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TDK Research Article

**Digital Twins In Supply Chains: A Systematic
Literature Review On Current Applications And Enablers
For A Successful Adoption**

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**2024
Győr**

Digital Twins in Supply Chains: A systematic literature review on current applications and enablers for a successful adoption

Abstract

Digital Twins (DT) is a longstanding, yet emerging trend the industrial sectors are currently embracing. Amidst the diversified use across different industries ranging from aerospace to manufacturing to healthcare, DTs are extensively integrated throughout their respective value chains as well. This study aims to consolidate current DT applications used within Supply Chains (SCs) and identify key enablers in SCs that will facilitate a successful DT adoption. The highest level of DT adoption can be seen in the field of manufacturing and as a result, the readiness of manufacturing environments has been improved with a high maturity level during the last decade to facilitate this new technological implementation. With this success in manufacturing, the applications of DTs are now expanding to the SCs, but studies on the readiness of SCs for effective DT implementation remain unclear with sparse literature addressing this aspect. While the existing literature provides individual applications of DTs within fields in SCs, there is a need to identify how DTs can be used to improve the capabilities of SC. Based on keywords developed through the PEO model, open-access articles from the Scopus database were selected through a PRISMA screening and they were analyzed using a systematic literature review. A steep inclination in the number of articles related to DT was observed for the past 10 years, most of them in manufacturing. Yet, areas of SCs including procurement, logistics, and warehousing have been using DTs for a while, which have not been exposed to academic eyes. Advanced technological infrastructure, standardized processes, continuous improvement, knowledge workers, technologies like IoT, IIoT, AR/VR, and managerial support were identified as key enablers in the SCs for their successful adoption of DTs.

Keywords: Digital Twins, Supply Chain Management, Digitalization, Industry 4.0

1. Introduction

A Supply Chain (SC) is a complex, global network of different, independent, and linked organizations that work together to create value for customers. The planning, controlling, and monitoring of the SC is known as Supply Chain Management (SCM) (Christopher, 2018). A SC contains multiple elements belonging to multiple stakeholders and includes every step that is involved in getting a finished product or service to the customer. To optimize the functional performance of the SCs, organizations are now heavily dependent on digital transformation. IBM defines digital transformation as “A strategic initiative that incorporates digital technology across all areas of an organization”(What Is Digital Transformation? | IBM, 2024.) Under this paradigm, organizations are exploring emerging technologies in the context of SCM to withstand the global competitive environment (Jenet et al., 2018.). Following this need, supply chains are now adopting the fourth wave of the industrial revolution, known as Industry 4.0. Industry 4.0 is introduced as a combination of a set of emerging technologies like cyber-physical systems (CPS), Internet of things (IoT), radio-frequency identification (RFID), big data, artificial intelligence, smart sensors, cloud computing, 3D printing, additive manufacturing, etc. (Mittal et al., 2019).

In the paradigm of Industry 4.0, Digital Twins (DTs) play a crucial role (Luo & Ball, 2023). A DT is a digital representation of merely anything. The use of DTs for industries other

than space has been a trending topic since the last decade, in which manufacturing has been prominent. Manufacturing firms are now at a high maturity rate in the DT adoption, and as a result, the SCs are also being subjected to the influence of DTs (Luo & Ball, 2023). Using DTs in SC will allow to creation of a virtual simulation model of the processes of the entire supply chain where the organizations can perform continuous cycles of improvements and adjustments of the entire SC in near-real time (Vasant et al., 2019), giving a view of end-to-end of the SC.

Despite the industrial discussions on potential advantages and future opportunities of integrating DTs into SCs, the current academia lacks scholarly work related to the present use of DT in the field of SCM (Li & Liu, 2019). Several studies have been conducted on separate elements of the SCM, but no work was found in the consolidated field of SCM. At the same time, expanding the use of DT from manufacturing to SCs has been a challenge due to the complexity of the SC elements. Therefore, before initiating plans to adopt DTs to SCs, it is highly necessary to identify the key enablers and success factors leading to the successful adoption of DTs so the organizations can identify the potential benefits and dominant areas the attention should be given. Therefore, this research is conducted with the goal of exploring the current applications of DTs in SCM and identifying the key enablers and success factors in the implementation and successful adoption of Digital Twin concepts in SCs.

To address this research goal in a more actionable way, below research objectives were designed.

Research Objectives:

1. To identify how Digital Twins enhances the capabilities of Supply Chain Management.
2. To identify key enablers and success factors for successful Digital Twin adoption in Supply Chains.

This study will answer the following key research questions to satisfy the above research objectives.

Research Questions:

- **RQ1-** What are the current applications of DT in SCM that facilitate delivering value-added products to the market?
- **RQ2-** What are the key Enablers and factors affecting successful digital twin adoption in a supply chain context?

To answer these two research questions, this study critically reviews the literature using the Systematic Literature Review methodology, and the current academic environment related to this field was analyzed using a mapping study. Through a narrative summary, answers to the research questions were analyzed and summarized.

The Supply Chain Operations Reference (SCOR) model identifies six primary processes in a SC: Plan, Source, Make, Deliver, Return, and Enable (Supply-Chain Operations Reference Model, 2017). These processes are cross-functional between the different business stakeholders and coordinate the flow of materials, information, and every other resource within the SC (Luo & Ball, 2023). Table 1 depicts the elements of an SC consolidated under the elements of the SCOR model.

Table 1 Elements of Supply Chain based on SCOR model.

Plan	• Demand forecasting. • Production planning. • Inventory planning. • Coordination.
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Source	• Procurement of raw materials/services • Supplier management
Make	• Manufacturing Operations • Packaging • Quality checks
Delivery	• Logistics • Order management. • Warehousing • Transportation
Return	• Return inventory management. • Customer queries • Disposition of returned items
Enable	• Portfolio management • Training and education • Research and development. • Information system

Source: Adopted from (Zhang et al., 2018.) and (Supply-Chain Operations Reference Model, 2017).

Apart from the elements of the SC, the structural hierarchy of the SC inherits a complex nature. (Luo & Ball, 2023) introduce four basic levels of SC hierarchy and state that they may evolve. According to him, an SC contains 1) an SC block, 2) an SC module, 3) an SC member, and 4) an SC system (Figure 1). Each of these levels contains multiple stakeholder involvements and is highly interoperable. The SC block represents specific business functions, the SC module includes a collection of business functions, the SC members refer to the firm-level operators of modules, and the SC system represents the inter-connected network of SC members. The above-described elements of an SC can be identified across these different levels of the SC, and they are integrated.

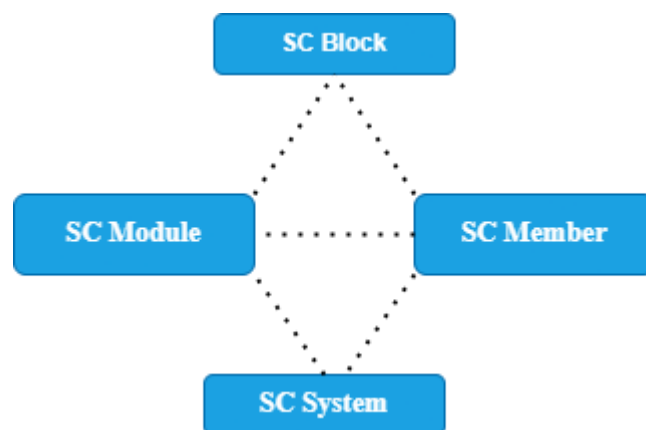


Figure 1 **Structural Hierarchy of a General Supply Chain**

Source: Adopted from (Luo & Ball, 2023)

The National Aeronautics and Space Administration (NASA) initially created the concept of DT to model real-world spacecraft situations, investigate potential solutions, and forecast outcomes that were crucial for planning, developing, operating, and managing spacecraft operations (Le & Fan, 2024). There are multiple definitions for a Digital Twin. NASA introduced it as “An integrated multi-physics, multi-scale, probabilistic simulation of a vehicle

or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its flying twin” (Cimino et al., 2019). Some researchers later introduced new definitions of DT: “The digital twin is a set of virtual information constructs that fully describes a potential or actual physical manufactured product from the micro atomic level to the macro geometrical level” (Grieves & Vickers, 2016). The DT terminology has different variants in the industrial context: Digital Twins, Digital Models, and Digital Shadows. These variants differ based on the level of data integration between the physical entity and its virtual representation (see Figure 2) (Juarez et al., 2021). This study solely focuses on Digital Twins (DTs) where the information flow is bi-directional.

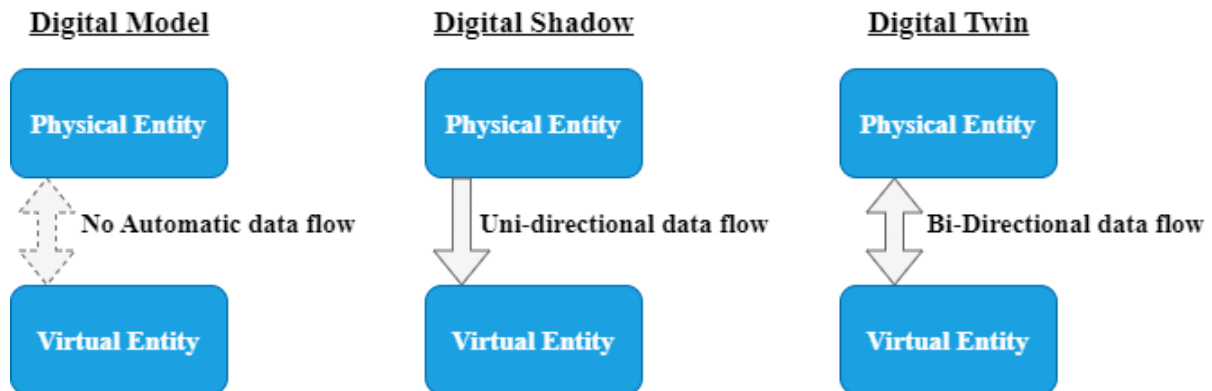


Figure 2 **Differences between the variants of Digital Twins**

Source: Adopted from (Juarez et al., 2021)

Despite these different definitions, a DT typically involves 1) A physical entity; 2) A virtual entity-usually the virtual representation of the physical entity; and 3) A connecting layer that communicates between the physical entity and virtual entity which has a bi-directional information flow (Srai et al., 2019) (See Figure 3). The physical entity usually refers to physical objects like machinery, vehicles, and any other physical objects related to the supply chain/manufacturing process. This contains all the real information including data, decisions, and actions. The communication layer has the tools for data transmission, and data conversion (to machine-readable forms and vice versa), and the virtual entity is the virtual replica of the physical entity. Virtual entity includes ways to interpret and process the data received, computational and simulation-based ways to mimic the physical environment, and tools for predictions and analysis (Le & Fan, 2024).

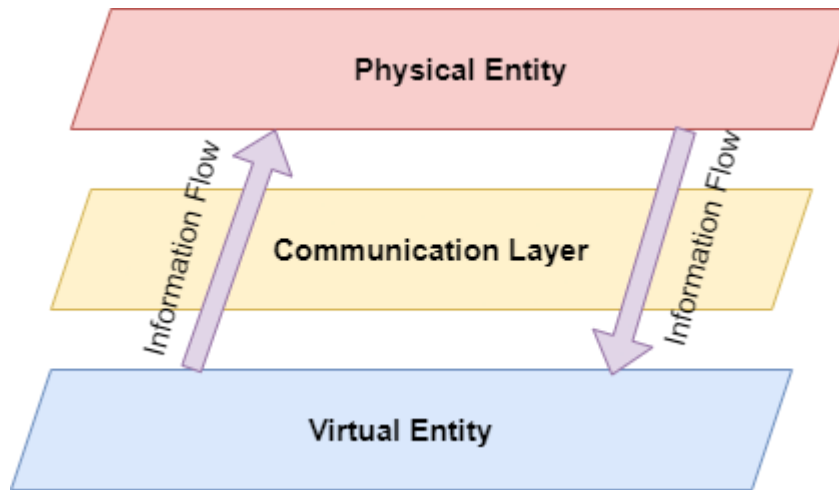


Figure 3 **Structural Architecture of a General Digital Twin**
Source-(Srai et al., 2019)

Though Industry 4.0 has been a paramount leap in the field of manufacturing, according to McKinsey studies, SCs have the lowest digitization level of 43% when compared with five other business areas (Gezgin et al., 2017a). However, using the DTs in SC and SCM is now emerging in wide supply chain areas (Marmolejo-Saucedo, 2018.; Van Der Valk et al., 2022). DTs are already in use in almost every sector of the economy. The most prominent application area found in the literature is manufacturing (Van Der Valk et al., 2022), but several DT applications have been used in SC processes like warehousing with little or no reference in the literature (*2018 IEEE 16th International Conference on Industrial Informatics (INDIN).*, 2018). A large proportion of the DT approaches in the literature are domain-neutral hence there is a burning need to identify, consolidate, and evaluate the current DT trends in the SC and SCM context. At the same time, McKinsey identifies the failure to adopt Digital Twins efficiently in SCs as the technology gaps and management choices (Gezgin et al., 2017).

2. Methodology

This study aims to address the current literature gap between the fields of Digital Twin applications (DTs) and Supply Chain Management (SCM) by consolidating the DT trends in SCM and identifying the critical enablers for successful adoption of DTs in Supply Chains (SCs). For this purpose, the existing literature was searched and critically evaluated using the systematic literature review (SLR) methodology followed by a mapping study and a narrative summary. SLR allows researchers to gain a thorough understanding of the current state of knowledge, identify gaps in the literature, and determine future research directions (Hammersley, 2019) and provides a rigorous framework for the researchers to synthesize and evaluate the existing literature (Gentles et al., 2016).

For conducting a methodological and transparent SLR, this study used the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) framework. This widely accepted framework (Moher et al., 2010) presents a minimum set of items needed for reporting in SLR and meta-analysis which provides an evidence-based guide for the writing (*PRISMA*, n.d.). Following this framework, SCOPUS was selected as the primary source of the database for the literature search, and several keywords were identified through an initial overview search.

These keywords were then organized based on the Population, Exposure, and Outcome (PEO) framework. Though this model is frequently used in the field of health sciences (Moola et al., 2015), it provided a qualitative framework to organize and conduct the keyword search for this study. Population is the type of participants- in this case Supply Chain Management and

Manufacturing. Though our primary focus is on the field of Supply Chain Management, Manufacturing was considered an area of study due to the interoperability between the elements in these two fields (Woldesilassie et al., 2024). Exposure refers to conditions the Population is exposed to. Digital Twin, Digital Twin Adoption, Digital Twin implementation, and Digital Twin applications were categorized under Exposure and Readiness models, and Readiness and Readiness assessment were categorized under Outcome, which is the result of Exposure to Population (Moola et al., 2015). Table 2 shows the categorization of keywords under the PEO model.

Table 2 Categorization of keywords under the PEO model

Population	Exposure	Outcome
Supply Chain Management	DT Adoption	Readiness models
Manufacturing	Digital Twin	Readiness
	DT implementation	Readiness assessment
	DT applications	

Source- Author's creation.

Combinations of the keywords were applied to the Scopus database using Boolean operators to generate more complex and effective search results. Keyword combinations were designed by the developed PEO model. Initial keyword search gave 989 articles and after applying the below exclusion and inclusion criteria, the search results were narrowed down to 292 articles.

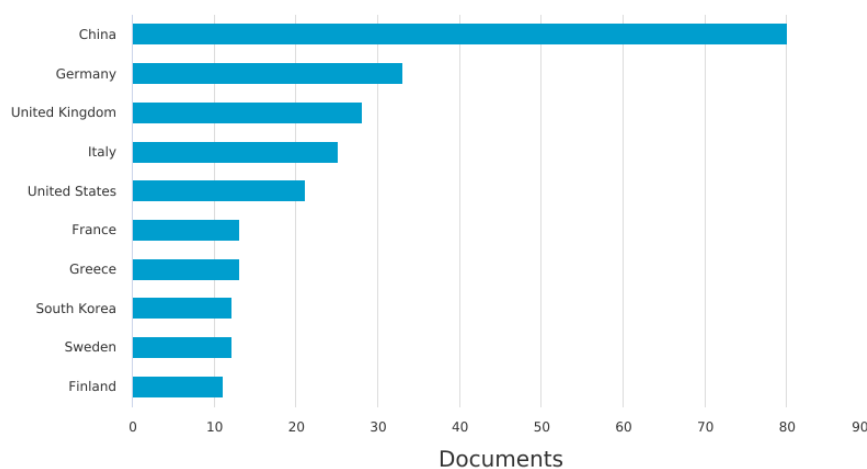
1. Documents should be openly accessible.
2. Documents should be between 2004 and 2024, between the last ten years.
3. Subject areas should be limited to engineering, computer science, business management and accounting, decision science social sciences, and economics.
4. Documents should be either articles or conference papers.
5. Articles/ Conference papers should be in English language.

As stated in Figure 4. when observing the published countries of these 292 articles, a leading percentage of 27% were from China, whereas Germany, Italy, and the United Kingdom from Europe had a collective percentage of 28%.

Documents by country or territory

Scopus

Compare the document counts for up to 15 countries/territories.



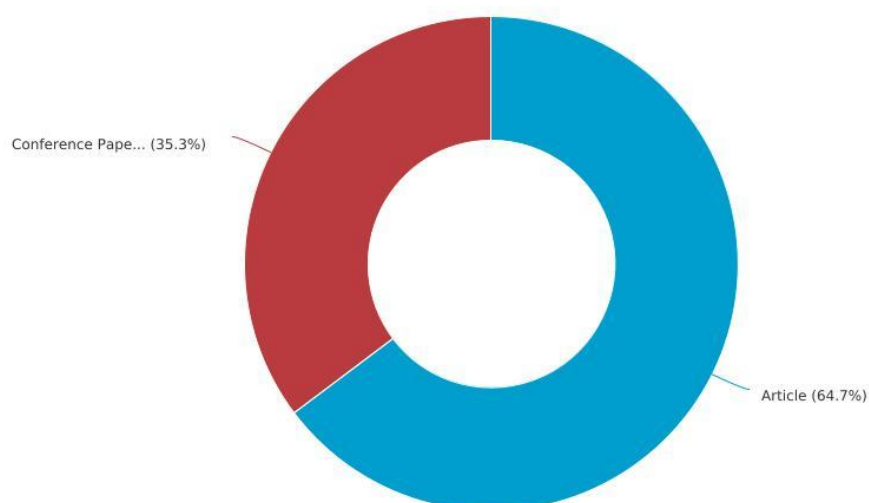
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Figure 4 **Documents by Country/ Territory** Source: Scopus

65% of these documents were articles and 35% were conference papers. 33% were from the field of Engineering, and 27% were from Computer Science (Fig 5 and 6).

Documents by type

Scopus



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Figure 5 **Classification of documents by type**. Source: Scopus

Documents by subject area

Scopus

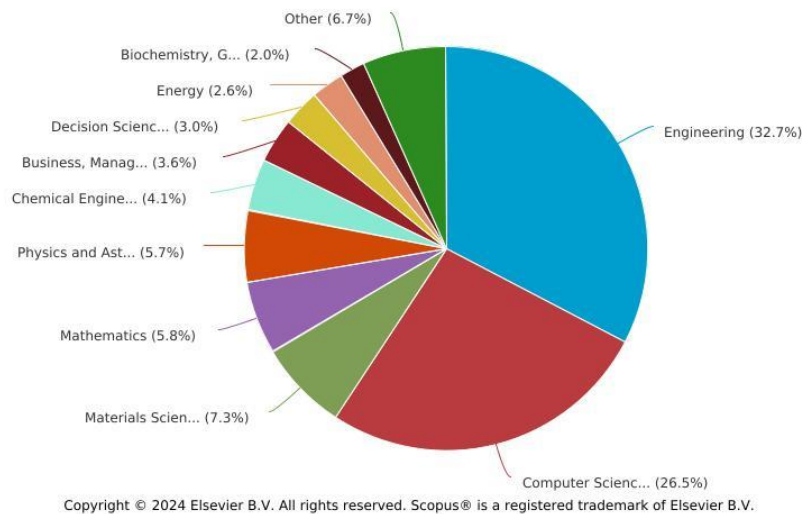


Figure 6 Classification of documents by Subject. Source: Scopus

When looking at the publication pattern of these articles, there is a clear indication of improved research in the area of DTs in SCs. When compared with 2017 where only 1 article was published, there is a nearly 30% improvement in publications by 2023 (Figure 7). This suggests the growing interest in this field while pointing out that SCs are in the process of being digitalized than before.

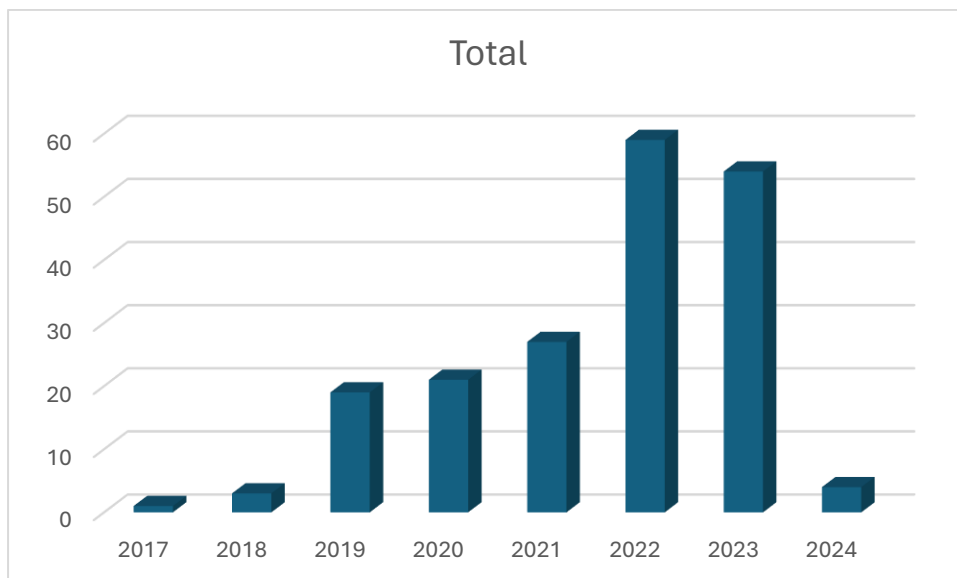


Figure 7 Yearly publication pattern of DT and SC-related literature. Source: Author's creation

These 292 articles were then screened for relevance based on the title which filtered 206 articles for the abstract screening. During the abstract screening phase, 23 duplicate articles were found and removed. After this, a total of 122 were selected for the full-text critical review. Of the 122 articles, 24 articles were excluded because they addressed the software architecture of Digital Twins and associated systems. 14 articles were identified as extended work of the

same authors, and 42 articles were excluded as they were not domain-specific resulting in including a total of 42 articles for the literature review. Figure 8 displays the above-described PRISMA steps.

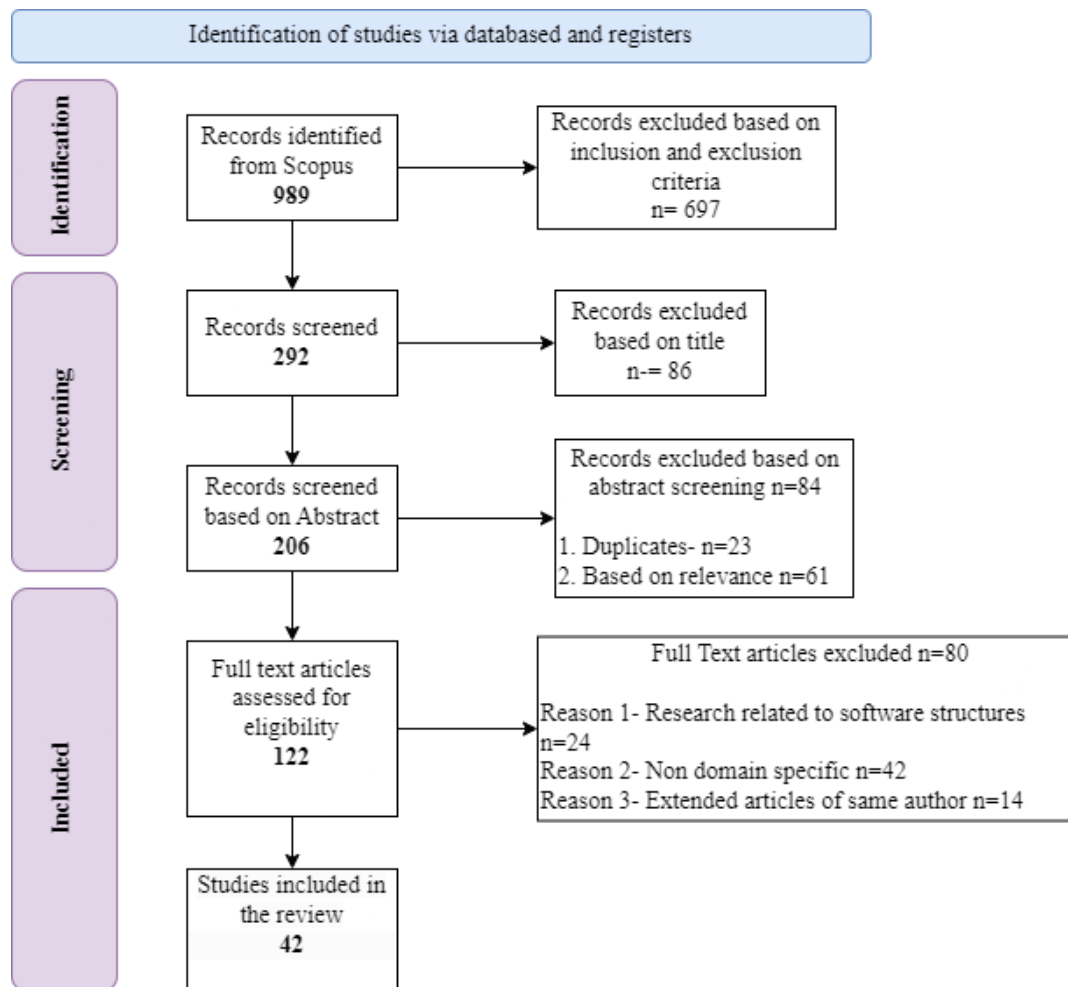


Figure 8 SLR selection criteria based on PRISMA method.

Source: Author's creation

Additionally, a word cloud analysis done on the keywords extracted from the abstracts (See Figure 9) suggests that the majority of the digital twin studies are related to manufacturing, and it is highly associated with other terms like simulation and industry 4.0. This word cloud was developed using a data model created in Microsoft Power BI.

have been a subtle solution for manufacturers. Meanwhile, these unique features of DTs are currently being implemented to improve the aspects of Supply Chains (SCs) as well. These can facilitate the interaction of components, products, and services within SCs (Luo & Ball, 2023). However, with the complexity of the DT structures and SC hierarchies, it has been difficult to integrate the DTs into SCs as it is (Tae Park et al., 2020). When conducting this review, to overcome this complexity we used the framework of the evolution of Supply Chain Management (SCM) (Hesse & Rodrigue, 2004) to classify the current DT applications used in SCM (Figure 11). The model was modified by consolidating materials management and physical distribution elements to suit the context of this study.

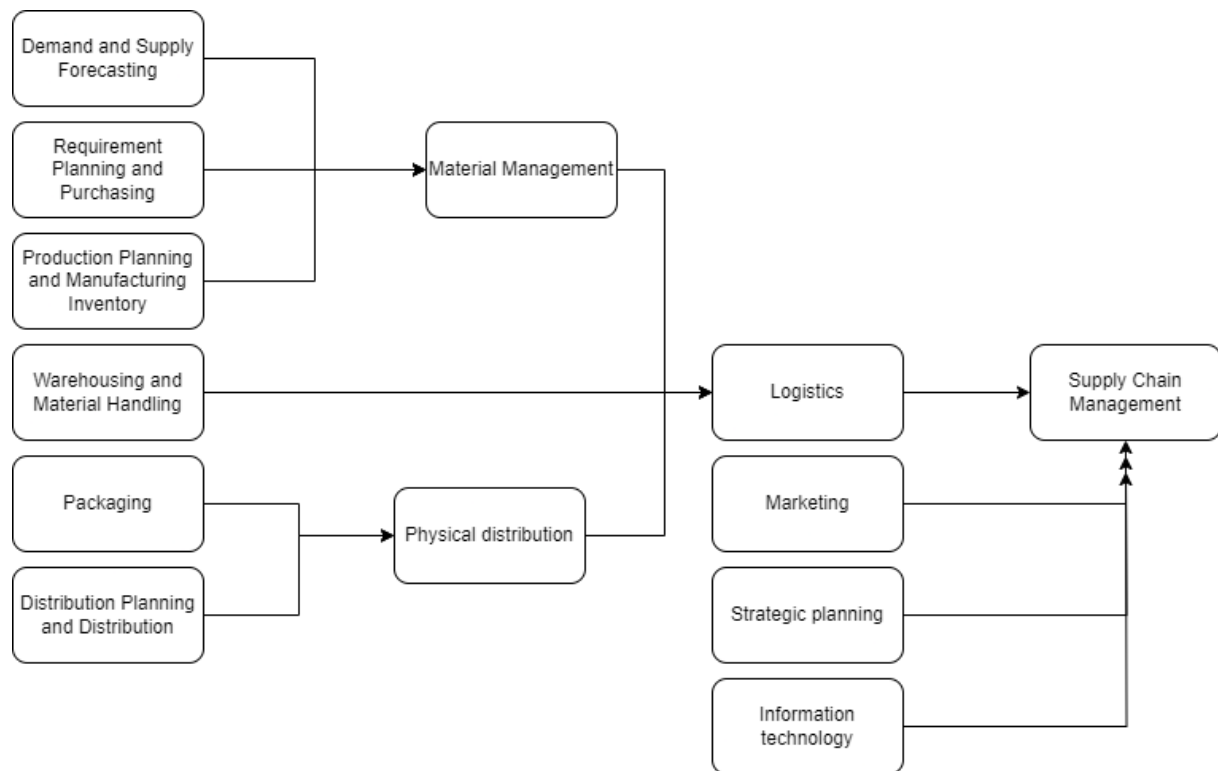


Figure 11 Elements of Supply Chain Management (SCM)
Source: Author's creation based on (Hesse & Rodrigue, 2004).

Prominent objectives of using DTs in SCs are Visibility and Monitoring, Optimization, Prediction, and Simulation (Van Der Valk et al., 2022). The majority of DTs are involved in optimization and simulation. Application of DTs in SCs often happens in isolation (Luo & Ball, 2023). Order picking and material handling have been two applications that highly benefited from DTs. In a review done on warehouse DT applications, (Belanger et al., 2023) present studies where DTs have been used in warehouses. Using a heuristic optimization algorithm running in a DT of a warehouse, material handling has been optimized. (Kauke et al., 2021) presents a conceptual framework for using DTs in supporting the operational control in order picking systems. This framework provides both the architectural and functional structures while describing the benefits of DTs in the process. In the material handling process, the workers play a crucial role, and safe human-machine interactions are widely adhered to. Using a DT framework (Sharotry et al., 2022) analyses the fatigue in workers in material handling motions. By identifying changes in the joints of the workers, it detects biomechanical fatigue leading to improved worker safety in warehouses.

Automated storage and retrieval systems are popular in the modern material handling context. Several simulation approaches are taken to address the complexity of these systems, but simulation models often do not depend on real-time data making the scope of digitization difficult (*What Is a Digital Twin?* | IBM, n.d.). (Ferrari et al., 2023) presents DT based approach to create a discrete event simulation model with both the physical system and the information technology architecture where the developed simulation models can be validated using the DT. Automated robots are now highly used in modern warehouses for storage and retrieval. (Kalinov et al., 2021) presents a novel human-robot interface operating on a DT of a warehouse which can be used to guide and navigate these automated robots through a secluded workstation. This solution can be highly advantageous during pandemics like Covid-19 where human interaction is strictly limited. This allows regular warehouse workers without any experience to control the automated robots and drones in stocktaking, inspection, and remote inventory monitoring. To enhance the advantages of these autonomous retrieval and storage systems (AS/RS) (Ferrari et al., 2022) propose a DT-based AS/RS system that collects data from the industrial processes, mimics them in the DT of the warehouse, and after elaboration from a simulation-based digital model feeds the information back to the AS/RS system. This has increased the scalability and the reliability of the AS/RS system.

In instances where the storage capacities are low, minimizing the movement of materials is crucial. By developing a location management system built upon the DT of the warehouse, (Félix-Cigalat & Domingo, 2023) introduce a simulation-based approach to optimize the internal transport within the storage locations. This novel DT application evaluates the alternatives during stock positioning and distribution while allowing agile position changes inside these low-capacity warehouses. Automated guided vehicles (AGVs) are currently being used in warehouses to improve transport efficiency. Crucial factors limiting the efficiency of these AGVs are the path conflicts and speed uncertainty of them. (Wu et al., 2023) proposes an AGV scheduling system based on a DT of the warehouse where the DT will collect real-time data of the warehouse, determine the optimal speed and number of AGVs needed, and improve the efficiency of the logistic system inside the warehouse. The traditional AGV scheduling systems need a lot of extra time in the charging process, leading to poor performance in the warehouse. (Han et al., 2022) proposes a DT-based dynamic AGV scheduling system addressing this charging problem by reducing energy consumption by 1.32%. Cold Chain Logistics is an area that frequently faces high product loss, temperature deviations, and low levels of informatization. Introducing a five-dimensional digital twin model, (Hu et al., 2023) proposes an approach to provide a real-time visualization of the cold chain warehouses and monitor all the elements of the warehouse. Through this DT, an optimized operating model is suggested for the warehouse, and it is involved in decision-making. By implementing this, the wastage of fresh food has been reduced by 25-30%.

Supply Chain Planning (SCP) is an essential element in global manufacturing. DTs have been prominently used in SCP for demand forecasting, aggregate planning, and inventory planning. Using DTs, the data needed for demand forecasting can be collected in real-time, processed, and visualized. Once the forecast information is received, DT extracts the real-time information about the manufacturing inventory, plans it based on the forecasted information, and indicates how to distribute supplies across the factory through aggregate planning. Once aggregate planning is done, the DT will conduct the inventory planning by reviewing and monitoring the inventory levels and re-ordering cycles (Wang et al., 2020). Apart from demand and supply planning, DTs are used for other SC process planning as well. A mathematical model built on a DT plans real-time optimization, routing, and scheduling of in-plant supply processes (Bányai et al., 2019) based on the demand. Not limited to the manufacturing context, DTs facilitate predictions and planning in other fields as well. DTs are used in Food Supply Chains to improve overall operation efficiency (OOE), improve makespan time, improve data

redundancy, and improve capacity utilization (Maheshwari et al., 2023). A DT used in horticulture helped to diagnose and predict potential problems in the supply chains that will reduce the quality of food and improve wastage. This DT predictively plans the optimal number of crops to be cultivated to minimize wastage based on the state of the supply chain environment (Defraeye et al., 2021).

Inbound and outbound logistics is another field where DTs are being used for different purposes. Last-mile logistics (LMLs) is a field that involves high organization costs, and time inefficiencies leading to customer dissatisfaction and organizational losses, and responsible for 25% of total GHG emissions. (Nava & Greco, 2023) introduces a DT-based solution to optimize the last-mile routing which not only optimizes the last-mile routes but also assesses the environmental and monetary values of these transport modes making the LMLs more greener. The traceability and transparency of logistics systems are often affected by the quality of the supply-chain data exchange. DTs are used in logistics for data collection, and data analysis to real-time optimization of the logistic processes based on the collected data. A study by (Brochado et al., 2024) proposes a DT architecture with a tool to integrate data collected from multiple national logistic data sources where KPIs are generated based on the data collected. These KPIs are then used to evaluate the performance of suppliers and contractors, optimize transport routes to improve the efficiency of the distribution processes, and allow real-time scheduling and monitoring of the transport vehicles. Intelligent logistic distribution systems are a growing trend in the era of AI. A simulation assignment done by (Miao & Lan, 2021) introduces a visual sensor imaging technology based on Digital Twins which captures the documents and receipts related to order receipt, distribution, and return management. This captures the images of target documents and effectively tracks and monitors information along the logistic distribution process. This eradicates inefficiencies of the current distribution processing systems including slow efficiencies, huge costs, complex data, and low degree of informatization. E-commerce has allowed many companies to excel in their businesses. However, the distribution network used in this category of businesses; multi-echelon supply chain networks are often challenged in network planning. A study by (Yan et al., 2022) introduced a DT-based 4PL planning and scheduling model which enhances the transportation flow and resource utilization while shortening the waiting times within this multi-echelon supply network. Table 3 summarizes the findings on key DT applications used in the field of SCM.

Table 3 Summary of literature contributions on DT and SCM

SCM area	Current DT trends	Literature contributions
Demand and Supply Forecasting Requirement planning and forecasting. Production planning, manufacturing inventory	• A DT model for aggregate planning, demand planning, and inventory planning. • A DT-based mathematical model to optimize in-plant SC process planning. • DT-based model to plan and forecast demand in food supply chains. • A DT-based model to predict the potential problems in food supply chains and minimize wastage.	(Wang et al., 2020), (Bányai et al., 2019), (Maheshwari et al., 2023), (Maheshwari et al., 2024), (Van Der Valk et al., 2022), (Luo & Ball, 2023)
Warehousing and material handling	• Optimizing material handling using DT algorithms.	(Belanger et al., 2023), (Sharotry et al., 2022),

	• DT-based Conceptual framework for improving order-picking efficiency. • A DT model to observe worker's fatigue in material handling. • DT-based interface to handle material-handling robots. • A DT-based system to validate the accuracy of warehouse simulation models. • A DT model to improve the reliability of AGVs. • A DT-based location management system to optimize storage of low-capacity warehouses. • A DT-based AGV scheduling method. • A DT-based model to optimize the routing of AGVs inside a warehouse. • A DT-based approach to reduce the wastage in food supply chains	(Ferrari et al., 2023), (Kalinov et al., 2021), (Kalinov et al., 2021), (Félix-Cigalat & Domingo, 2023), (Wu et al., 2023), (Wu et al., 2023), (Han et al., 2022), (Hu et al., 2023)
Distribution Planning, Distribution and Marketing.	• Optimize last-mile routing and carbon emission using a DT-based solution, • A DT architecture to manage the traceability, and optimize transport routes of items within a SC. • A DT-based solution to capture documents used in SC processes and process them share information across the SC. • A DT-based model to improve the resource utilization in multi-echelon supply chain network.	(Nava & Greco, 2023), (Brochado et al., 2024), (Miao & Lan, 2021), (Yan et al., 2022)

Source: Author's creation

Despite the growing application of DT in SCM, it is necessary to identify the key enabling factors for a successful DT adoption in Supply Chains. In the studies of (Perno et al., 2022) he identifies different categories of DT enablers that are impacting process industries. AI, IoT, and VR/AR have been identified as industry 4.0-related DT enablers. AI and machine learning (ML) are some major driving factors that improve the functionalities of DTs, pushing them to function at full capacities (Qi & Tao, 2018; Rasheed et al., 2020). Two of the core functionalities of DTs; Predictions and Simulations generate large numbers of data that use the algorithms based on ML for data interpretation. When it comes to processing documents and images related to supply chain functions, AI tools like Microsoft AI Builder are highly used in industries as they require minimum developer knowledge to use them. The Internet of Things (IoT)/ Industrial Internet of Things (IIoT) is another key enabler in supply chain DT applications (Ezhilarasu et al., 2019). A core requirement of a DT is communication between physical entities. IoT/IIoT facilitates this by collecting and receiving information between the physical entities (Cai et al., 2020). Operators in a supply chain environment can use virtual reality (VR) and augmented

reality (AR) for a range of purposes, such as conducting simulations in a virtual environment, virtual commissioning, remote assistance, and gaining a deeper understanding of the production process (Alcácer & Cruz-Machado, 2019; Minerva et al., 2020). Proper hardware and communication technologies and development technologies like blockchain, open-source software, and centralized databases are also identified as DT enablers (Errandonea et al., 2020; Rasheed et al., 2020).

(Pfoser et al., 2016) identified network, collaboration, trust, sophisticated planning, ICT/ITS technologies, physical infrastructure, legal and political framework, awareness, mental shift, and pricing/cost/services as critical enablers for a successful DT adoption in supply chains. According to (Giusti et al., 2019) having proper traceability software, use of proper data analytic practices, and maintaining optimization and simulation integration platforms act as critical success factors in adopting and implementing DTs in Supply Chains. (Deepu & Ravi, 2021) categorize the key success factors/enablers for DT adoption under four themes namely Economic factors, Technological factors, Ethical factors, and Operational factors. Availability of funds and financial investments and having a profitable sharing model with supply chain partners are identified as key economic enablers. Access to state of art technologies, high data security and data management protocols, standard ways of information sharing like ERP systems, and access to real-time data analytics are identified as the key technological enablers for DT adoption. Maintaining proper relationships with SC partners to encourage change, improving the commitment among SC partners for DT adoption, and making necessary cultural alignments between SC entities to embrace new digital initiatives are identified as key ethical enablers. Operational factors including top management commitment and support, extended enterprise, long, medium, and short-term planning, and proper risk mitigation strategies are considered as key operational factors/enablers of successful DT adoption in SCM. Organizational competencies including knowledge building through reskilling and upskilling of the workforce, knowledge-based intelligent skills, and asset modeling are also identified as key enablers for successful DT adoption in process industries. Organizational practices like standardized processes, continuous improvements, process designs based on simulations, and optimization techniques also act as enablers in the DT adoption journey (Piras et al., 2024). A summary of the identified key factors and enablers are listed in Table 4.

Table 4 Key Enablers and Success Factors

Category	Key Enablers and Success Factors	
Technological enablers	• AI, ML, AR/VR, IoT, IIoT, • High data management protocols. • Standard information sharing systems. • Access to real-time analytics	(Perno et al., 2022), (Qi & Tao, 2018), Ezhilarasu et al., 2019, (Cai et al., 2020)
Infrastructure enablers	• Cutting-edge hardware, 5G • Blockchain • Open-source software • Centralized databases	(Alcácer & Cruz Machado, 2019), (Minerva et al., 2020), (Errandonea et al., 2020),

		(Rasheed et al., 2020),
Legal and Political Framework	• Data governance policies • Legal conditions • Insurance conditions • Government investments	(Pfoser et al., 2016)
Economic factors	• Financial investments, Availability of funds	(Deepu & Ravi, 2021)
Ethical enablers	• Proper relationships with SC partners • Encourage SC partners for change. • Cultural alignments with SC partners to embrace change. • Investing in Supplier and Customer development	(Deepu & Ravi, 2021), (Minerva et al., 2020),
Organizational factors	• Knowledge building • Reskilling and upskilling • Asset modeling • Improve standardization. • Foster continuous improvements in process design	(Piras et al., 2024), (Minerva et al., 2020),

Source: Author's creation

4. Conclusion and future research implications

Digital Twins are being integrated into the SCM as a major driver of digitization. From the provided text, several key themes and applications emerge through an academic lens. DTs provide a comprehensive set of capabilities to solve the most important SCM problems such as visibility, monitoring, optimization, prediction, and simulation. These capabilities enable the SCM professionals to make better decisions in a variety of processes, by providing them with actual time insight, predicted analysis, and simulation models. Several different areas are covered by significant use of DTs in the SCM sector, e.g. warehouse management, material handling, order picking systems, automated storage, and retrieval systems as well as cold chain logistics. These applications illustrate the flexibility and impact of DTs to improve efficiency, reduce waste, enhance security as well as optimize resource utilization within SCM operations. Furthermore, the multidimensional benefits and complexity of adopting DT in SCM are underlined by scientific studies cited in the text. While DTs offer promising solutions, the challenges related to integration, complexity, and scale continue to require a nuanced understanding and strategic approach for implementation. The multifaceted nature of the implementation of DT within the SCM context is highlighted by the identification of key enabling factors for the successful implementation of DT, including advances in Industry 4.0 technologies such as Artificial Intelligence, Internet of Things, and Virtual Reality, as well as organizational competence, ethical considerations, and operational factors. Overall, the academic debate on DTs in supply chain management highlights their transformative potential to change traditional business practices, increase operational effectiveness, and foster innovation. Nevertheless, to realize the full benefits of DTs it is necessary to adopt a holistic approach that considers technology, organizational, and ethical dimensions while dealing with challenges related to their integration and deployment within supply chain management. To realize the perceived benefits of DT applications in SCM, organizations should conduct a proper evaluation of their readiness to embrace the new change. With this in mind, this study identifies

the future research potentials for measuring the maturity of SCs to adopt DTs, and to assess the readiness of SCs to adopt DTs.

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