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Digital twin applications in supply chain management: A systematic literature review

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A B S T R A C T

Article history:
Received August 29, 2024
Received in revised format October 16, 2024
Accepted February 3 2025
Available online February 3 2025

Keywords:
Digital twins
Supply chain
Logistics
Simulation
Optimization
IoT
Artificial intelligence

The new economic context has brought new challenges to the supply chain and has increased the complexity of its processes. The digitalization; as one of these challenges, is a rapidly evolving paradigm that transforms supply chains by integrating data and communication technologies to optimize operations, enhance sustainability, and improve overall performance. Digital twin technology emerged as one of the most promising digital tools that offer an innovative approach to supply chain management. However, the adoption of digital twins in the supply chain is still in its early stages. Previous research papers presented limited overviews of the applications of digital twin technology in supply chain systems that need to be extended, as it is inevitably a work in progress. In this matter, we conducted a systematic literature review built upon 31 articles to determine the applications of supply chain digital twins (SCDT). This study is divided into three core themes; the first is a comprehensive review of the paradigm of digital supply chain with a focus on digital twin technology and its primary features. The second theme presents an analysis of the 31 papers where we explore the different purposes of SCDTs and their integration. in the third theme by using VOSviewer to conduct a network analysis. We aim; through this paper, to contribute significantly to the supply chain management field by summarizing and analyzing existing research and developments in the applications of digital twins in the different areas of supply chains.

1. Introduction

In recent years, the growing complexity of global supply chains has posed significant challenges for organizations across various industries. According to (Farahani, 2015) following challenges and trends are identified for the next couple of years: globalization and sales growth, supply chain visibility, process standardization and automation, supply chain collaboration, flexibility in responding to the volatile markets, innovation and new business models. Therefore, the need for real-time visibility, enhanced operational efficiency, and proactive decision-making has driven the adoption of innovative and digital technologies to tackle these complexities.

Digitalization is described as the increasing penetration of digital technologies in society with the associated changes in the connection of individuals and their behaviors (Gimpel & Röglinger, 2015). The impact of digitalization has been and still tremendous; forcing companies across the globe to act and react to changing business rules. Among the digital technologies, the concept of digital twins has emerged as a promising digital solution to create new supply chain opportunities.

Digital twin technology involves creating virtual replicas of physical assets, systems, or processes to simulate their behavior, monitor their performance, and gain valuable insights. Initially popularized in the manufacturing sector, digital twins have now found their way into the realm of supply chain management. By creating digital twins of their systems, the companies can gain several benefits, including data collection and analysis, constant monitoring of the system functioning, identification of trends and patterns, problem detection and optimization of maintenance activities, as well as process enhancement and minimization of human decision making (Javaid et al., 2023).

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ISSN 2291-6830 (Online) - ISSN 2291-6822 (Print)

doi: 10.5267/j.uscm.2025.2.001

Researchers have extensively explored various aspects of digital twin technology's integration and impact on supply chain processes in multiple fields. Including the food industry, where the application of digital twins mainly targets the production (agriculture) or the food processing stage. Nearly all applications are used for monitoring and many for prediction. However, only a small amount focuses on the integration in systems for autonomous control or providing recommendations to humans (Henrichs et al., 2022). Additionally, DTs can be employed to reduce the quality loss of fruits and vegetables during the packaging, storage, and transportation cold chain operations and take measures against potential problems affecting the quality of fresh produce in the supply chains. The study gives promising insight towards the use of advanced technologies in reducing losses in the postharvest supply chain of fruits and vegetables (Onwude et al., 2020).

In the field of smart ports, review studies have been conducted comprehensive overview of DT managing capabilities together with details of necessary architecture to support effective simulations in virtual port's space. They have shown that a DT-driven platform will enable better management across the smart port activities from design to transport to operation and sustainment of innovative plans (Wang et al., 2021).

Kosacka-Olejnik analyzed the current state of the art of the Digital Twins applied in internal transport systems, in order to: first, acknowledge the most influential and high-impact journals, papers, and researchers; second, identify the major research trends related to the DTs applications in internal transport systems, third, present future research agendas in investigating DTs applied for internal transport systems (Kosacka-Olejnik et al., 2021).

Many researchers have focused on understanding the digital twin concept, the enabling technologies, and challenges of integration. Gerlach aims to derive a unified definition of SCDT, including possible scopes of applications. Subsequently, they synthesized 14 individual use cases to give present five application areas of SCDTT as well as its intended benefits (Gerlach et al., 2021).

In their paper, Moshood found that DTs would help companies develop predictive metrics, diagnostics, projections, and physical asset descriptions for their logistics. They also suggested some steps to overcome the challenges in implementing a Digital Twins in the logistics industry (Moshood et al., 2021).

Through his review, (Van Der Valk et al., 2022) has uncovered four main purposes of DTs in supply chain: Visibility and monitoring, prediction optimization, and simulation.

Recent studies have highlighted how the advancements in technologies such as IoT, cloud computing, and blockchain have increased the potential of digital twin applications in the supply chain. Furthermore, they indicate that a supply chain digital twin should include the things and humans from the entire supply chain and not be restricted to the local manufacturing systems.

Other reviews have delved into the growing potential of both AI and DT to optimize warehousing. The algorithms are utilized in different ways to ensure warehouse digital twin characteristics and potential, and on the other hand DT presents a mature and sophisticated and interactive modeling environment for AI (Elbouzidi et al., 2022).

In comparison to the previous literature, our paper aims to explore the new dimensions of digital twin applications within supply chain management. By conducting a bibliometric and content analysis, this research advances the understanding of how digital twins enhance decision-making, efficiency, and resilience within supply chains. The application area of supply chain digital twins often focuses on the production part, like shop-floor digital twins (Qi et al., 2018). Therefore, the paper's originality lies in its in-depth examination of uncharted applications of DT in SCM processes beyond manufacturing, and the resulting contributions to transforming traditional supply chain practices.

Through this paper, we intend to provide an up-to-date review of the applications of digital twins in supply chain management based on a systematic literature review of 31 papers. A systematic literature review on the applications of digital twins in supply chain management can make valuable contributions to both academic and managerial domains. First, the review would provide a contemporary and comprehensive synthesis of existing academic literature, summarizing the current state of research on digital twins in supply chain management. This can serve as a knowledge base for researchers and students. Second, through this review, researchers can identify gaps in the existing literature and highlight areas where further research is needed. Third, this paper can provide valuable insights into the practical applications of digital twin technology in supply chain management, enabling managers to understand its real-world implications and gain a better understanding of the potential benefits and challenges associated with its implementations.

In summary, a systematic literature review on the applications of digital twins in supply chain management contributes to academia by advancing knowledge and theory in the field, while also providing practical insights and guidance for managers to make informed decisions regarding the adoption of digital twin technology in their supply chain operations. Hence, this paper aims to answer the following research questions:

RQ1) What are the different areas and scopes of implementations of digital twins in the supply chain?

RQ2) How digital twins are employed within supply chains, and for which purposes?

2. Theoretical background

2.1 Digital Supply Chain

The advent of digitalization has revolutionized supply chain management, ushering in a new era of efficiency, visibility, and agility. At the core of the digital supply chain lies the seamless integration of advanced technologies that foster connectivity, data exchange, and intelligent decision-making.

The traditional supply chain model, once reliant on manual processes and disconnected systems, is giving way to the era of the digital supply chain. Digital supply chain is commonly defined as “the integration of advanced digital technology to transform supply chain operations and processes.” Yet, we can enlarge this definition by adding its purposes and uses. Many authors focus on the role of the digital supply chain in collaboration and communication. Such as (Büyüközkan & Göçer, 2018) who defined digital supply chain as intelligent optimized-technology systems that perform functions such as massive data processing and excellent collaboration and communication using digital hardware and software that synchronize and support interactions among organizations. (Büyüközkan & Göçer, 2018) defined it as a new concept of interconnected business systems expanding from isolated and local single-firm applications to a supply chain where extensive and systematic smart technologies are implemented. Many authors emphasize the fact that all stages of a supply chain are connected, which enables robust data collection as well as intelligent decision making based on real-time communication; it also requires an efficient system based on immediate responses to provide better customer services (Wu et al., 2016). On the other hand, (Kinnet, 2015) focused on value creation, defining a digital supply chain as a value-oriented intelligent network that embraces analysis and technology using new approaches to generate fresh profits and business value.

Combining the different definitions, we deduce that digital supply chains have the capabilities to process vast amounts of information and to empower supply chain partners to collaborate and communicate seamlessly employing emerging technologies, so as to create value throughout the supply chain network. Emerging digital technologies are new technologies that are currently developing or will be developed over the next few years, which will substantially alter the business and social environment. There are several technologies that can be applied in supply chain, including but not limited to artificial intelligence, augmented reality, big data, cloud computing, internet of things, robotics. Accordingly, the digital supply chain is characterized by a host of innovative features that revolutionize traditional logistics and operations. The different digital supply chain features are listed in Table 1 according to (Büyüközkan & Göçer, 2018).

Table 1
Features of Digital Supply Chain

Feature	Definition
Speed	The ability to react quickly to demand is going to be one of the most important pillars of a digital supply chain as organizations look for new ways to get product delivery rapidly.
Flexibility	Digital supply chain has the ability to predict disruption events and taking suitable measures and reacting efficiently by using the information collected and modeled.
Global connectivity	Digital supply chain establishes a way to build effective global hubs to locally supply goods and services, instead of carrying them across the world for a sole order.
Real-time inventory	While customer behavior changes promptly, the supply always needs to meet the demand. Digital supply chain provides advanced analytics of buying trends and future demand for goods and services to make informed decisions.
Intelligent	Digital supply chain provides smart products that are equipped with enough computing power so that self-learning and autonomous decision-making could be enabled based on defined algorithms.
Transparency	Digital supply chain can enable companies to act transparently and be better prepared to disruptions by anticipating, modeling the network, creating what-if scenarios and adjusting the chain instantaneously to changing conditions.
Scalability	Scaling supply chains up or down with digitalization brings easier optimization and duplication of processes and simpler spotting of anomalies and errors.
Innovative	The world is being swamped with novel technologies at a seemingly faster rate than ever before. Excellence in SCDT is a key feature so that digital supply chains are always open for a change.
Proactive	Digital supply chain offers proactive solutions to anticipate issues prior to their occurrence, an effective analytics framework and operational intelligence to satisfy digitally enabled consumers.
Eco-friendly	Supply chains have a certain level of impact on the environment. Digital supply chain can be able to extend eco-friendly process capabilities.
Interconnected	Customers, suppliers and partners communicate and collaborate real-time based on shared and standardized data via platforms in a network of companies.

To achieve the expected outcomes of digital supply chain, companies must focus on some critical components and strategies so as to effectively leverage digital technologies and achieve optimal performance. Hence, some key success factors of digital supply chain are crucial to define, including:

- **Data management and integration:** Effectively managing and integrating data from various sources, such as ERP, IoT sensors, suppliers, and partners, is essential for real-time visibility and data-driven decision-making.
- **Real-time visibility:** Access to real-time data and end-to-end visibility into the supply chain enables organizations to track products, monitor inventory, and respond to disruptions promptly.
- **Collaboration and communication:** Effective collaboration tools and communication platforms facilitate real-time information exchange and collaboration among supply chain partners.
- **Cyber-security measures:** Implementing robust cyber-security solutions to protect against cyber threats, data breaches, and safeguard sensitive supply chain data.
- **Change management:** Developing strategies for effectively managing organizational and cultural changes required for digital supply chain adoption, including upskilling the workforce.
- **Customer-centric approach:** Prioritizing customer needs and expectations by offering customization, fast responses, and on-time deliveries to improve customer satisfaction.
- **Innovation and continuous improvement:** Encouraging a culture of innovation and continuous improvement within the organization to adapt to emerging technologies and best practices.

2.2 Digital Twin

2.2.1 Definition

The origin of the digital twin (DT) can be attributed to the need for better visibility, monitoring, and control over complex and interconnected systems. The early applications of DTs were predominantly found in the aerospace and automotive industries. For instance, in aerospace, digital twins were used to simulate and test the performance of aircraft components, optimize maintenance schedules, and improve fuel efficiency. In the automotive industry, DT facilitated virtual prototyping, manufacturing process optimization, and predictive maintenance of vehicles. Strictly speaking, DT is not a completely new concept. It is rooted in some existing technologies, such as 3D modeling, system simulation, digital prototyping (including geometric, functional, and behavioral prototyping), etc. (Qi et al., 2021). The timeline in Fig. 1 shows the history of the development of the digital twin paradigm.

Today, digital twins continued to evolve beyond product-centric applications to encompass entire systems, processes, and even ecosystems. With multiple advanced technologies, digital twin has found applications in various industries, including manufacturing, healthcare, energy, transportation, and smart cities. Internet of Things (IoT), artificial intelligence (AI), and advanced analytics enabled the integration of real-time data from sensors, connectivity, and machine learning algorithms, allowing DTs to continuously update and adapt to their physical counterparts.

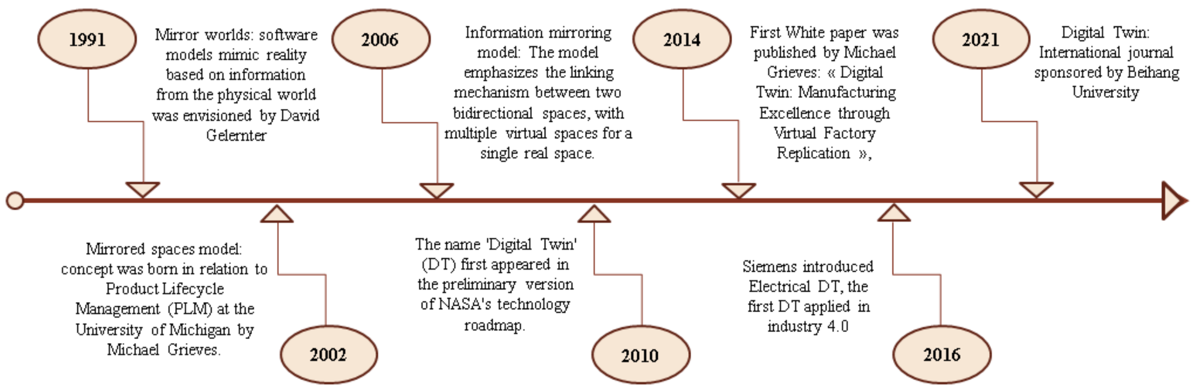

Fig. 1. Digital Twin History

3. Characteristics and classification

The basic DT model was introduced by (Michael Grieves, 2015). It consists of three main parts: (a) physical products in real space, (b) virtual products in virtual space, as well as (c) the connections of data and information that tie the virtual and real products together (Michael Grieves, 2015). In essence, DT entails creating a virtual representation of a physical object to simulate its behaviors, monitor real-time status, identify internal and external complexities, detect irregular patterns and evaluate the overall system performance. Besides, Tao et al. extended the existing 3-dimension DT model adding two dimensions: data and services to propose a five-dimension DT model (Tao et al., 2018).

Klar et al. uncovered some of the core aspects of the DT, temporal span and functional scope (Klar et al., 2023):

a. Temporal span

- Complete lifecycle:

A DT is designed to synchronize its physical counterpart at all stages covering design, prototyping, manufacturing, deployment, maintenance, and disposal.

- Changing requirements:

Depending on the application domain, the DT may have different requirements depending on the time cycle.

- Increased value over time:

A DT is a self-improving system that can be progressively improved and extended through the increasing accumulation of data and knowledge over time.

b. Functional scope

- Modelling:

A DT is a grouping of models and algorithmic components jointly describing a complex system. The comprehensive modeling involves all aspects of the physical entities as well as the prediction of additional likely outcomes to test.

- Visualization:

With its distinctive visualization capabilities, the DT allows permanent monitoring of the processes and thus contributes to situational awareness and enables the cooperation of different actors in the digital space.

- Interaction:

A DT is characterized by its Bi-directional character. It directly influences the actual system based on its actions, changes and predictions. Furthermore, the DT interacts with other fleet members if there are multiple instances.

- Synchronization:

The DT is continuously updated in a timely manner This ensures a consistent up-to-date virtual representation and is required for a number of ongoing online tasks.

Digital twins can be classified into several categories based on their complexity, purpose, and applications. Three different categories of DTs were identified by (Kritzinger et al., 2018) according to their level of data integration:

- *Digital Model:* They are static and does not change unless manually modified. Digital models are primarily employed for design and visualization.
- *Digital Shadow:* They are dynamic and change in real-time as data is collected and analyzed due to automated one-way data flow between the physical object and its virtual twin. Yet, they lack behavioral simulation.
- *Digital Twin:* They offer a comprehensive digital representation of a physical object or system that combines a digital model with real-time data between physical and digital objects in both directions

Recent classification was made by (Henrichs et al., 2022) within the context of food supply chain, who proposed a DT taxonomy detailed in Table 2.

Table 2
Classification of Digital Twins

Type	Capabilities
Statistical	Solve simple analytical equations or an ordinary differential equation (ODE).
Intelligent	Use of artificial intelligence techniques
Mechanistic	Performance of multiphysics modeling and simulation.
Imaginary	Simulates objects that do not physically exist in the real-world.
Monitoring	Monitor the current state and behavior of a real-life object.
Predictive	Project future states and behavior of a physical object based on real-time data.
Prescriptive	Recommend corrective and preventive actions while using monitoring outcomes and predictions.
Autonomous	Control and manage autonomously the behavior of the real-world twin without human intervention.
Recollection	Maintains the complete history of physical twins that no longer exist in real-life.

4. Supply Chain Digital Twin

Due a digital twin is a dynamic virtual representation of a physical object or system; we can define a supply chain digital twin (SCDT) as a detailed simulation model of an actual supply chain which predicts the behavior and dynamics of a supply chain to make mid-term/short-term decisions. The primary purpose of the SCDT is to enhance supply chain management by capturing and analyzing vast amounts of data, enabling organizations to gain valuable insights, make informed decisions, and optimize their supply chain operations. It acts as a digital mirror of the physical supply chain, reflecting its structure, processes, and dynamics. Three main attributes characterize the data exchange between the supply chain system and its digital twin (Busse et al., 2021) : (1) Bidirectional: Data flows in both directions. Thus, changes in the state of the supply chain system led to changes in the state of the digital twin. Similarly, the knowledge gained from the digital twin influences actions and decision-making within the supply chain system. (2) Timely: Data flows promptly, but it's not a prerequisite. The specific frequency depends on the supply chain requirements. (3) Long-term: SCDT are designed for ongoing and extended usage and thus the data flow lifetime.

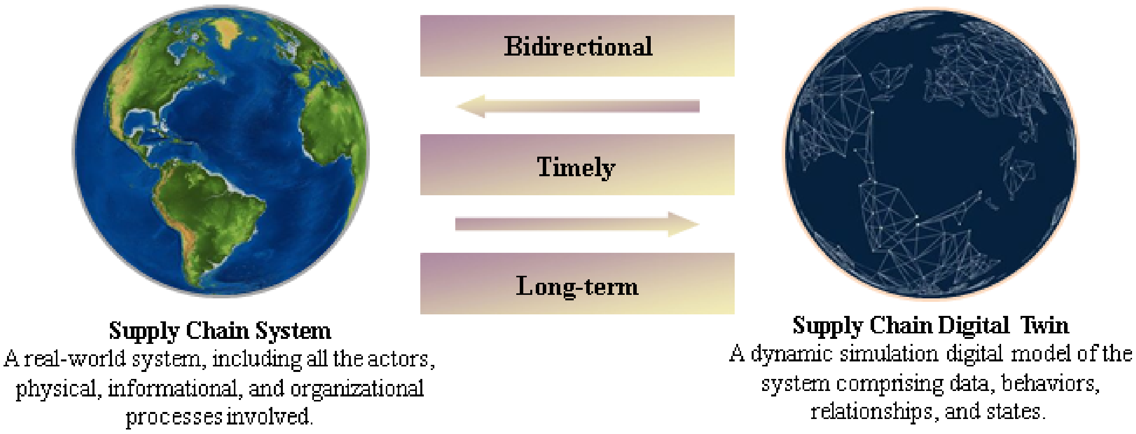

Fig. 2. Data exchange between real supply chain and supply chain digital twin

In the context of recent disruptions; such as the coronavirus outbreak and geopolitical conflict of Russia-Ukraine tensions, supply chains have faced unprecedented challenges and became more vulnerable. In order to be protected and prepared, companies must turn to innovation and advanced technologies to enhance visibility, responsiveness, and agility. In this case, SCDT can play a crucial role in building robust supply chain networks. Drawing on the work of (Wang et al., 2022) some of the advantages that the DT concept brings to the supply chain are summarized in Table 3.

A SCDT is emerging as an important part of the supply chain management toolbox, enabling supply chain control towers to provide decision-making support at strategic, tactical, and operational levels (G. Zhang et al., 2022). Nevertheless, the adoption of DTs in logistics and supply chains is not yet widespread. Many of the key Industry 4.0 technologies are already in place, including: internet of things (IoT), cloud computing, data analytics and big data, 3D printing, advanced manufacturing, intelligent control system, cyber physical systems (CPSs), and smart production (Azevedo et al., 2021).

Table 3
Advantages of Digital Twin in Supply Chain Management

Supply chain objective	How DT can achieve it	Reference
Improved connectivity	DT offers a connected and holistic view of production logistics by providing production information to different stakeholders in the chain. Giving the example of the recycling industry, the application of the DT can increase the impact on sustainability.	(Zafarzadeh et al., 2021)
Improve end-to-end visibility	DT facilitates asset tracking across supply chain, which is a highly desirable capability in supply chain. DT has the capacity to overcome the limited visibility of the logistics processes with a data-driven trade-in pricing policy in fully transparent platforms.	(Moshood et al., 2021) (Tozanli et al., 2020) (Y. Wang et al., 2020)
Increase supply chain agility and resilience	The adoption of DT in managing disruption risks helps supply chain managers to quantify tradeoffs between efficiency and resilience under disruption better. Furthermore, DT provides optimization and simulation methods to evaluate the impact of potential failure on supply chain performance, which enables supply chain agility.	(Seif et al., 2019) (Ivanov & Dolgui, 2019)

JD Logistics developed the "Logistics Mirror" platform; the first digital twin for the supply chain to increase their supply chain efficiency and minimize costs. First deployed in JD's Beijing Asia number 1 logistics park, the platform now covers over 8,000 transportation routes across JD's own logistics and warehousing network, providing accurate capacity forecasts and alerts for sales peaks (Klar et al., 2023).

The integration of DT can occur at various levels, depending on the scope and complexity of the system being replicated. Zhang developed a supply chain digital twin framework based on the SCOR model with four integration levels shown in Fig. 3.

Supply chain system: a SC system is a dynamic and complex network, which includes multiple echelons. Each echelon may contain multiple members. At this level, DT enables ecosystem-wide optimization, resource sharing, and value creation through data exchange, interoperability, and collaboration.

Member: every member has its supplier and customer, wherein the supplier and customer also have their own supplier and customer, respectively. Thus, a chain is formed naturally. In the framework, each member is independent on this design level.

Module: Module is the location of the material or product in the SC, which represents the geography changing. Each member can comprise one or more modules. Each module is composed of multiple standard process blocks.

Block: Block is a process-set based on the business functions in each specific module. There are a total five kinds of blocks in the module according to the SCOR model: (1) obtain, (2) make, (3) distribute, (4) return (to upstream), (5) return (from downstream).

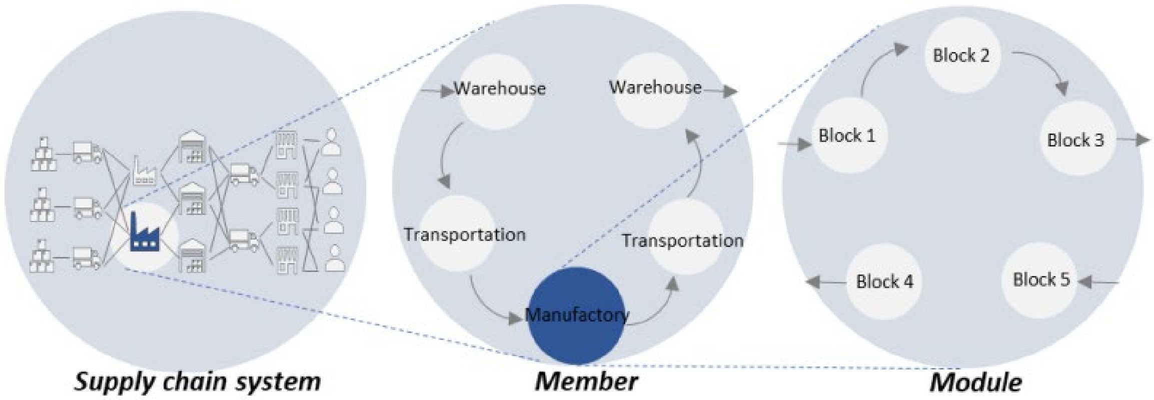

Fig. 3. The 4-level structure of supply chain system (Zhang et al., 2021.)

5. Research Design

Literature review serves as a foundational component of academic and scientific studies. They aim to summarize and synthesize previous studies to illuminate the current state of knowledge regarding a particular research problem or subject, also, to identify potential avenues for further research highlighting the boundaries of existing knowledge (Tranfield et al., 2003). There are two main review methodologies; narrative reviews and systematic reviews. The first one tends to be mainly descriptive, lacks a systematic search of the literature and thereby often focuses on a subset of studies in an area chosen based on availability or author selection. Thus, narrative reviews, while informative, can often include an element of selection bias. They can also be confusing at times, particularly if similar studies have diverging results and conclusions (Uman, 2011). The systematic reviews in the other hand, adopt a comprehensive, scientific and transparent process, since they follow a structured approach that aims to minimize bias through exhaustive literature searches of published and unpublished studies and by providing an audit trail of the reviewers' decisions, procedures and conclusions (Cook et al., 1997). Our literature review is mainly skewed towards exploring and understanding the applications of digital twins in supply chain management beyond the manufacturing environment. Thus, the DT applications in manufacturing processes were excluded from our review. The foundation of the research process is a Systematic literature review (SLR) based on the framework proposed by (Koutsos et al., 2019). SLR aims to summarize research studies related to a specific research question in a way that is fair, rigorous, and auditable. Fig. 4 presents the SLR design for our study. The review protocol of (Koutsos et al., 2019) proposes the six steps: (1) Scoping; (2) Planning; (3) Identification; (4) Screening; (5) Eligibility/Assessment, and (6) Presentation. In our review, we will group these steps in three core phases presented in Fig. 4.

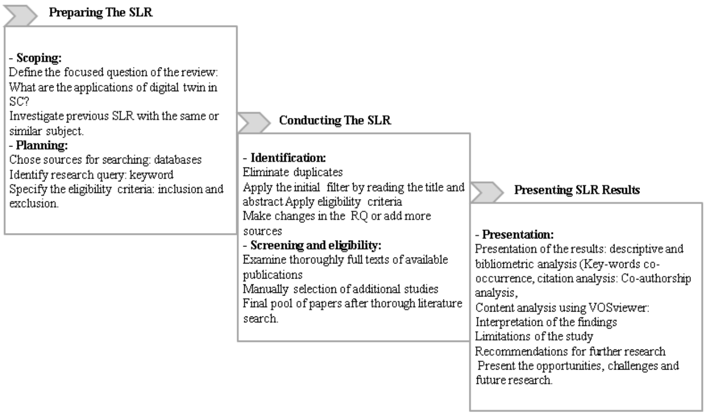

Fig. 4. Research Design

Inclusion and exclusion criteria are predefined criteria that are used to determine which papers will be included in the study and which will be excluded. These criteria help to ensure that the study's sample is appropriate and representative of the research question and objectives.

To systemize the review process, we identified clear inclusion and exclusion criteria in Table 4.

Table 4
Inclusion and exclusion criteria of SLR

Inclusion criteria	Exclusion criteria
Include studies found using the combination of keywords from the search query indicated in Fig. 5, Include only articles from journals published in English language, Include studies based on title, abstract, and keywords, and by conducting a content analysis of the full text, Include articles that only present case studies or frameworks.	Exclude irrelevant or duplicate studies, Exclude articles that focus on the manufacturing processes, Exclude articles that solely concentrate on literature reviews Exclude reports, white papers, theses, book chapters.

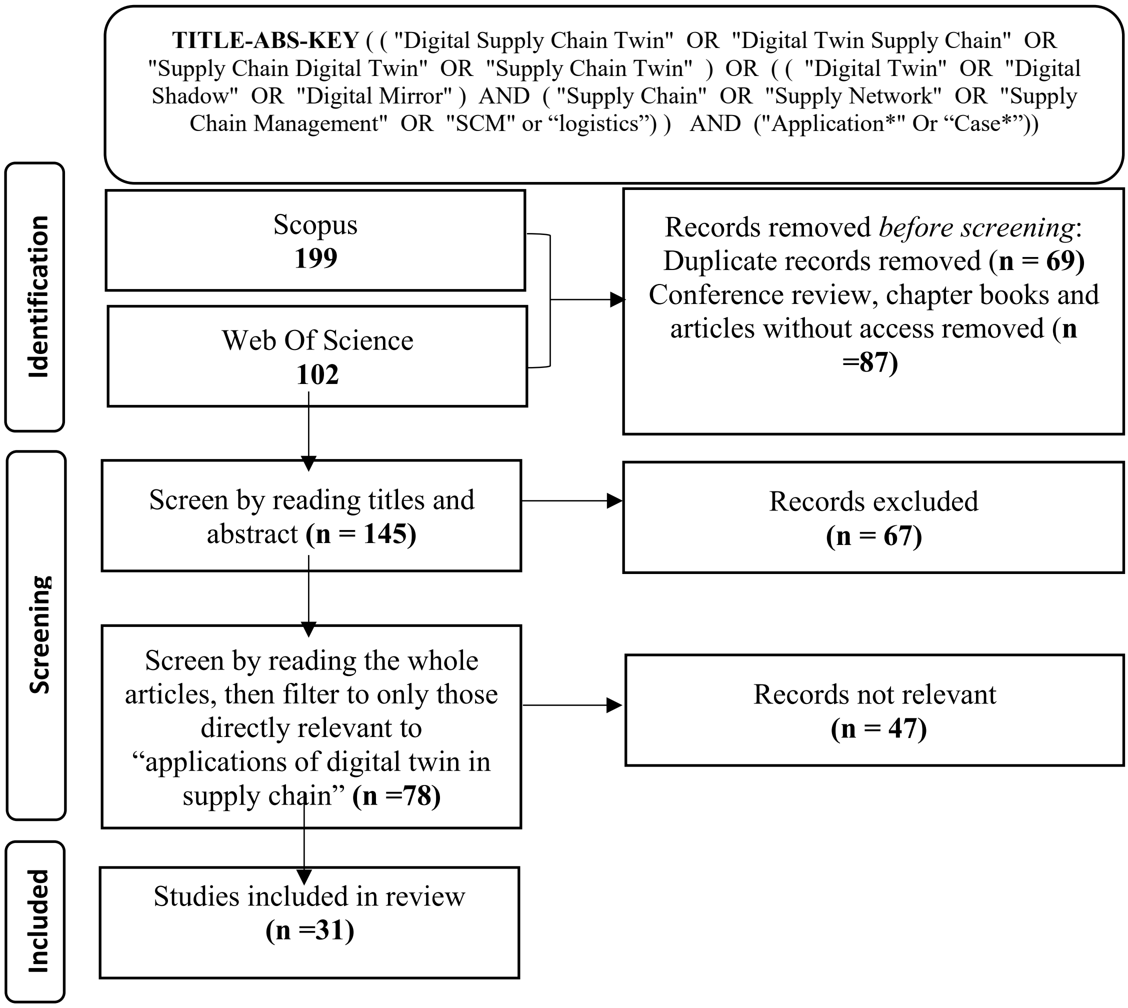

Fig. 5. SLR process based on PRISMA flowchart

6. Results

Data analysis comprises two main parts; "bibliometric analysis" and "content analysis". A bibliometric analysis provides an overview of data, which provides a broad perspective on the research activities and their impact, particularly in terms of highly cited researchers, articles, keywords, journals, and universities.

Content analysis is a qualitative research technique used in academic research to systematically analyze and interpret the content of different publications. The purpose of content analysis is examining and identifying patterns, themes, and meanings within the collected data.

For conducting our two analyses, we have opted for the freely available software package VOSViewer. This user-friendly tool possesses the distinction of being both technically robust and relatively simple to use (Kirby, 2023). VosViewer growth has been exponentially exponential due to its capability to map a body of literature and spot potentially interesting concepts (Sinkovics, 2016).

6.1 Descriptive Analysis

The initial author and affiliation statistics obtained from our initial analysis of the 31 papers are presented and discussed in this section. Identifying the key researchers and universities in different geographical regions can help scholars and students who are interested in conducting research of SCDT with researchers from other universities.

Fig. 6 illustrates the number of publications per year from 2019 to 2023, suggesting the applications of SCDT to be a fairly nascent field of study. A constant growth in the number of publications can be observed with a particularly significant increment in 2022. The initial statistics also show that 99 journals have contributed to the publication of those 31 papers. Those journals appear to represent the engineering and logistics fields more substantially.

Fig. 7 shows the contribution of authors in which 6 papers of the applications of DT in SC are published by Dmitry Ivanov from Berlin School of Economics and Law.

Distribution of papers by subject areas is presented in Fig. 8. The most dominant areas where SCDT is applied are: Engineering by 24.3%, followed by Business and management (16.2%), Decision science (15%) and Computer science (13.5%).

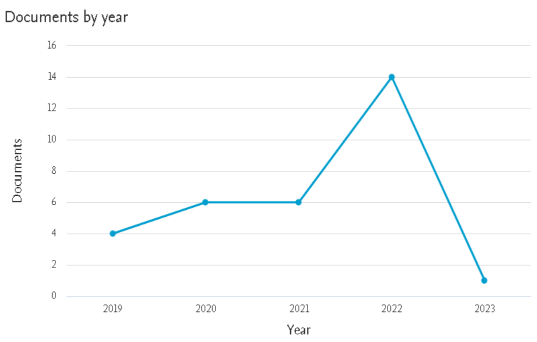

Fig. 6. Publications per year

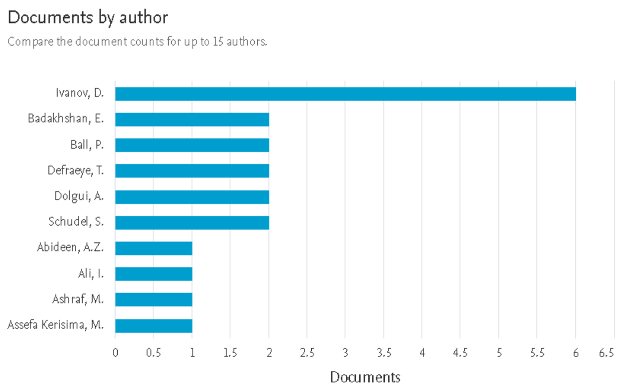

Fig. 7. Publications per author

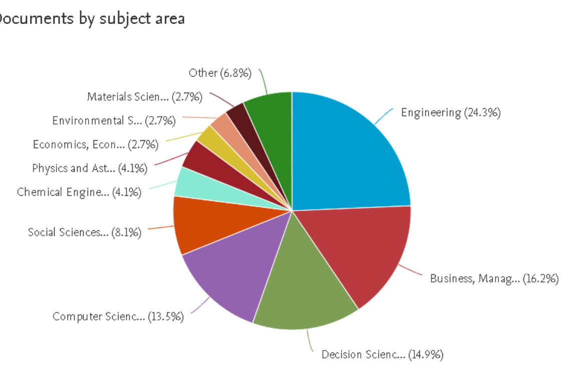

Fig. 8. Papers by subject area

In the following section we analyze the selected papers based on the research questions. The objective is to provide a comprehensive examination of the 31 articles by identifying the key elements of our study. First, the different application areas and supply chain features are influenced by the implementation of SCDT. Second, we identify the different levels of integration of SCDT. Third, we present the key SCDT purposes spotted in the selected articles. Finally, we investigate some technical components of SCDT.

6.2 *Analysis of applications areas of SCDT*

Digital twins are used in different areas of application from healthcare (Feng, 2018) to construction industry (Kaewunruen et al., 2019). As shown in Fig. 9, most authors have developed SCCDT for non-specific area, yet, there are some dominant fields such as food supply chain, pharmaceutical industry and transportation.

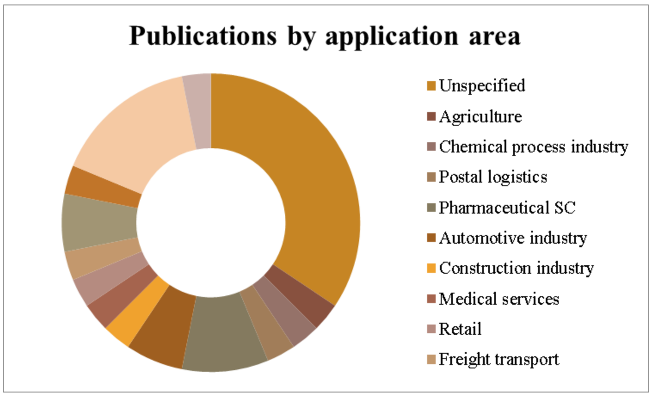

Fig. 9. Industries using Digital Twin in their SCs

Supply chain digital twins can be applied for a specific SC process or focus on the entire supply chain system. They provide real-time data of products and processes in the supply chain and increase the transparency (Singh Srai et al., 2019). Wang et al. (2022) presented a motivating case of JD.COM, China's largest retailer by revenue, in reconfiguring the supply chain network during the COVID-19 pandemic using a DTSC platform. As a result, applying a DTSC platform significantly improves the response efficiency of JD.COM. DTSC platform builds end-to-end digital representations for the entire supply chain. Compared with traditional retail supply chains, which consist of several distinct stages, JD.COM has an integrated supply chain structure, where products are directly delivered from factories and manufacturers to consumers through a single jd.com platform. This integrated supply chain structure has a higher level of collaboration, more effective information sharing, and a higher level of agility than existing supply chain structure. The DTSC platform is developed to model JD.COM's nationwide supply chain network, which requires large-scale simulation and optimization tools. Second, the platform is expected to realize high-frequency synchronization between physical supply chain and digital models. The daily operational efficiency can be improved by exploring real-time data. Third, analytics will be used proactively to foresee potential disruptions and to get JD.COM fully prepared. The initial analysis is based on the first research question, where we aim to present the supply chain features influenced by the application of DTs (i.e. Resilience, sustainability, performance…). Besides, we identified the level of SCDTs integration based on the framework developed by (J. Zhang et al., 2021). The results of this analysis are outlined in Table 5.

Table 5
Summary of research on applications of DT in SC

Reference	Supply chain feature	Application area	Purpose	Level of integration of DT (scs, member, model, block)
(Ivanov & Dolgui, 2021)	Resilience, Risk management	Unspecified	Design and implementation of a digital twin to manage disruption risks in SCs.	Supply Chain System
(Perez et al., 2022)	Business processes optimization	Unspecified	Present an integrated digital twin framework for supply chain business processes.	Block (distribute)
(Cavalcante et al., 2019)	Supplier selection	Manufacturing industry	Conceptualize a digital twin to analyze the risk profiles of supplier performance under uncertainty by utilizing the data analytics capabilities.	Block (obtain)
(Badakhshan & Ball, 2022)	Resilience -Risk management - Disruptions management	Manufacturing industry	Design a SC digital twin framework to help decision-makers in managing inventory and cash throughout the SC during disruption.	Block (make)
(Ivanov, 2022)	Resilience -Risk management - Disruptions management	Unspecified	Perform a simulation analysis using digital SC twin to identify potential impacts of blackouts (interruptions in energy supply) on SCs.	Member
(Barykin et al., 2020)	Risk management - Optimization	Unspecified	Propose a concept for a supply chain digital twin, which is based on the combination of simulation, optimization, and data analytics to manage the risks in supply chains.	Model
(Ko et al., 2022)	Supply chain network	Unspecified	Model supply chain process based on digital twin concept.	Supply Chain System
(Zdolsek Draksler et al., 2023)	Process optimization	Postal logistics	Implementation of a digital twin of cross-border postal distribution for real-time information management.	Block (distribute)

Table 5
Summary of research on applications of DT in SC

Reference	Supply chain feature	Application area	Purpose	Level of integration of DT (scs, member, model, block)
(Marmolejo-Saucedo, 2020)	Resilience	Pharmaceutical supply chain	Design and development of a digital twin based on simulators, solvers and data analytic tools that allow these functions to be connected in an integral interface for the company.	Block (distribute)
(Gallego-García et al., 2019)	Capacity planning - forecasting	Automotive industry	Develop a digital twin for capacity management model in order to be able to react to all potential demand scenarios.	Block (make)
(Lee & Lee, 2021)	Risks management	Construction industry	Develop a digital twin framework for real-time logistics simulation, which can predict potential logistics risks and accurate module arrival time.	Block (distribute)
(Abideen et al., 2021)	Performance	Unspecified	Propose a framework for data-driven digital twin generation and reinforced learning.	Model
(Pilati et al., 2021)	Sustainability	Services	Develop a digital twin that allows a real-time mapping of the patient flow to create a sustainable and dynamic vaccination center.	Block (distribute)
(L. Wang et al., 2022)	Supply chain network reconfiguration	Retail	Present the case of JD.COM, China's largest retailer by revenue, in applying the DTSC platform to address supply chain network reconfiguration challenges during the COVID-19 pandemic.	Supply Chain System
(Defraeye et al., 2019)	Sustainability	Cold Supply Chain	Develop a digital twin for the cold chain (shipment of fruits).	Block (return)
(Burgos & Ivanov, 2021)	Resilience	Food Supply Chain	Examine the impact of the COVID-19 pandemic on food retail supply chains and their resilience by applying digital twin.	Supply Chain System
(Leung et al., 2022)	Hyperconnected City Logistics (HCL)	Freight transport	Present a digital twin-based inbound synchronization framework to streamline the operations of a PI-hub in a hyperconnected city logistics system.	Block (distribute)
(Moder et al., 2020)	Supply chain planning	Semiconductors manufacturing	Develop a Semantic Web representation of supply chains deploying and manufacturing semiconductors. The digital twin aims for a holistic digitalization across the entire product life cycle.	Block (make)
(Hofmann & Branding, 2019)	Maritime logistics	Port operations	Present a digital twin for truck dispatching operator assistance, which enables the determination of optimal dispatching policies using simulation-based performance forecasts.	Block (distribute)
(Santos et al., 2020)	Supply chain collaboration	pharmaceutical supply chain	Create a digital twin of the internal supply chain with the goal of increasing awareness to stakeholders and decision-makers by delivering information regarding past and present tasks and performance indicators.	Model
(Melesse et al., 2022)	Quality	Food Supply Chain	Present a new approach to create a machine learning-based digital twin of banana fruit to monitor its quality changes throughout storage.	Block (distribute)
(Shoji et al., 2022)	Quality	Cold chain - postharvest chain	Study the cold chain of cucumber, eggplant, strawberry, and raspberry, imported from Spain to Switzerland. This study applies the knowledge and advantages of the physics based digital twins to evaluate the impact of possible measures and to improve the postharvest supply chain.	Block (distribute)
(Ivanov, 2020)	Resilience - Risk management	Selling the lightning equipment	Present the results of a simulation study that opens some new research tensions on the impact of COVID-19 (SARS-CoV-2) on the global SCs.	Supply Chain System
(Binsfeld & Gerlach, 2022)	Inventory management	Food supply chain	Develop a framework of SCDTT in multi-echelon inventory management of an organic FSC in terms of performance.	Supply Chain System
(Ivanov & Dolgui, 2022)	Resilience - Ripple effect	Supply chain network	Present the digital supply chain twin as a contemporary instrument for stress testing supply chain resilience.	Supply Chain System
(Maheshwari & Kamble, 2022a)	Optimal inventory policies (OIP)	Unspecified	Provide an application of the supply chain digital twin in OIP measurement. SCDT helps provide a better trade-off between the stakeholders of the SC.	Member
(Park et al., 2020)	Supply chain control	Automotive industry	Propose a cyber physical logistics system (CPLS) that is coordinated with the agent cyber physical production systems in a multi-level CPS structure. This multi-level architectural framework is designed to provide technical functionalities for resilient SC control on a distributed digital twin (DT).	Member
(Ashraf et al., 2022)	Resilience	Virtual supply chain	Introduce an approach to enhance Supply Chain Resilience using deep learning-based techniques in a Cognitive Digital Supply Chain Twin environment.	Member
(Busse et al., 2021)	Multimodal supply chain	Maritime transport	Present an initial framework for a holistic digital supply chain twin capable of including an entire multimodal supply chain.	Block (distribute)
(Pehlken et Baumann, 2022)	Reverse supply chain	Renewable energy industry	Demonstrate that urban mining represents a high-impact application of sustainable engineering within life cycle management where Digital Twins help increase impact on sustainability.	Member
(Badakhshan et al., 2022)	Inventory and cash management	Unspecified	Present a supply chain digital twin framework that integrates machine learning and simulation to identify the inventory replenishment policies that minimize the cash conversion cycle of an SC.	Block (make)

As shown in Fig. 10, 31% of DTs are implemented in the level of block (distribute), followed by the supply chain system level (25%), member (16%), and block (make) with 13%. The least levels are; model (9%), blocks (obtain) and (return downstream) with 3%. These ratios indicate that the authors focused on the implementation of DT in the distribution and the supply chain systems levels, but they are less interested in other levels such as return processes (upstream and downstream) and source processes.

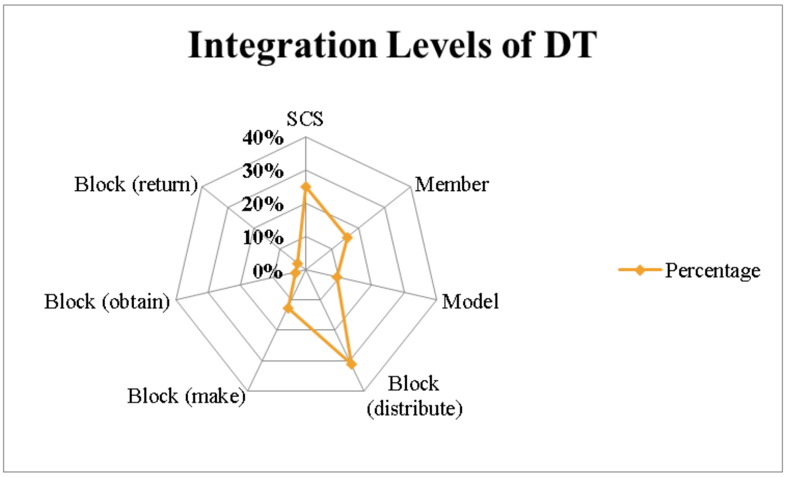

Fig. 10. DT applications by integration level

6.3 *Network analysis*

This section provides a visualization of the most important terms used in the 31 papers of this review in order to define recent trends in the subject of DT applications for SC. Fig. 11 illustrates the results of a co-occurrence analysis employing VOSviewer, which generates connections between key terms. On the network map below, lines link various terms, and the thickness of the links indicates the number of publications in which two terms occur together; thicker lines indicate a stronger link. VOSviewer determines the dependency between terms based on the software's calculation of association strengths between items that are similar. Association strength is determined by the ratio of total co-occurrences between items to the expected total co-occurrences between those items, assuming they are statistically independent.

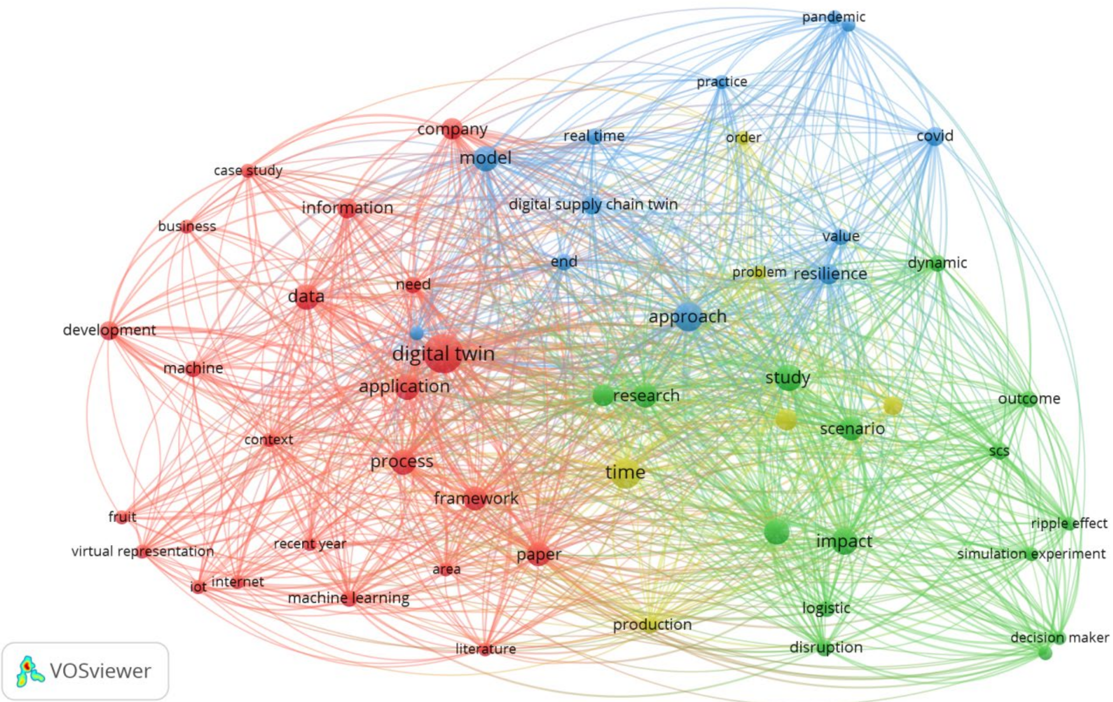

Fig. 11. Co-occurrence map based on text data (Title, abstract, and keywords) with VOSvieweer

The VOSviewer algorithm generated four clusters of keywords, representing distinct groupings of academic activity and research publications. Table 6 presents the proposed interpretation for each cluster. Three of them are value clusters and the fourth is an enabling cluster.

Value clusters are articles that describe how the application of digital twin can enhance supply chain activities at the level of business processes as well as the level of supply chain capabilities (Bhandal et al., 2022).

The enabling cluster is the foundation for the successful implementation of digital twin in supply chain activities. This cluster underlies infrastructure, tools, and technologies that create a supportive architecture of digital twin to enhance the overall efficiency and effectiveness of the supply chain.

Table 6
Clustering analysis

Cluster	Color	Keywords	Label
1	Red	Resilience, risks, disruption, viability, ripple effect, covid-19.	Digital twin for supply chain resilience.
2	Blue	Processes, performance, optimization, analysis, operation, inventory, decision system, real time, forecasting, demand, information.	Digital twin for supply chain performance.
3	Yellow	Quality, improve, cold chain, value, temperature, visibility.	Digital twin for supply chain sustainability.
4	Green	Internet of Things, machine learning, cyber physical system, digital supply chain, technologies, data.	Enabling technologies for SCDT.

Cluster 1: Digital twin for supply chain resilience

Supply chains are multi-structural systems composed of organizational, informational, financial, technological, process, product and energy structures (Ivanov, 2018). As every complex system, SCs are exposed to uncertainty and risks that range from internal SC problems such as supplier failure to external events such as societal disasters (e.g. the financial crisis in 2008) that lead to disruptions in physical and financial flows of the SCs (Badakhshan & Ball, 2022).

A digital SC twin is a model that represents the network state for any given moment in time and allows for complete end-to-end SC visibility to improve resilience and test contingency plans (Ivanov & Dolgui, 2021).

Digital twins make it easier to evaluate the resilience of the supply chain network and develop contingency plans accordingly by identifying critical nodes, vulnerabilities, and potential bottlenecks, enabling proactive risk mitigation strategies. On the one hand, Digital twins can simulate different network configurations, supplier relationships, and transportation options. Decision makers can evaluate the robustness and flexibility of their supply chain network, identify single points of failure, and explore alternative sourcing strategies. (Barykin et al., 2020) developed a DT model that helps to simulate and plan scenarios. The model makes it possible to observe the impact various failures in the supply chain and recovery policy have on its productivity. By inputting changes into the supply chain digital twin model, it becomes possible to understand the dynamics of a physical supply chain.

On the other hand, Digital twin can identify patterns, forecast potential disruptions, and implement proactive risk mitigation strategies by analyzing historical data, performance indicators, and external factors, organizations can. Predictive analytics capabilities of digital twins help in identifying potential risks before they occur, enabling organizations to take preventive actions.

Cluster 2: Digital twin for supply chain performance

Digital twins allow for real-time asset visualization, behavior and performance monitoring, and operation simulation and optimization (Lee & Lee, 2021). With the integration of real-time data, digital twins enable analyzing, simulating, and optimizing processes. The key application of digital twins in the supply chain for optimization and performance improvement is inventory optimization. Analyzing real-time data is the key to adjust inventory levels, safety stock levels, and replenishment strategies. Digital twins lead to optimize inventory to minimize holding costs, reduce stock outs, and improve customer service levels. Another application of DTs is supply chain network optimization. DTs have the ability to identify the most efficient and cost-effective supply chain configurations by simulating different network structures, transportation routes, and sourcing strategies. Therefore, they enable optimization of the network to minimize transportation costs, reduce lead times, and improve overall supply chain performance.

Digital twins also provide real-time performance monitoring capabilities by tracking key performance indicators (KPIs), such as delivery lead times, order fulfillment rates, inventory turnover, and customer satisfaction in real-time. Thus, decision makers can monitor the effectiveness of optimization strategies, evaluate the impact of implemented changes, and identify areas for further improvement. Besides, DTs enable better visibility between the stakeholders which improves the SC performance (Maheshwari & Kamble, 2022.

Cluster 3: Digital twin for supply chain sustainability

Digital twins have proven to play a significant role in making supply chains more sustainable by providing end-to-end visibility and improving decision-making processes.

In the food supply chain for example, the digital twins lower the uncertainty associated with estimating food quality attributes for each solution by quantifying the gain of different measures before implementing them. In this way, retailers, together with other stakeholders, can make a result-oriented decision and manage their financial planning better (Shoji et al., 2022). Moreover, the measured temperature history in the cold chain needs to be translated to actionable metrics. For this purpose, digital twins of the fruits have shown their potential, among other digital technologies (Badia-Melis et al., 2018). In other words, the integration of data from IoT sensors, quality control systems, and other sources assist decision makers in tracking quality-related metrics such as defect rates, process variations, or product non-conformities. Real-time visibility into quality metrics allows for immediate detection of quality issues, enabling prompt corrective actions.
The ability of analyzing historical data, process parameters, and external factors can widen the digital twins' application from evaluating the existing chain's fruit quality to predicting the impacts of the potential changes (Shoji et al., 2022).

Cluster 4: Enabling technologies for SCDT

According to most experts, a combination of simulation modeling, optimization, and data analytics makes up the full range of technologies which are needed to create a supply chain digital twin model (Barykin et al., 2020). The digital twin functioning is based on Industry 4.0 technologies, such as simulation, Internet of Things, big data analytics artificial intelligence and machine learning, and cloud computing (Fuller et al., 2020). The integration of digital twins with other technologies can significantly enhance supply chain operations, improve decision-making, and drive efficiency.

Table 7 examines how these technologies complement and enhance the capabilities of DT, enabling real-time data capture, advanced analytics, predictive modeling, and secure transactions.

Table 7
Enabling technologies of DT

Technology	Purpose in DTs
Internet of Things	Monitor and track assets, optimize inventory management, and detect potential issues or disruptions in real-time.
Artificial Intelligence and Machine Learning	AI and ML algorithms can analyze real-time data, historical patterns, and external factors to provide insights and recommendations for improving supply chain operations, demand forecasting, risk management, and decision-making.
Big Data Analytics	The integration of BDA enables the identification of trends, patterns, and correlations that can enhance forecasting accuracy, identify areas for process improvement, and support strategic decision-making.
Cloud Computing	Cloud-based platforms can store and process large volumes of data, facilitate collaborative decision-making, and enable real-time visibility and analytics.

7. Analysis of SCDT Purposes

In this second section we will analyze the 31 articles based on the purposes of DTs presented in these studies. As stated by (Van Der Valk et al., 2022), we could identify four primary purposes:

Visibility & Monitoring: the DT provides real-time monitoring of supply chain processes and operations by collecting and analyzing data from various sources, which helps to enhance transparency over the supply chain.

Optimization: the DT enables improving efficiency, reducing costs and enhances overall performance within the supply chain, because it utilizes advanced data analytics to analyze data streams from the physical world.

Prediction: DTs have the ability to create models to forecast future supply chain outcomes, based on real-time data, historical information and mathematical algorithms

Simulation: Since DTs can create virtual representations of the entire supply chain network, this allows for the testing of different scenarios and strategies, in order to assess the impact of different variables on the supply chain's performance

As revealed in Table 8, there are two methodologies adopted by the selected papers; frameworks and case study. The results show that the proportions are almost similar; 38% of the papers are case studies, 31% frameworks, and 31% used both methodologies. This means that the application of digital twins in supply chains is just in their infancy. The lack of comprehensive guidelines and suitable approaches lead the authors to focus on developing frameworks for their unique supply chain requirements. Although, there is a need for more case studies that showcase concrete evidence of the actual performance improvements achieved through the adoption of SCDT.

Table 8
Purposes of DT applications

Reference	Methodology	Visibility & Monitoring	Prediction	Optimization	Simulation	Holistic
(Ivanov & Dolgui, 2021)	Framework					√
(Raba et al., 2022)	Case study	√		√		
(Perez et al., 2022)	Framework			√	√	
(Cavalcante et al., 2019)	Case study	√	√		√	
(Badakhshan & Ball, 2022)	Framework		√		√	
(Ivanov, 2022)	Case study		√		√	
(Barykin et al., 2020)	Conceptual			√	√	
(Ko et al., 2022)	Framework	√		√		
(Zdolsek Draksler et al., 2023)	Case study		√	√		
(Marmolejo-Saucedo, 2020)	Framework + Case study			√	√	
(Gallego-García et al., 2019)	Case study		√		√	√
(Lee & Lee, 2021)	Framework + Case study	√	√		√	
(Abideen et al., 2021)	Framework					√
(Pilati et al., 2021)	Case study	√		√		
(L. Wang et al., 2022)	Case study	√		√		
(Defraeye et al., 2019)	Case study	√			√	
(Burgos & Ivanov, 2021)	Framework + Case study				√	
(Leung et al., 2022)	Framework + Case study			√	√	
(Moder et al., 2020)	Case study			√	√	
(Hofmann & Branding, 2019)	Case study	√			√	
(Santos et al., 2020)	Framework					√
(Madni et al., 2019)	Framework + Case study	√	√		√	
(Melesse et al., 2022)	Case study			√	√	
(Shoji et al., 2022)	Case study		√		√	
(Ivanov, 2020)	Case study				√	
(Binsfeld & Gerlach, 2022)	Case study				√	
(Ivanov & Dolgui, 2022)	Framework				√	
(Maheshwari & Kamble, 2022a)	Framework	√		√	√	
(Park et al., 2020)	Framework + Case study				√	
(Ashraf et al., 2022)	Framework + Case study		√			
(Busse et al., 2021)	Framework					√
(Badakhshan et al., 2022)	Framework + Case study				√	

The results show that 53% of DTs combine two purposes, 19% have only one purpose (simulation or prediction), 16% combine three purposes, just 13% of the DTs combine all four purposes simultaneously in a holistic way. Many DTs with the visibility purpose are providing simulations, as we need to simulate the state of the supply chain to create visibility. 25% of the analyzed DTs link visibility with optimization or prediction purpose, which signifies that the purpose of creating visibility in supply chain is, either, to optimize its processes or predict insights.

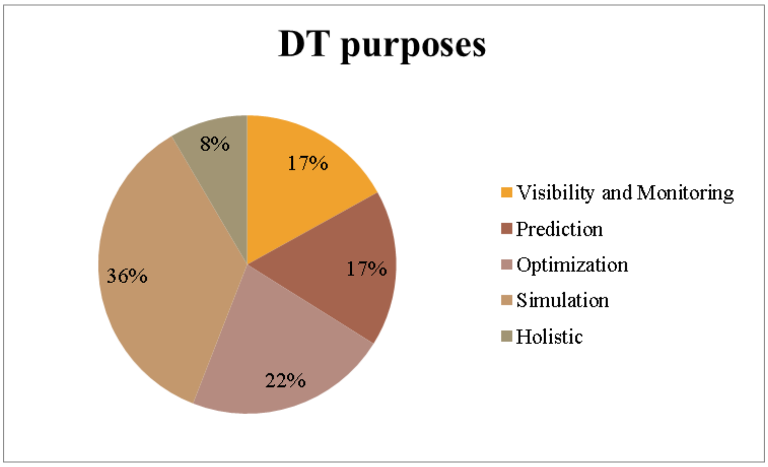

Fig. 12. Distribution of DT purposes

Optimization algorithms and simulation algorithms work together to support integrated supply chain design and intelligent operations. By directly connecting with decision and execution systems, these optimized insights can be quickly implemented to respond to changes.

8. Analysis of SCDT Technical Components

The third section of bibliometric analysis is devoted to analyzing some technical components of DTs related to the data collecting methods and the integration of artificial intelligence.

Digital twins can integrate knowledge and data resulting from modeling and simulation activities, with historical and real-time data captured by sensors during the real operation (Schluse et al., 2017). Furthermore, the digital twin functioning is based on Industry 4.0 technologies, so we aim to scope the papers that integrate internet of things (IoT) and artificial intelligence (AI) algorithms in their DTs. These elements are outlined in Table 9.

Table 9
Data flow type and AI integration in DT applications

Reference	Real-time data (IoT)	Historical data	Integration of AI
(Ivanov & Dolgui, 2021)	√	√	
(Raba et al., 2022)		√	√
(Perez et al., 2022)		√	√
(Cavalcante et al., 2019)		√	
(Badakhshan & Ball, 2022)	√		√
(Ivanov, 2022)	√		√
(Barykin et al., 2020)		√	
(Ko et al., 2022)	√		
(Zdolsek Draksler et al., 2023)	√		√
(Marmolejo-Saucedo, 2020)	√		
(Gallego-García et al., 2019)	√		
(Lee & Lee, 2021)	√		
(Abideen et al., 2021)		√	
(Pilati et al., 2021)	√		√
(L. Wang et al., 2022)		√	
(Defraeye et al., 2019)	√		
(Burgos & Ivanov, 2021)		√	
(Leung et al., 2022)	√		√
(Moder et al., 2020)		√	
(Hofmann & Branding, 2019)		√	
(Santos et al., 2020)		√	
(Madni et al., 2019)		√	
(Melesse et al., 2022)		√	
(Shoji et al., 2022)		√	
(Ivanov, 2020)		√	√
(Binsfeld & Gerlach, 2022)		√	
(Ivanov & Dolgui, 2022)		√	√
(Maheshwari & Kamble, 2022a)		√	
(Park et al., 2020)		√	
(Ashraf et al., 2022)		√	√
(Busse et al., 2021)		√	
(Badakhshan et al., 2022)		√	√

Developing digital twins involves utilizing a combination of software tools and technologies to create virtual replicas of physical entities or systems. Different tools have been employed by the authors of the selected papers. AnyLogistix/Anylogic were the most popular and widely used multi-method simulation software within the academic society. This software allows users to model and simulate complex systems across various domains, including manufacturing, logistics, supply chain, healthcare, transportation, and more. It is known for its flexibility, powerful capabilities, and ease of use, making it suitable for both beginners and advanced simulation professionals. Some authors opted for Python with the SimPy library as an excellent choice for simulating digital twins models. SimPy is a discrete-event simulation library that allows the modeling and simulation of complex systems using events, processes, and resources. The R programming language was deployed by a couple of papers to model and analyze certain aspects of digital twin. R is a versatile language known for its statistical analysis capabilities, data manipulation, and visualization, which can be beneficial in specific aspects of digital twin projects. Other powerful simulation tools were used including COMSOL Multiphysics and Vensim.

9. Conclusion and Discussion

Based on a systematic literature review, we offered a comprehensive overview of the applications of digital twins in supply chain management by identifying and analyzing diverse frameworks and use cases from the literature.

Through the analysis of 31 articles, we demonstrated that digital twins offer many capabilities to the supply chain. First, the ability to simulate and analyze supply chain operations in a virtual environment empowers decision-makers to make informed choices, optimize resources, and identify potential risks or bottlenecks. Second, digital twins enable the seamless exchange of data and insights, fostering collaboration and transparency among supply chain partners. Third, integrating real-time data from various sources and enabling predictive capabilities. By leveraging this technology, organizations can optimize their procurement processes, streamline logistics operations, improve quality and traceability, and enhance customer service.

Looking ahead, the future perspectives of digital twins in supply chain management are promising. As organizations continue to invest in digital twin technology and refine their strategies, it's clear that these virtual representations of the supply chain will play an increasingly vital role in the future of supply chain management. Indeed, their potential for driving resilience, sustainability and global performance in supply chain networks. Moreover, technologies such as advanced analytics, internet of things, and machine learning techniques will further enhance the decision-making capabilities of digital twins, enabling intelligent and autonomous SCDTs. Although, digital twins also come with challenges related to data accuracy, implementation costs, and the need for change management.

This paper has limitations as the literature search was limited to Web of Science and Scopus databases with defined keywords. Even though additional use cases that could not be found with the used search engines and keywords may exist. Furthermore, use cases may exist that have not yet been published in scientific papers or reported by companies.

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