoT devices and other data collection tools are employed to gather this data, ensuring that the virtual model remains updated and aligned with the real-world counterpart.

- **Virtual entity:** The virtual entity is the digital representation or the simulation of the physical entity. It captures the real-world object's characteristics, behaviour and interactions in a virtual environment. The virtual model is typically created using various technologies, such as 3D modelling, simulation software and data analytics. It mirrors the physical entity, providing a dynamic real-time view of its state and performance (Jones et al., 2020).
- **Data integration and communication:** The connection between both entities is a crucial component of the DT concept. It allows real-time synchronisation and data exchange between the physical and virtual realms. Data from sensors, IoT devices, historical records, and external data streams are collected and integrated into the virtual model. This connection enables the DT to continuously update and reflect the current state of the physical entity, providing insights and analysis for monitoring and optimisation purposes (Barricelli et al., 2019).

Figure 1: DT components and high-level processes



(VanDerHorn & Mahadevan, 2021)

3.3 Key technologies

Several key technologies form the foundation of DT implementation in supply chain management. These technologies enable data acquisition, integration, analysis, and visualisation, allowing a holistic supply chain representation.

- **IoT (Internet Of Things):** The IoT plays a critical role in connecting physical assets, devices, and systems to collect real-time data. Sensors embedded in various objects within the supply chain generate continuous data streams related to location, temperature, humidity, vibrations and other relevant parameters. This data is instrumental in creating an accurate, up-to-date representation of the physical entity in the DT (Fuller et al., 2020).
- **Big Data Analytics:** DTs generate a vast amount of data, including structured and unstructured data from diverse sources. Big data analytics techniques, such as data mining, enable organisations to extract valuable insights, identify patterns, detect anomalies, and optimise supply chain operations based on the analysis of this data. These techniques support decision-making processes by providing actionable information and facilitating proactive measures (Singh et al., 2021).
- **Simulation Modelling:** Simulation modelling techniques enable organisations to replicate real-world scenarios and test different strategies or configurations within the DT environment. By simulating various supply chain scenarios, organisations can evaluate the impact of different decisions, optimise resource allocation, and assess alternative approaches' potential risks and benefits. Simulation modelling enhances understanding of complex supply chain dynamics and helps make informed decisions (M. Liu et al., 2021).
- **Cloud Computing:** Cloud computing provides the necessary infrastructure to store, process, and analyse large volumes of data generated by DTs. It enables scalability, accessibility, and collaboration across different stakeholders within the supply chain. Cloud-based platforms and services offer flexible computing resources, facilitating real-time data integration, sharing, and collaboration (Kamble et al., 2022).
- **AI (Artificial Intelligence):** AI techniques, such as machine learning, natural language processing, and cognitive computing, enhance the capabilities of DTs. AI algorithms can analyse complex data patterns, predict future events, automate decision-making processes, and even simulate human-like reasoning within the DT environment. For example, machine learning can predict demand patterns, optimise inventory levels, or identify potential bottlenecks in the supply

chain, enabling intelligent monitoring, diagnostics, and predictive capabilities (Rymarczyk, 2020).

3.4. Auxiliary technologies

While the key technologies lay the foundation for digital twin systems, auxiliary technologies play a pivotal role in enhancing and optimising the overall functionality and user experience. These supplementary technologies bring added layers of security, interactivity and innovation to the digital twin system.

- **Blockchain technology:** While not fundamental, blockchain technology can enhance the security and traceability of data in digital twins, especially in shared or multi-party environments. It ensures data integrity and can be used for secure transactions involving digital twins (Bhandal et al., 2022).
- **AR (Augmented Reality) and VR (Virtual Reality):** AR and VR technologies can be used to visualise and interact with the DT. This allows users to virtually explore the supply chain, simulate scenarios and gain a deeper insight into operations, leading to better planning, training, and decision-making (Kamble et al., 2022).

Table 1: The three parts of DT and their technologies

	Technology
Physical entity	IoT
Virtual entity	Simulation modelling, AI, AR & VR, Cloud computing
Connection	Big Data Analytics, Blockchain technology

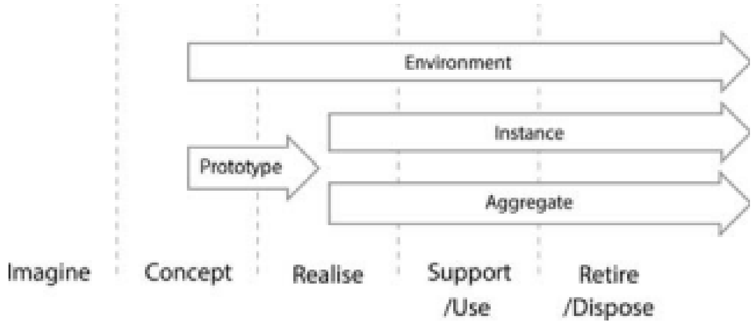
4 Classification

4.1 Creation Time

Jones et al. (2020) state that there are different phases of DT (two sorts of DT) depending on when it is developed over the product's life cycle:

- **DT:** A DT fully incorporates both the physical twin and its digital counterpart, as well as the connection between the two. The DT is accurate to both micro and macro levels.
- **DT prototype (DTP):** A DTP refers to an initial version or demonstration of a DT concept or system. A DTP aims to showcase the key features, capabilities, and potential benefits of the DT technology in a practical setting. This contains all the information required to create the DT.
- **DT instance (DTI):** A DTI refers to a specific instance of a digital twin for a particular physical entity. For example, while there might be a generic digital twin for a type of machine, each individual machine of that type would have its own digital twin instance, reflecting its unique characteristics, history and current state.
- **DT aggregate:** This refers to a collection of DTIs, representing a more complex system or assembly of individual components. For instance, a manufacturing line might have individual DTs for each machine, but an aggregate digital twin would represent the entire line, showing how the individual machines interact and work together.
- **DT environment:** This is the broader context in which multiple DTs operate. It might encompass the infrastructure, tools and platforms that support DTs' creation, maintenance and interaction. This environment ensures that DTs can effectively communicate, share data and function as part of a larger system or network.

Figure 2: The scope and transitions/relationships between the Digital Twin elements and physical product



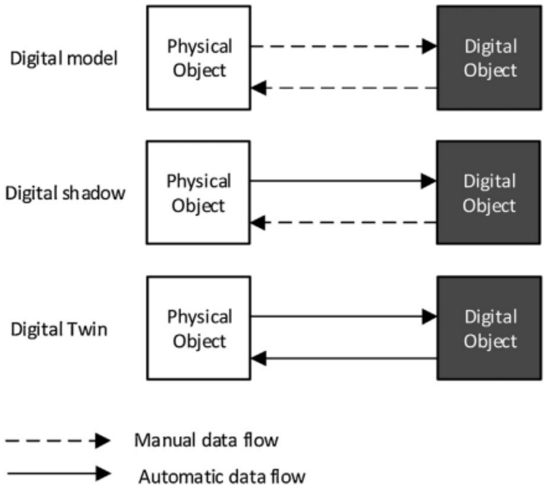
(Jones et al., 2020)

4.2 Integration

Kritzinger et al. (2018) categorise the integration level of DTs into three classes:

- **Digital model:** A Digital model is a virtual depiction of an existing or planned physical object without automated data synchronisation (Segovia & Garcia-Alfaro, 2022). It can vary in detail and includes designs like factory simulations or product blueprints. While they may use data from real-world systems, all data transfers are manual, and changes in one do not directly affect the other.
- **Digital shadow:** A Digital shadow refers to a Digital Model with an automated one-way data flow from a physical object to its digital counterpart. Changes in the physical object's state affect the digital one, but not the other way around.
- **DT:** A DT is a fully integrated two-way data connection between a physical and digital object. The digital object can control the physical one, and changes in either directly affect the other. Other entities, whether physical or digital, can also influence the digital object's state.

Figure 3: Flow on different integration modes



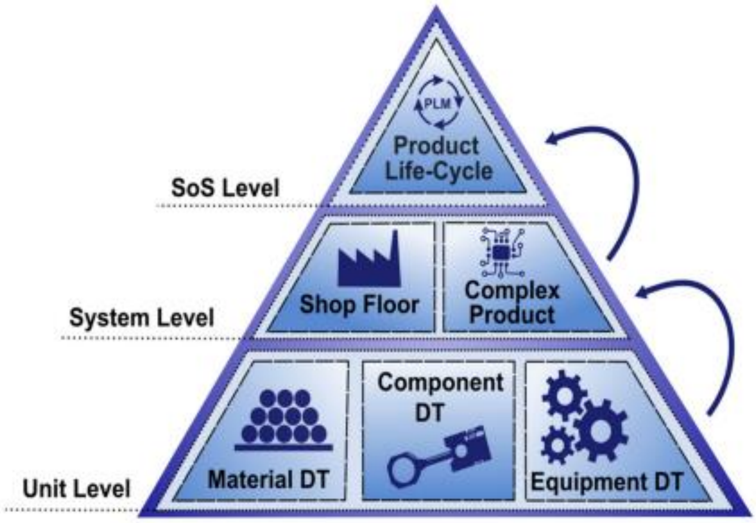
(Errandonea et al., 2020)

4.3 Hierarchy

According to Tao, Qi, et al. (2019), DT can be broken down into three levels from a hierarchical standpoint:

- **Unit level:** The Unit level involves basic manufacturing elements like equipment or sensor-tagged materials. These form the basis of unit-level DTs. DTs are distinguished by their detailed modelling, focusing on shape identity and function, facilitating precise visual simulations.
- **System level:** Multiple unit-level DTs connect via industrial networks, forming a system-level DT that represents structures like factories. While they share physical systems, system-level DTs combine various unit models. Complex products, like aircraft with various components, can be viewed as system-level DTs, where individual DTs (e.g. engine or wing) assess specific aspects and together create a comprehensive product DT.
- **System of Systems level:** Using a smart service platform, system-level DTs interconnect to form an SoS-level DT, emphasising broad enterprise collaboration. For DTs, continuous data flow across its life-cycle is vital. An SoS-level DT integrates all product life-cycle data, promoting innovation, improving future designs and reducing both time and costs.

Figure 4: Hierarchical levels of DT in manufacturing



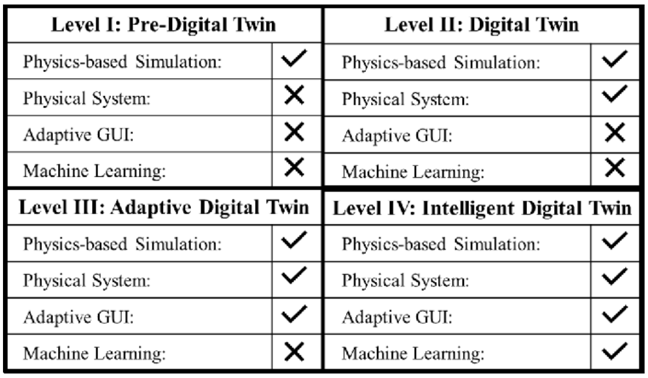
(Singh et al., 2021)

4.4 Sophistication

Madni et al. (2019) define four levels of virtual representation. Each level has a specific purpose and scope:

- **Pre-DT:** A Pre-DT is a virtual prototype developed in early engineering stages to guide design decisions and identify risks. While these models help validate system choices, they are not always the basis for the final system. An example includes a basic car model, useful for tasks like testing autonomous vehicle controls, even though it is of low fidelity.
- **DT:** DTs use real-world data to enhance design and maintenance decisions. They interact bidirectionally with their physical counterparts for optimisation. Through simulations, they identify and rectify system behaviours. An example is a car model in Modelica, reflecting various vehicle components and environmental conditions.
- **Adaptive DT:** The Adaptive DT features a smart user interface that adjusts to both the physical and digital twins, tailoring itself to user preferences. It can learn operator priorities in various contexts using a neural network and supervised machine learning. The models within this twin are constantly updated with real-time data from the physical twin or in batches. It aids in real-time decisions during operations and maintenance.
- **Intelligent DT:** The Intelligent DT builds on the Adaptive DT's features by adding unsupervised machine learning to recognise patterns and objects in operational settings and reinforcement learning for uncertain environments. This level offers greater autonomy and can deeply analyse performance, maintenance and health data from its real-world counterpart.

Figure 5: The four levels of DT sophistication



Level I: Pre-Digital Twin		Level II: Digital Twin	
Physics-based Simulation:	✓	Physics-based Simulation:	✓
Physical System:	✗	Physical System:	✓
Adaptive GUI:	✗	Adaptive GUI:	✗
Machine Learning:	✗	Machine Learning:	✗
Level III: Adaptive Digital Twin		**Level IV: Intelligent Digital Twin**	
Physics-based Simulation:	✓	Physics-based Simulation:	✓
Physical System:	✓	Physical System:	✓
Adaptive GUI:	✓	Adaptive GUI:	✓
Machine Learning:	✗	Machine Learning:	✓

(Danilczyk et al., 2019)

4.5. Purpose

According to Enders & Hoßbach (2019), DTs can be classified based on their applications into three main purposes:

- **Simulation:** This involves replicating the behaviour of a physical system in a virtual space. For instance, before introducing changes in the real world, a company might use a digital twin to simulate various scenarios to anticipate outcomes. Such simulations are particularly valuable during the design and testing phases, allowing for risk mitigation and informed decision-making.
- **Monitoring:** Here, the focus is on tracking the real-time status and performance of a physical entity. By integrating sensors and data collection tools, information from the physical system is continuously fed to the digital twin. This real-time data flow enables stakeholders to closely monitor the system's state and performance. An example would be a manufacturing setup where a digital twin continuously monitors machinery, alerting operators to potential wear or malfunctions.
- **Control:** Going beyond mere observation, this purpose is about actively influencing the physical system based on insights from the digital twin. After analysing the data, the digital twin can send commands back to the physical system to enhance performance, rectify issues, or adapt to new conditions. For instance, in a smart energy grid, a digital twin might adjust energy distribution in real-time in response to consumption patterns or potential disruptions.

5 Applications

This section explores the applications of DT technology in the five stages of supply chain management. From planning to delivering and returning phases, DTs play a transformative role in optimising processes, enhancing collaboration and gaining a competitive edge in today's dynamic business landscape.

5.1 Planning

The planning phase in supply chain management serves as a strategic foundation for organising and optimising supply chain activities. It encompasses processes like forecasting, demand planning and resource allocation, which are crucial in coordinating subsequent supply chain stages. To tackle the complexities of modern supply chains and gain a competitive advantage, businesses are turning to DT technology.

5.1.1 Demand forecasting

A study by Marmolejo-Saucedo (2020) delves into the design and development of a DT for a pharmaceutical company's supply chain. This DT employs simulators, solvers, and data analytic tools, all integrated into a single interface for the company. Such a setup provides insights from past performances, optimises current operations, and predicts future outcomes in the analysed areas. This capability is particularly beneficial for demand forecasting, as it allows businesses to anticipate market needs more accurately and adjust their supply chain operations accordingly.

Another example can be seen in the production of SARS-COVID-19 vaccines (Schmidt et al., 2021). A DT of the mRNA vaccine manufacturing process was proposed to enhance production's speed, scale, robustness, and flexibility. This DT aimed to address bottlenecks in manufacturing capacity, reduce batch failures, and optimise the utilisation of resources. The DT could identify potential improvements by simulating the entire production process, from plasmid DNA to mRNA, such as reducing the number of purification steps, streamlining the supply chain and ensuring timely vaccine delivery.

Imagine a top-tier fashion brand in today's dynamic market. Trends shift quickly, making accurate demand forecasting essential. Facing challenges in predicting seasonal demand, the brand introduces a DT across its supply chain. This DT actively analyses real-time data from diverse sources, including social media and current sales. If, for example, a specific shoe style starts trending online, the DT immediately anticipates a surge in demand. Thanks to these insights, the brand can then adjust its production, ensuring optimal stock levels.

Figure 6: Demand forecasts are achieved through advanced analysis of qualitative and quantitative supply chain insights

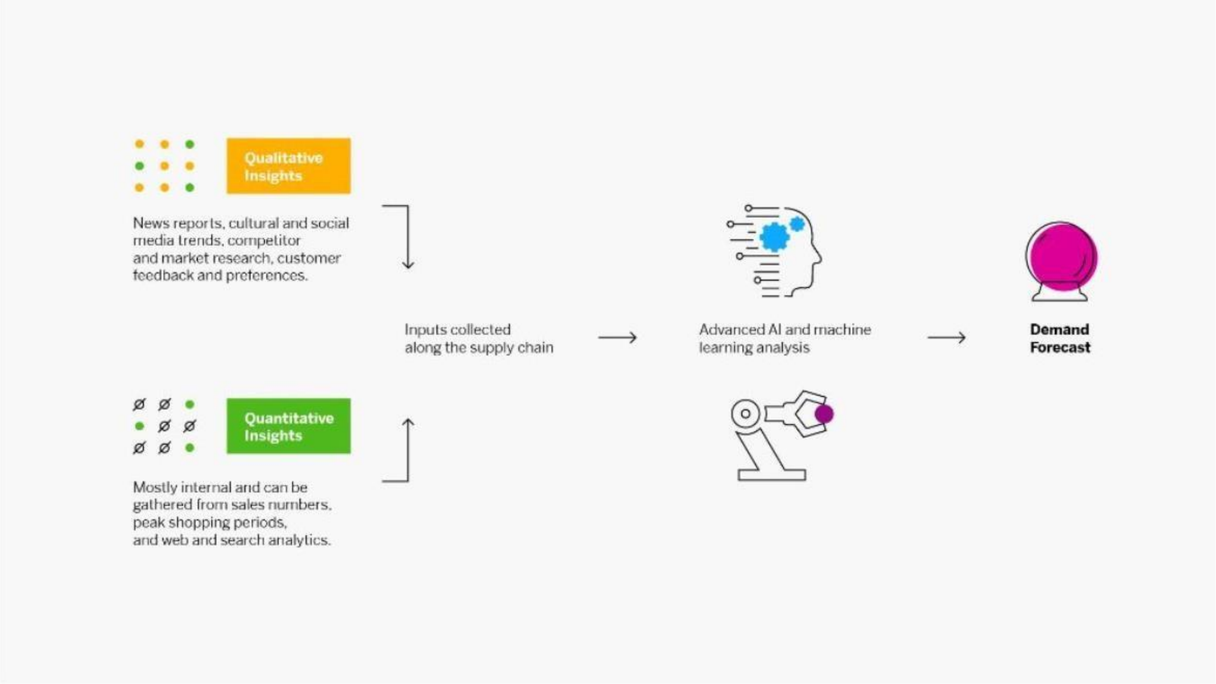


Illustration from sap.com

5.1.2 Inventory management

DTs enable supply chains to monitor inventory levels in real-time. This means that any disruptions, whether they be sudden spikes in demand or supply shortages, can be immediately identified. For instance, a study by Ehsan & Ball (2022) highlighted how supply chains face disruptions in both product and cash flows. By employing a DT framework that integrates machine learning and simulation, decision-makers can identify inventory and cash replenishment policies that minimise the impact of these disruptions. The result is a more efficient supply chain with higher customer service levels.

Consider a global electronics company. They can create virtual representations of their warehouses worldwide by implementing DT technology. When there is a sudden surge in demand for a particular product in Europe, the DT can immediately alert the Asian manufacturing unit to ramp up production. Simultaneously, the North American warehouse can be informed to transfer some of its stock to Europe to meet the immediate demand. All these decisions can be made in real-time, ensuring that the right product is always at the right place at the right time.

5.1.3 Risk management

In today's dynamic business environment, supply chains are vulnerable to many risks, ranging from demand fluctuations to geopolitical tensions. DTs can provide a comprehensive view of the entire supply chain, enabling businesses to anticipate potential disruptions and formulate proactive strategies. For instance, a study by Bhandal et al. (2022) highlighted the emerging value of DTs in bolstering supply chain resilience and risk management. Companies can assess the potential impact or risks by simulating various scenarios and devise appropriate mitigation measures.

Another significant concern for supply chains is the ripple effect of disruptions. A blackout, for example, can halt production, disrupt logistics and impact retail operations. Ivanov (2022) used a digital supply chain twin to simulate the effects of blackouts on supply chains. The study revealed that the simultaneous shutdown of multiple supply chain processes, combined with unpredictable customer behaviour, can have cascading effects. However, businesses can predict these impacts with a DT and develop effective recovery strategies.

Imagine a global pharmaceutical company that relies on ingredients from various parts of the world. Political unrest in one region might disrupt the supply of a critical ingredient. Using a DT, the company can simulate this scenario, assess its potential impact on its supply chain, identify alternative sources, or adjust production schedules accordingly.

5.2 Sourcing

The sourcing phase is a critical aspect of supply chain management that focuses on identifying, evaluating and establishing supplier relationships. Efficient sourcing ensures the timely availability of materials or services while optimising costs and maintaining quality standards. In today's dynamic business landscape, sourcing teams face numerous challenges, including supplier disruptions, changing market dynamics and global uncertainties. Organisations increasingly turn to DT technology to overcome these hurdles and streamline the sourcing process.

5.2.1 Supplier selection

In the complex world of supply chains, selecting the right supplier is crucial for ensuring product quality, timely deliveries and cost-effectiveness. DTs can provide an in-depth, real-time view of potential suppliers, enabling businesses to evaluate their capabilities, track records and potential risks more effectively. A study by C.-N. Wang et al. (2022) delved into integrating Industry 4.0 technologies, including DTs, in the supplier selection process. The research emphasised the significance of criteria like "green image", "green product innovation" and "cloud computing" in evaluating sustainable practices in the supply chain from an Industry 4.0 perspective.

Consider a fashion brand looking to source sustainable fabrics for its new eco-friendly clothing line. The brand can create virtual replicas of potential suppliers' operations by leveraging DT technology. This allows the brand to assess the sustainability practices of each supplier, from raw material sourcing to production processes. If a particular supplier claims to use solar energy for its operations, the DT can validate this in real-time, ensuring that the brand partners with genuinely sustainable suppliers.

5.3 Manufacturing

The manufacturing phase stands at the core of the supply chain, where raw materials and components are transformed into finished products. Efficiency and quality in this phase are crucial for meeting customer demands and maintaining a competitive edge in the market. In the pursuit of continuous improvement and operational excellence, businesses are turning to innovative technologies. DT technology has emerged as a powerful tool in modern manufacturing, offering a virtual mirror of physical production processes and assets.

5.3.1 Predictive maintenance

DTs can provide a comprehensive view of equipment and machinery health. By simulating these assets in real-time, these virtual models can offer insights into potential wear and tear, predicting when maintenance is required before a breakdown occurs. For instance, Z. Liu et al. (2018) discuss the aerospace industry's shift from reactive to proactive and predictive maintenance. In this context, the DT continually adapts to operational changes based on collected online data and can forecast the future of the corresponding physical counterpart. This predictive capability ensures increased operational availability and efficiency, extending the useful life cycle of aerospace platforms.

Furthermore, the growing number of offshore wind farms demands highly reliable turbines to reduce maintenance costs and downtime. Sivalingam et al. (2018) propose a novel methodology to predict the remaining useful life of an offshore wind turbine power converter in a DT framework. This approach ensures maintenance is performed just in time, preventing unexpected breakdowns and ensuring uninterrupted power generation.

Consider a large manufacturing plant with hundreds of machines operating simultaneously. Over time, some of these machines may start to show signs of wear, leading to reduced efficiency or even potential breakdowns. By implementing a DT for each machine, the plant manager can monitor the health of every machine in real-time. If the DT of a particular machine predicts an impending failure based on its current operational data, the management can schedule maintenance for that machine before it breaks down. This reduces repair costs and ensures the production line remains uninterrupted, leading to higher overall productivity.

5.3.2 Quality assurance

DTs can offer insights into potential quality issues, allowing for timely interventions and corrections. (Defraeye et al., 2021) discuss how DTs can help horticultural produce maintain its quality by providing a real-time view of the environmental conditions surrounding the produce. This real-time monitoring ensures that the produce remains fresh throughout its postharvest life, reducing food loss and ensuring optimal quality upon reaching the consumer.

Imagine a large-scale tomato farm exporting globally, experiencing spoilage in transit. To ensure freshness, they integrate a DT system into their transportation. Shipments have sensors monitoring conditions like temperature and humidity. The DT uses this data to simulate container environments, predicting potential spoilage. If any issues are detected, such as temperature spikes, the DT will notify the farm and transport teams to make necessary adjustments, ensuring the tomatoes remain fresh upon arrival.

5.3.3 Sustainability and environmental impact

Park & Li (2021) delve into the potential of blockchain technology, a form of DT, to reshape supply chain management. With its decentralised database of transactions, the blockchain platform brings transparency, reliability, traceability and efficiency to supply chain management. This transparency ensures that sustainable practices are followed throughout the supply chain, from sourcing raw materials to product disposal.

Additionally, Ebinger & Omondi (2020) highlight the importance of digitalisation in sustainable supply chain management. The paper discusses various digital approaches that can be leveraged to enhance transparency in supply chains. This transparency ensures that all stakeholders, from suppliers to consumers, are aware of the sustainability practices being followed, leading to a reduced environmental footprint.

Consider a sustainability-focused clothing brand facing consumer demands for transparent eco-practices. To provide proof, they incorporate DT technology throughout their supply chain, tracking everything from water usage in cotton cultivation to transportation's carbon footprint. Consumers can scan a QR code on garments to trace their eco-journey. This transparency, combined with DT's analytical capabilities, allows the brand to identify and reduce environmental inefficiencies.

5.4 Delivering

The delivering phase marks the culmination of the supply chain journey, where the final products reach the hands of the customers. The critical stage involves intricate logistics, precise coordination and a focus on meeting customer expectations with timely and efficient deliveries. In an era where customer satisfaction is paramount, businesses seek innovative solutions to optimise their delivery processes. Here, DT technology emerges as a game-changer, offering a virtual representation of the physical supply chain operations.

5.4.1 Route optimisation and last-mile delivery

DT technology, as highlighted in a study by Gutierrez-Franco et al. (2021), revolutionises the efficiency of last-mile delivery, especially in complex urban settings. By gathering data from sources like operators, traffic, and customers, the DT anticipates and strategies for potential delivery scenarios. This ensures alignment with organisational goals and accurate performance metrics. In cities like Bogota, the DT simulates delivery conditions, allowing for proactive adjustments based on real-time data from sensors and GPS tools. Essentially, DT provides a holistic view of the delivery process, enabling businesses to optimise operations, predict challenges, and make informed decisions swiftly.

Consider a leading e-commerce delivery service that struggles with last-mile deliveries in a bustling city due to unpredictable traffic, road closures, and parking challenges. To address this, they have integrated a Digital Twin (DT) system into their fleet. Vehicles are equipped with sensors that track location and route, and the DT simulates and optimises routes based on real-time conditions. For instance, if a route is blocked, the DT recommends a quicker alternative and also suggests the most efficient delivery times based on historical and current data.

5.4.3 Customer communication and service

Customers expect real-time updates and seamless communication regarding their orders and services in today's interconnected world. By simulating and monitoring supply chain activities in real-time, DTs can provide customers with accurate and timely information about their orders, from production to delivery. This real-time visibility enhances customer trust and allows businesses to address any potential issues or delays proactively.

Integrating DT technology with the IoT can lead to more agile and responsive customer service. Mostafa et al. (2019) investigate the potential of IoT enhancing supply chain operations, including warehouse management. IoT, in conjunction with DT technology, can increase speed and efficiency, prevent inventory shortages and enhance customer service by providing real-time visibility into everything in the warehouse.

Additionally, as supply chains become more digital, there is a need for effective integration of various processes to ensure seamless customer communication. Korpela et al. (2017) delve into how digital supply chain integration can offer a cost-effective business model for interoperable digital supply chains. By leveraging technologies like blockchain in conjunction with DTs, supply chains can achieve better visibility, thereby improving customer communication and service.

Consider an online electronics retailer integrating a DT system with IoT across its supply chain to enhance customer communication. Each product in their warehouse had an IoT tag, allowing real-time tracking from assembly to delivery. Customers could access live updates on their orders, and any potential delays were communicated proactively. Additionally, the retailer used blockchain for data transparency, ensuring consistent and accurate information. This integration led to increased customer trust, fewer service inquiries and higher customer satisfaction.

5.5 Returning

The returning phase, also known as reverse logistics, is an integral part of the supply chain that deals with managing product returns, repairs and recycling. In today's consumer-centric landscape, an efficient and customer-friendly return process is essential for building trust and loyalty. As products reach the end of their life-cycle or encounter issues, businesses must handle returns seamlessly while minimising costs and environmental impact. This is where DT technology becomes a valuable tool to optimise the returning phase.

5.5.1 Fault diagnosis and repair optimisation

Li & He (2021) delve into the capabilities of DT technology in various applications, including virtual simulation, condition monitoring, power optimisation and fault diagnosis for renewable energy generation systems, transmission equipment and storage systems. The DT technology can be instrumental in identifying faults in real time, predicting potential issues, and optimising repair strategies to minimise downtime and costs. The paper emphasises the importance of DTs in ensuring the operational reliability of electric power equipment throughout its entire life cycle.

Consider a company managing renewable energy systems, facing unexpected equipment failures, resulting in expensive downtimes. To mitigate this, they integrate Digital Twin (DT) technology. Every equipment piece, from wind turbines to transmission lines, has a digital replica. Sensors provide real-time data to these replicas. If a turbine exhibits wear signs, the DT predicts potential faults. The company receives early alerts, enabling them to strategise repairs, pre-order parts, and conduct maintenance during off-peak times. This DT-driven approach minimises downtimes and costs, ensuring a steady energy supply to users.

5.5.2 Asset recovery and refurbishment

Tozanlı et al. (2020) demonstrate the potential effects of DTs in trade-in policymaking through a simulated product-recovery system using blockchain technology. The paper highlights how DTs can play a critical role in facilitating faster decision-making in product trade-ins by nearly eliminating the uncertainty in the conditions of returned end-of-life products. This approach can be particularly useful in asset recovery and refurbishment, where accurate and timely information is crucial.

Furthermore, Frankó et al. (2020) present a novel, working, reliable, low-cost, scalable solution for asset tracking, supporting global asset management for Industry 4.0. The solution uses high-accuracy indoor positioning based on ultra-wideband (UWB) radio technology, combined with Radio- Frequency Identification (RFID) based tracking features. Identifying assets is one of the most challenging parts of this work, so this paper focuses on how different identification approaches can be combined to facilitate an efficient and reliable identification scheme.

Consider an electronics refurbishment company that adopted a DT based on the research of Tozanlı et al. (2020). Each traded-in device's history was recorded using blockchain, allowing for quick and accurate assessments during trade-ins. Additionally, inspired by Frankó et al. (2020)'s findings, the company equipped its inventory with UWB radio and RFID tags for precise asset tracking. This integration streamlined trade-in evaluations and warehouse operations, leading to faster decision-making, reduced costs and improved customer service.

6 Benefits

After delving into the applications of DT technology in each phase of the supply chain, this section will summarise the most relevant and game-changing benefits.

- **Real-time monitoring:** DTs allow for real-time monitoring of supply chain components, ensuring that operations run smoothly and effectively. It provides visibility into the current state of assets, inventory levels, transportation, and other supply chain elements.
- **Predictive Maintenance:** Using DTs, businesses can predict when a piece of equipment or machinery might fail. This helps in proactive maintenance, reducing downtime and ensuring uninterrupted supply chain operations.
- **Risk Mitigation:** By simulating various scenarios, supply chain managers can identify potential risks and create strategies to mitigate them before they become significant issues.
- **Improved Forecasting:** With accurate data and simulations, businesses can make better-informed predictions about demand and supply. This leads to optimised inventory levels, reduced carrying costs, and minimised stockouts or overstock situations.
- **Enhanced Collaboration:** The technology allows for a unified view of the supply chain, enabling different stakeholders, from suppliers to distributors, to work together more efficiently. This can lead to reduced lead times, improved service levels, and faster decision-making.
- **Scenario Planning:** DT technology allows for testing different scenarios in a risk-free virtual environment. This is invaluable for planning strategies in response to events like geopolitical changes, natural disasters, or market disruptions.
- **Optimised Routes:** For logistics and transportation, DTs can be used to optimise routes, considering factors like weather conditions, traffic, and fuel consumption. This leads to faster deliveries and reduced costs.
- **Enhanced Customer Experience:** With a more responsive and efficient supply chain, businesses can better meet customer expectations, increasing satisfaction and loyalty.
- **Sustainability:** DTs can assist in creating more sustainable supply chains by optimising routes, reducing waste, and ensuring efficient use of resources. This not only helps in reducing costs but also in meeting environmental and social responsibilities.
- **Cost Savings:** By identifying inefficiencies, predicting maintenance needs, and optimising operations, DTs can lead to significant cost savings across the supply chain.

7 Challenges

As organisations increasingly integrate DT technology into their operations, they unlock unprecedented capabilities in real-time monitoring, predictive analytics, and operational efficiency. However, like any innovative technology, the journey to full-scale adoption and optimisation is not without its hurdles. This section delves into the multifaceted challenges businesses may encounter as they endeavour to harness the full power of DT technology. From data accuracy concerns to scalability issues, this section will explore the obstacles that stand in the way of seamless implementation and the strategies to navigate them.

7.1 Data accuracy and quality

As Sacks et al. (2020) discussed, integrating Building Information Modelling (BIM), lean project production systems, automated data acquisition, and artificial intelligence can be complex. The challenge lies in ensuring that the data feeding into the DT is accurate and high-quality. For instance, if sensors on a construction site provide flawed data about material usage or environmental conditions, the DT's predictions about project timelines or resource needs might be off the mark.

Similarly, in the food manufacturing sector, traceability is crucial. Shahbazi & Byun (2020) highlight the challenges of ensuring data accuracy in the traceability mechanism. Many food manufacturing systems need help with readability, scalability and data accuracy issues. For example, suppose a DT of a perishable food item receives incorrect data about its storage conditions. In that case, it might inaccurately predict the item's shelf life, leading to potential wastage or health risks.

7.2 Scalability issues

Blockchain technology, particularly in the food industry, has garnered significant attention. However, as highlighted by Vu et al. (2023), there are challenges to overcome. One of the primary issues is scalability. As the number of transactions and data points in the supply chain increases, the blockchain must be able to handle this growth without compromising performance. For example, a blockchain system designed for a local food distributor might face performance issues when scaled up to handle the operations of a multinational food corporation.

7.3 Security concerns

DT technology involves creating virtual replicas of objects or processes that simulate the behaviour of their real counterparts. As Marmolejo-Saucedo (2020) outlined, these virtual models can reveal information from the past, optimise the present, and even predict future performance. However, with the integration of vast amounts of data, there is a heightened risk of data breaches or unauthorised access. For instance, if a pharmaceutical company's DT, which contains sensitive information about drug formulations or patient data, is compromised, it could lead to significant financial and reputational damages.

Blockchain technology, often seen as a solution to enhance transparency and traceability in supply chains, is not without security concerns. As discussed by Nurgazina et al. (2021), while blockchain can provide a secure and immutable record of transactions, it is still vulnerable to certain types of attacks, such as the 51% attack, where a single entity gains control of the majority of the network's computational power. For example, if a food supply chain relies on a blockchain-based DT to ensure the authenticity of organic products, a security breach could lead to false data being entered, misleading consumers and stakeholders.

7.4 Cost implications

In a study by Moshood et al. (2021), the authors delve into the benefits of introducing DTs to enhance logistics supply network visibility. However, they also touch upon the challenges of implementing such technology. One of the primary cost implications is the initial investment required for setting up the DT infrastructure, which includes sensors, data analytics tools, and integration platforms. Additionally, there is the ongoing cost of maintaining and updating this infrastructure to ensure it remains adequate and relevant.

Another study by Amentae & Gebresenbet (2021) highlights the potential of digitalisation in the food supply chain. While the benefits of traceability, sustainability, and reducing food waste are evident, the challenges related to infrastructure and cost must be addressed. For instance, a farm-to-fork traceability system using DTs would require sensors at every food production and distribution stage. The cost of implementing and maintaining such a comprehensive system can be substantial, especially for smaller players in the supply chain.

7.5 Interoperability

The rise of IoT has brought about a new era of connectivity and data exchange. However, as highlighted by De Vass et al. (2021), while IoT offers numerous opportunities for supply chain enhancement, it also presents challenges related to interoperability. Retailers, for instance, might face difficulties integrating IoT devices from various manufacturers, each with its own communication protocols and data formats. This can lead to data silos, where information is trapped within specific systems and cannot be easily shared or analysed.

Furthermore, the adoption of blockchain technology in supply chains, as discussed by Nurgazina et al. (2021), resents its own set of interoperability challenges. While blockchain can enhance transparency and traceability, ensuring it can interact with existing supply chain systems is crucial. For example, a food distributor might use a specific Enterprise Resource Planning (ERP) system. Integrating this ERP with a blockchain-based traceability solution requires careful planning and customisation.

7.6 Ethical issues

The integration of DT technology into supply chains brings a host of ethical considerations. One of the primary concerns is the shared responsibility in supply chains, particularly regarding data security, privacy, reliability, and management. As DTs rely heavily on data, the ethical handling of this data becomes paramount. For instance, in the healthcare sector, the use of DTs in managing COVID-19 vaccine supply chains has raised questions about data security and privacy and the transparency and accountability of supply chain cyber risk from IoT systems (Radanliev et al., 2021).

7.7 Cultural and organisational challenges

Ageron et al. (2020) discuss digital supply chain management's current developments and challenges. One of the key challenges highlighted is the need to explore new strategic, organisational, and human dimensions of the digital supply chain. This implies that while the technology itself is transformative, its successful implementation hinges on the organisation's ability to adapt culturally and organizationally. For instance, employees at various levels might need to be trained or re-skilled to work with the new technology. Additionally, there might be resistance to change, especially from those accustomed to traditional supply chain practices.

Another study by Moshood et al. (2021) emphasises the benefits of introducing DTs to enhance logistics supply network visibility. However, the paper also discusses deployment issues and the challenges in implementing DTs in the logistics industry. These challenges can be both technical and organisational. For instance, a need to restructure specific departments or teams might be needed to better align with the DT framework. Moreover, there could be cultural challenges in terms of accepting and trusting the insights provided by the DT, especially if they contradict traditional wisdom or practices.

8 Future research directions and opportunities

The exploration of DT technology in supply chain management has opened many possibilities, from optimising operations to improving decision-making processes. As we explore the digital age further, it becomes increasingly important to integrate DTs with emerging technologies like Artificial Intelligence (AI), Internet of Things (IoT), and blockchain.

There is an intriguing potential to investigate further the synergy between DT and newer technologies like quantum computing and edge computing. Quantum computing, which uses the principles of quantum mechanics, can supercharge DT simulations, offering real-time optimisations in supply chains. On the other hand, Edge computing processes data closer to its source, enhancing DT's responsiveness. In a manufacturing setup, this means immediate insights and actions from real-time data, minimising downtimes.

While the current scope of research has provided a broad overview of DT's applications in supply chain management, there is room for further research in more specialised areas. For instance, the role of DT in niche sectors like cold chain logistics or the pharmaceutical industry, where precision is essential, could be a promising avenue of study. Moreover, the dynamics of global supply chains, with their vast and intricate networks, differ significantly from more localised chains. Understanding how DT can be tailored to these distinct scenarios can offer insights into its adaptability and versatility.

Beyond the technical and operational aspects, DT's societal and ethical implications warrant attention. As industries increasingly adopt this technology, questions surrounding data privacy, job displacements and DT's role in promoting sustainable and ethical business practices will inevitably arise. Addressing these concerns through comprehensive research will be crucial in ensuring DT's responsible and beneficial deployment.

Furthermore, as DT becomes an integral part of supply chain operations, there will be a growing demand for professionals skilled at managing and optimising these systems. This presents an opportunity to focus on the educational and training needs specific to DT, possibly leading to the development of specialised courses or certifications. On a broader scale, understanding the long-term economic impacts of widespread DT adoption can provide valuable insights into its potential benefits and challenges on a macroeconomic level.

9 Conclusions and insights

The exploration of Digital Twin (DT) technology within supply chain management underscores its transformative capabilities, particularly in the context of an increasingly digitalised industrial landscape. By creating a digital replica of physical systems, DT technology offers a unique perspective that bridges the gap between the digital and physical worlds. This bridge is not just a technological phenomenon but a strategic tool that can lead to enhanced operational efficiencies and customer experiences.

A significant portion of the discussion revolved around the seamless integration of DT technology across various facets of the supply chain, from the initial stages of production to the final delivery. This integration facilitates real-time monitoring and proactive decision-making, anticipating and promptly addressing potential challenges. By offering a real-time simulation of supply chain activities, DTs can provide stakeholders, especially customers, with accurate and up-to-date information, thereby reinforcing trust and transparency.

However, the path to harnessing the full potential of DT is burdened with challenges. Integrating digital replicas with their physical counterparts can be complex, and there are valid concerns surrounding data security, especially given the vast amounts of data DTs handle. Additionally, the infrastructural changes required for DT integration can be significant, demanding both time and resources. The paper also delved into the promising synergy between DT and other cutting-edge technologies, such as the Internet of Things (IoT) and blockchain. While these combinations can lead to groundbreaking solutions, they also introduce new complexities that need careful consideration and management.

In wrapping up, the paper posits that DT technology, with all its potential and challenges, stands at the forefront of a new era in supply chain management. Its integration promises not only operational enhancements but also a paradigm shift in how supply chains are perceived and managed. As industries continue to evolve, the insights from this paper underscore the importance of understanding, adapting, and innovating with technologies like DT, ensuring a future-ready and resilient supply chain landscape.

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