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The role of digital twins in lean supply chain management: review and research directions

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ABSTRACT

Digital twins in Industry 4.0 enhance lean supply chains by optimizing efficiency, reducing costs, and ensuring responsiveness to consumers. However, their relationship with lean supply chains remains understudied. We address this gap through a systematic literature review, analyzing 33 selected papers from 759 articles. Utilizing the supply-chain operations reference (SCOR) framework, we assess digital twins' impact on supply chain processes and performances. Our findings indicate that digital twins are primarily used in plan, make, and delivery processes, with limited exploration in source and return processes. They enhance lean practices by improving information flow, eliminating waste, optimizing logistics, and enabling just-in-time production. However, top management commitment, supplier relationship management, and customer relationship management are understudied areas. We also recognize two additional areas where digital twins contribute: enhancing supply chain coordination, and bolstering supply chain resilience, particularly against disruptions such as COVID-19 and geopolitical events. Additionally, we propose a framework for digital twin-driven smart lean supply chain management and highlight the importance of future research in areas such as supply chain digital twins (SCDT) mapping, convergence, interaction, cognition and service. This study pioneers exploring the motivations, applications, and contributions of digital twins in lean supply chain management.

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(JIT)

SUSTAINABLE DEVELOPMENT GOALS

SDG 12: Responsible
consumption and production

1. Introduction

Efficiently managing the supply chains is crucial for running modern business operations, and the adoption of lean principles plays a key role in driving operational improvement (Jasti and Kodali 2015a). Lean philosophies have been instrumental in increasing efficiency in the manufacturing industry over the past few decades, and the literature suggests that many companies have greatly benefitted from lean manufacturing practices. The lean concepts, initially introduced in Japan by Toyota in the 1950s (Womack, Jones, and Roos 1990) have evolved from manufacturing to cover the entire supply chain. The concept of lean supply chain management became popular from the 1990s when academic studies researched the application of lean principles to the entire supply chain beyond the factory floor. David Levy (Levy 1997) proposed that lean production principles can stabilise supply chains by reducing defects and engineering change orders, helping to mitigate the problems associated with global supply chains, such as longer lead

times, expensive transportation costs, higher inventory levels, and delays in forecasting demands and resolving technical problems.

Lean supply chain management (SCM) aims to minimise waste and maximise supply chain efficiency, and reduce costs of manufacturing and supply by fostering collaboration among companies in the supply chain (Vitasek, Manrodt, and Abbott 2005). It is defined as a set of companies directly linked by upstream and downstream flows of products, services, information, and funds that collaborate to reduce cost and waste by efficiently meeting the needs of the customer (Vitasek, Manrodt, and Abbott 2005). Jasti and Kodali (2015b) critically analyse the existing frameworks in lean supply chain management and provide a conceptual framework with 8 elements (e.g. elimination of waste, continuous improvement) that are integral part of an organisation. Present-day global supply chains are complex and face many challenges such as high inventory costs, poor collaboration between supply chain partners, and complex logistics

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networks. These challenges motivate companies to seek innovative solutions that leverage digital advancements in Industry 4.0 to enhance their supply chain operations. One such concept that holds promise for improving supply chain visibility and performance is the digital twin.

Digital twin, defined as a virtual representation of a physical object, process or system, enables real-time monitoring, analysis, and optimisation of supply chain operations (Tao, Cheng et al., 2018). The digital twin model was first presented by Grieves at a Society of Manufacturing Engineering conference in Michigan in October of 2002 (Grieves 2023). This concept deals with the creation of a virtual counterpart that faithfully represents its physical counterpart in real-time, enabling seamless convergence between the two realms. Over the years, the advancement of various technologies such as data acquisition, management and processing, information and communications, as well as simulation, has transformed the digital twin into a comprehensive concept encompassing digital representations of objects, processes, and systems, which are dynamically updated as their physical counterparts evolve (Jones et al. 2020; Liu, Fang, et al. 2021; Lu et al. 2020). By creating the digital replica of a physical asset or process, organisations can gain intelligence that enables responsiveness of the supply chains (Ivanov and Dolgui 2020). With the Covid-19 pandemic exposing the vulnerabilities of companies with complex supply chains, such as supply and demand fluctuations, unpredictable productivity levels and inventory placement problems, prominent scholars (Burgos and Ivanov 2021; Ivanov 2023; Tozanli and Saénz 2022) argue for the need for digital twins to map supply networks and ensuring visibility to handle such shocks. Seven major elements of a digital twin in the supply chain and operations management with scope, technology, people, organisation, modelling management and task have been identified in a recent study (Ivanov 2024). Moreover, a four-layered digital twin reference architecture has been introduced to structure digital twin perception, interaction, cognition, and application capabilities, which has been successfully adopted in the real-world manufacturing industry to support cost-efficient and scalable digital transformation (Guo et al. 2023).

We use the supply-chain operations reference model (SCOR) framework to assess the application of digital twins within the supply chain processes. The SCOR framework has emerged as a widely used tool to analyse and optimise supply chain processes and performance. SCOR, released by the Supply Chain Council (SCC) in 1996, is the first cross-industry framework that provides a standardised, cross-functional approach to analyse and optimise supply chain processes and performance (Huan, Sheoran, and Wang 2004). SCOR defines a set of

major processes (plan, source, make, deliver, return and enable) aimed at managing materials, information, and financial resources to enhance the performance (reliability, responsiveness, agility, costs, and asset management efficiency) of the supply chain (Lockamy and McCormack 2004). The framework is further decomposed into lower levels (e.g. process categories level, process elements level and improvement tools/activities level) to describe, measure, and evaluate supply chains in support of strategic planning and continuous improvement (Lima-Junior and Carpinetti 2019). Due to its ability to provide a standardised approach to communication, analysis, and optimisation of supply chain processes and performance, SCOR has gained widespread adoption across various industries and organisations of all sizes, including manufacturing, retail, healthcare, and logistics (Zhou et al. 2011). Through the utilisation of SCOR, companies can effectively map out the current state of their supply chain processes, identify areas of inefficiency or waste, and leverage the framework for continuous improvement.

Although lean supply chain management and the SCOR framework are two different approaches to improve supply chain efficiency, in this paper we use them as complementary approaches to explain the applications of digital twins. By using SCOR, we present the definition and standardisation of supply chain processes to make it easier to identify where lean thinking can be applied. For example, in identifying and eliminating non-value-added activities in the processes.

1.1. Theoretical background

This paper draws upon three core concepts derived from existing studies: the SCOR framework, lean supply chain management (Jasti and Kodali 2015b) and the digital twin framework in supply chain management (Guo et al. 2023; Ivanov 2024) as presented in Figure 1. These concepts provide a strong theoretical foundation for understanding the integration and impact of digital twins in lean supply chain management. The intersection of the Venn diagram in Figure 1 indicates our core research area.

While the principles of lean supply chain management have been well-established and the potential benefits of emerging Industry 4.0 technologies such as digital twins in the context of lean SCM are evident, the literature on the specific roles and applications of digital twins is still scarce. To explore this gap, our paper aims to review the existing literature to provide insights into their motivations and applications. To better understand the context and challenges of digital twins for lean SCM, it is crucial

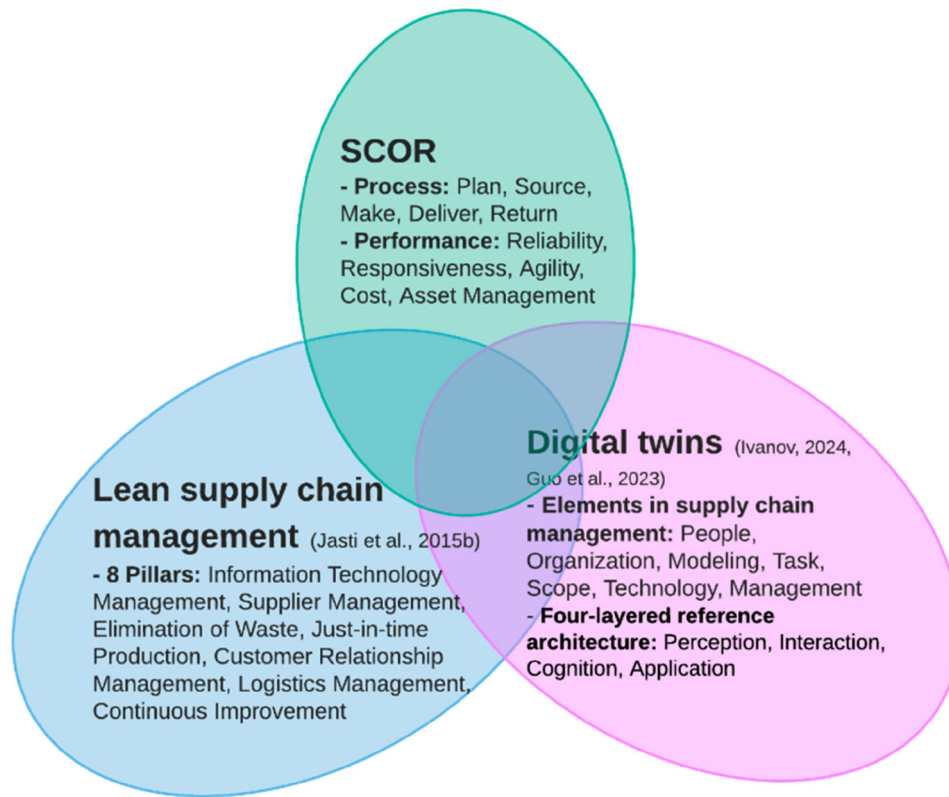


Figure 1. Theoretical background and research scope. Notes: The illustration of theoretical background and research scope of this work.

to first study the applications of digital twins in the supply chains. While there are no recent literature reviews on digital twins for lean supply chain management, the table below summarises key studies in the overall supply chain context.

The recent literature on the role of digital twins in supply chains highlights several issues that motivate the need for a comprehensive literature review on lean supply chain management and the exploration of research directions. While many studies explore exciting concepts of smart supply chain management enabled by digital twins (Bhandal et al. 2022; Ivanov 2024; Wang et al. 2022), their specific roles in the context of lean are underexplored. Other literature streams explore potentials of digital twins in improving the performance and efficiency of supply chains (Guo et al. 2023; van der Valk et al. 2022), but focus on specific use cases without lean practices. Moreover, most of these studies do not explore the digital twin application in SCOR-based supply chain processes and performances. In light of these issues, there is a strong need for a comprehensive study on digital twins within lean supply chain practices to offer guidance for both academics and practitioners in the field to assess the readiness and detailed working of digital twin applications to provide the way forward.

1.2. Problem statement

Despite the transformative potential of digital twins in the context of Industry 4.0 and supply chain management, there are significant gaps in understanding their role and impact on the lean supply chain as mentioned above in Table 1. There are also significant knowledge gaps on how digital twins affect the performance of supply chains based on the SCOR framework and the future research directions in this area are not clear. Considering the limited literature specifically exploring the role of digital twins in lean SCM, this paper aims to answer the following questions:

- RQ 1: What is the current state of the digital twin application in supply chain management?
- RQ 2: What is the role of the digital twin in enhancing lean management and improving the SCOR-based supply chain performance?
- RQ 3: What are the research directions and future research agenda for leveraging the digital twin in lean supply chain management?

Section 2 describes the methodology used for the literature review and Section 3 presents the descriptive analysis of the literature review followed by a thematic

Table 1. Summary of recent literature reviews on digital twins for supply chain management.

Author (s)	Aim of the paper	Challenges identified for lean SCM context
(Wang et al. 2022)	To explore a new concept of digital twin-driven smart supply chains	• New modelling approaches and decision-making patterns to make full use of real-time data and adapt • Digital twin applications in lean practice not covered • The role of the digital twin in SCOR-based supply chain processes and performances not covered
(Bhandal et al. 2022)	To capture the potentials of digital twins for operations and supply chain management	• Need for conceptualisations at a lower level of abstraction to capture mechanisms of interaction between the digital twin and supply chain processes • Digital twin applications in lean practice not covered • The role of the digital twin in SCOR-based supply chain processes and performances not covered
(van der Valk et al. 2022)	To review research on digital twins in supply chains, focusing on use cases and the level of technology readiness	• Digital twins in supply chains are less developed to autonomously control the system compared to the ones in production
(Guo et al. 2023)	To provide a cost-effective and scalable digital transformation approach enabled by digital twins.	• Digital twin applications in lean practice not covered • The role of the digital twin in SCOR-based supply chain performances not covered • Need for digital twin services to facilitate value-adding activities across the product lifecycle
(Ivanov 2024)	To determine which elements belong to research on digital twins in supply chain and operations management.	• Digital twin applications in lean practice not covered • The role of the digital twin in SCOR-based supply chain processes and performances not covered • New interaction/cognition paradigms between a future supply chain and operations manager and the digital twin

analysis in Section 4. Section 5 discusses the findings to answer the research questions of the paper and presents the future research directions while proposing a novel framework for digital twin-enabled lean supply chain management. Finally, conclusions are drawn in Section 6.

2. Methodology

We use a systematic literature review to identify the current state of literature on the role of digital twins for lean supply chain management in the manufacturing industry. In this section, we describe the approach we took to identify the relevant studies and the protocols used and the data extraction process and screening for their eligibility. Our research design followed the widely accepted Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) (Moher et al. 2009) framework to manage various stages of the literature starting from identification of research question, searching, screening, and charting the data and synthesising for findings. The review process was designed to cover studies from both Industry 4.0 as well as operations management field.

2.1. Search strategy

We conducted the search using multiple electronic databases, including Scopus, Web of Science and ABI Inform. We also ran searches on Google Scholar to capture prominent studies in the selected field, while

acknowledging the overlaps with the main databases. The search strategy includes titles and abstracts appropriate to the selected databases. We used search keywords such as ‘digital’, ‘supply chain’, ‘logistics’, ‘value chain’, and ‘twin’ to identify the articles.

2.2. Inclusion & exclusion criteria

Our inclusion criteria selected articles that are peer-reviewed and written in English language. Our Exclusion criteria omitted articles in languages other than English and those less than 8 pages in length. The decision of including papers longer than 8 pages was to ensure quality and depth of the selected studies and to review more substantial contributions on the digital twin applications and evaluations in lean. We noted from previous literature that restricting to only English was a common practice in systematic reviews and the majority of the journals indexed in the databases we considered are in English language, we did not include non-English language studies to avoid any potential translation errors and misinterpretations. We have also excluded articles with digital twin applications other than those in the manufacturing industry. For example, many studies we came across studied the digital twin for construction and mining problems, and they did not meet our inclusion criteria. Our study covers articles from the year 2019–2022 and Table 2 below provides further information on the protocol and the search string.

Table 2. Summary of the search strategy.

Dataset	Quantity	Search strategy	Keywords	Language	Type
Web of Science	424	Topic (search title, abstract, keywords and keywords plus)	(digital twin) AND ((supply chain) OR (logistic) OR (value chain))	English	Peer-reviewed journal and conference articles
Scopus	587				
ABI/INFORM Collection	112				

2.2.1. Extraction and synthesis

Following the PRISMA framework, we created a systematic method to perform our data screening. Figure 2 presents different steps involved in the process.

The different phases of the review process is as follows:

- **Identification phase:** We imported a total of 1123 studies from three databases for screening and removed duplicates ($n = 364$), leaving us with 759 studies for further screening.
- **Screening phase:** We screened articles on the basis of title and abstract and excluded 322 irrelevant papers that did not meet the criteria of digital twin's application for operations management problems. This phase

left us with 427 studies to be screened in the eligibility phase.

- **Eligibility phase:** This phase involved two steps and only selected articles with full text access were deemed eligible. In Step 1, articles that were less than or equal to 8 pages in length ($n = 157$) were excluded. In Step 2, articles not related to the supply chain process or supply chain performance ($n = 237$) were removed. This left a total of 33 studies that met the eligibility criteria and we included them for final analysis.

We followed a four-eye screening process as all the co-authors independently evaluated the eligibility of selected articles to guarantee rigour and consistency. The

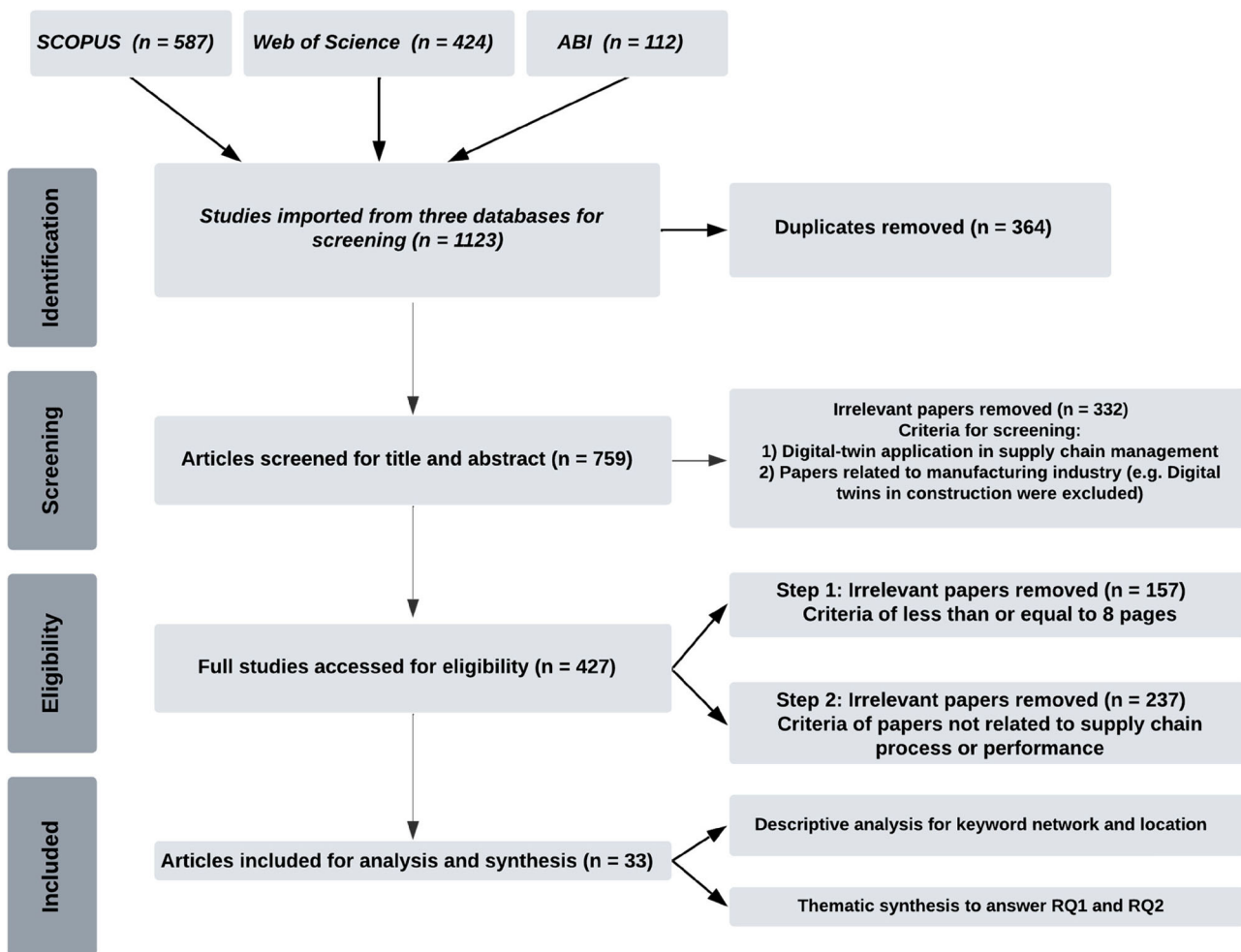


Figure 2. The PRISMA flow diagram. Notes: The illustration of PRISMA flow diagram for the literature review.

data extraction and synthesis process aimed to analyse the findings from the included articles based on two approaches:

- **Descriptive analysis:** A keyword analysis was performed to descriptively analyse the literature. The occurrence of keywords related to the digital twin in supply chain management was examined, providing insights into their frequency and distribution over time. Through this quantitative analysis of systematically counting and tracking the occurrence of keywords in the literature, we could visually present how prevalent and influential certain topics are within the field including the geographies that are active in these areas of research. This approach enables a data-driven understanding of trends and patterns contributing to a comprehensive overview of the field of investigation.
- **Thematic analysis:** Through a qualitative approach to uncover and explore underlying themes, patterns, or categories within a dataset, we have analysed manually each of selected 33 papers and categorised them into distinct groups based on shared characteristics or themes. As an example, all the selected papers were grouped according to their application industry. We used Excel spreadsheets to extract relevant information and presented the findings using tables. Thematic analysis served to derive insights and answering research questions through in-depth exploration of the data.

We used Mendeley to manage the references and synthesised the information from individual articles. PRISMA protocol allowed the systematic reporting of the review process, ensuring that all essential elements were adequately addressed.

3. Descriptive analyses

Figure 3 shows the number of published documents and their citations over years from the Web of Science database. It can be seen that the topic of the digital twin in the supply chain is relatively new with the first document published in 2019. The number of published documents and associated citations has experienced a rapid increase in recent years, indicating a growing attention to this topic.

Figure 4 shows the top fields of the published documents from the Web of Science database. The studies span across a range of research fields, with the top five fields, as per Web of Science categorisation, being engineering manufacturing, engineering industrial, operations research, management science, computer science

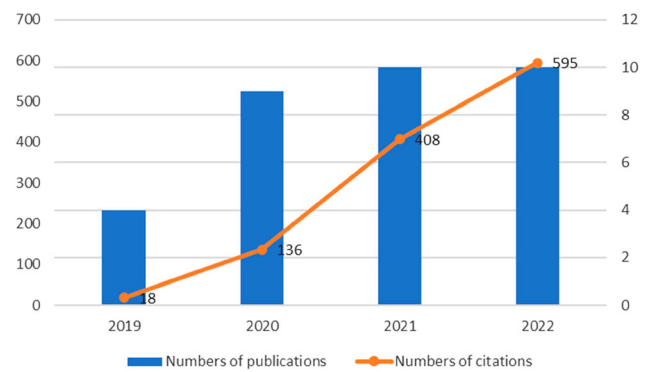


Figure 3. The number of published documents and their citations over years. Notes: The statistical results of published documents and their citations from the year 2019–2022 collected from the Web of Science database.

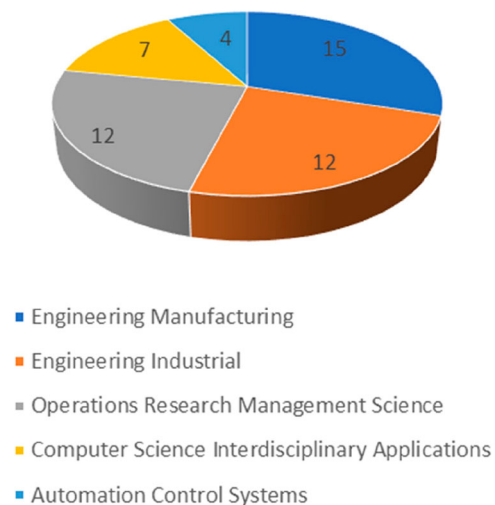


Figure 4. The top fields of the published documents. Notes: The statistical results of the top fields of the published documents from the Web of Science database.

interdisciplinary applications, and automation control systems, with 15, 12, 12, 7 and 4 publications, respectively.

The keywords of the included articles have been collected and are presented as a co-occurrence network as depicted in Figure 5 using VOSviewer software. In the visualisation of the keyword co-occurrence network, a link between two nodes denotes the co-occurrence of the associated keywords, with the thickness of a link is proportional to the number of articles in which the linked keywords co-occur. Additionally, the size of a node corresponds to the number of articles in which the associated keyword occurs. As shown in Figure 5, ‘digital twin’, ‘simulation’ and ‘design’, are the top three frequent keywords, occurring in 22, 12 and 11 articles, respectively.

The descriptive analysis reveals that the topic of digital twins in supply chain management is attracting increasing attention from scholars, with both the number of

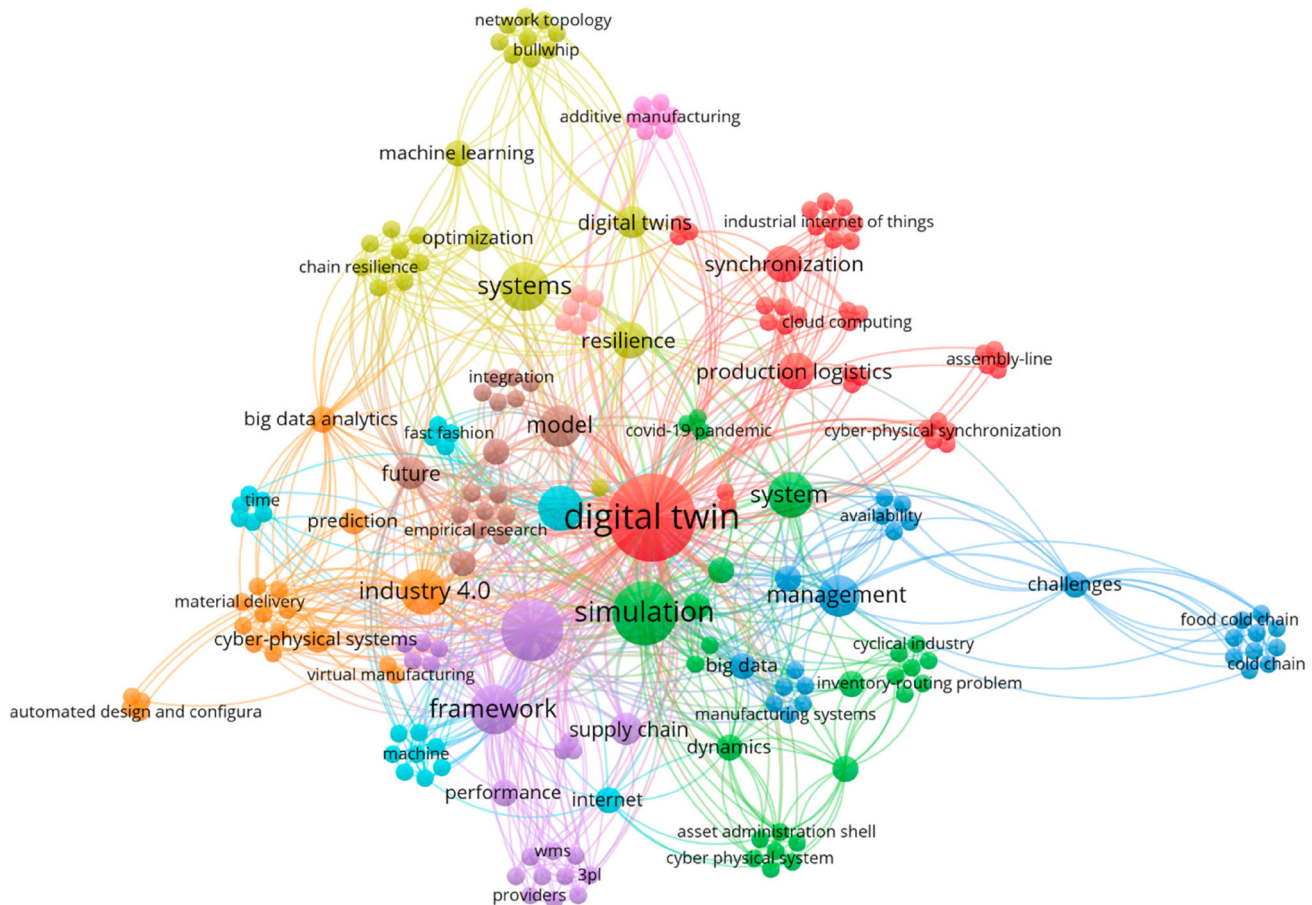


Figure 5. Keyword co-occurrence network of the selected studies. Notes: The visualisation of the keyword co-occurrence network using VOSviewer software.

research studies and associated citations experiencing a rapid increase from 2019. The topic draws interest from cross-disciplinary fields, including engineering, management science, operations research, economics and computer science. The bibliometric analysis indicates that current studies on digital twins in the supply chain are primarily associated with simulation and design.

4. Thematic analyses

4.1. The application of the digital twin in supply chain management: RQ1

With a total of 33 studies that met the eligibility criteria and we included them for the thematic analysis in this section. This section gives a summary of the application of the digital twin in the supply chain regarding the industry sector using SCOR-based major supply chain processes, digital twin application and development degree with 33 selected studies, please refer to Appendix Table A for details. Below, we provide the major summary of Appendix Table A:

- **Industry sector:** According to the Global Industry Classification Standard (GICS), the concept of digital twin related to supply chain management is being exploited in various industries, such as 351020-Health Care Providers & Services (Baruffaldi, Accorsi, and Manzini 2019), 201010-Aerospace & Defense (Mandolla et al. 2019), 201060-Machinery (Guo, Li, Ling et al. 2021; Guo, Zhong et al. 2021; Liu, Cao et al. 2021; Toro, Seif, and Akhtar 2020; Wang et al. 2021; Wang and Wu 2020; Xia et al. 2022; Zhang et al. 2022), 201040-Electrical Equipment (Ciano et al. 2021), 352020-Pharmaceuticals (Marmolejo-Saucedo 2020), 251020-Automobiles (Park, Son, and Noh 2020; Park, Woo, and Choi 2020), 251010-Automobile Components (Wang, Zhang, and Zhong 2020), 151010-Chemicals (Pan et al. 2021; Zhang et al. 2020), 302020-Food Products (Burgos and Ivanov 2021; Shoji et al. 2021), 202010-Commercial Services & Supplies (Kombaya Touckia, Hamani, and Kermad 2022), 252030-Textiles, Apparel & Luxury Goods (dos Santos et al. 2021; Rahmanzadeh, Pishvae, and Govindan 2023; Tang et al. 2022), 301010-Consumer

Staples Distribution & Retail (Wang et al. 2022); 452020-Technology Hardware, Storage & Peripherals (Wu et al. 2022), 201020-Building Products (Zhao et al. 2022).

- **SCOR -based major supply chain processes:** The selected studies were analysed for application of digital twins in the plan, source, make, deliver and return processes across the supply chain. Plan, make and delivery are the three major processes that the digital twin is being used and exploited in the supply chain, which has been reported in 27, 26 and 18 studies. While the application of digital twins in source and return processes is relatively less explored, only one published research has been reported on the implementation of digital twins in return processes.
- **Digital twin application and development degree:** With digital mapping of the physical entity in a digital twin supply chain, the digital twin enhanced supply chain connectivity, optimisation, and collaboration across multi-echelons and multiple stakeholders by combining simulation and optimisation algorithms. In terms of development degree, nearly half have reported successful implementation in an authentic industry setting or have been utilised to address real-world problems through qualitative and quantitative studies. The remaining studies have reported their work as proof-of-concept demonstrations, or have been implemented solely in simulation or laboratory environments.

4.2. The application of the digital twin in enhancing lean management and improving supply chain performance: RQ2

Table 3 provides a comprehensive overview of the application of the digital twin in enhancing lean management and improving supply chain performance from the aspects of major pillars of lean supply chain management (Jasti and Kodali 2015b), SCOR-based supply chain performance metrics (Lockamy and McCormack 2004) and method for 33 selected studies. Below, we provide the details of each column:

- **Major pillars of lean supply chain management:** The analysis of the selected studies presents the application of the digital twin to enhance major pillars of lean supply chain management. Eight pillars include top management commitment, supplier relationship management, customer relationship management, information technology, JIT production, elimination of waste, continuous improvement and logistics management, identified from 30 lean supply chain management frameworks in the literature (Jasti and Kodali 2015b).
- The utilisation of digital twins has been identified as an emerging information technology with significant potential in the realm of supply chain management, as indicated by all 33 papers reviewed. Among these papers, 21 specifically highlight how the integration of digital twin-enabled visibility has contributed to the enhancement of waste elimination within supply chain management practices. Furthermore, the improvement of logistics management through the implementation of digital twins is mentioned in 16 papers, emphasising its efficacy in optimising logistical operations. The pillar of just-in-time (JIT) production is discussed in 7 papers with a particular focus on employing digital twins for facilitating JIT production within supply chains. Additionally, 6 papers emphasise the potential of digital twins in enabling continuous improvement initiatives, thereby promoting ongoing enhancements in supply chain performance. In examining the application of digital twins in supply chain management, attention was also given to three key pillars: top management commitment, supplier relationship management, and customer relationship management. Although relatively limited in number (2, 1, and 2 papers respectively), these studies shed light on the importance of these pillars and their interactions within the context of digital twin applications.
- **SCOR-based supply chain performance improvement:** The analysis of the examined studies reveals significant improvements in SCOR-based supply chain performance metrics, including reliability, responsiveness, agility, cost, and asset management efficiency (Lockamy and McCormack 2004). 20 of the studies highlighted a clear enhancement in asset management efficiency, including improved utilisation of materials, machines, and manpower, which can be attributed to the implementation of digital twins. The second most frequently reported improvement was observed in the domain of reliability, as seen in 12 studies. These studies emphasised improvements in order fulfillment, on-time delivery, and maintaining products in perfect condition. Furthermore, the studies consistently demonstrated that the application of digital twins yielded considerable improvements in responsiveness, as presented in 11 studies. This enhancement included reduced lead time and cycle time, contributing to a more agile and responsive supply chain. Additionally, the positive impact of digital twins on agility, including factors such as adaptability, resilience, and risk management, was underscored by 8 studies. The potential for cost optimisation through the utilisation of digital twins was acknowledged in 6 studies, highlighting the benefits of enhanced cost management

Table 3. The overview of the application of the digital twin in enhancing lean practices and improving supply chain performance.

Reference	Major pillars of lean supply chain management (Jasti and Kodali 2015b)								Performance improvement					Method	
	Top management commitment	Supplier relationship management	Customer relationship management	Information technology	JIT production	Elimination of waste	Continuous improvement	Logistics management	Reliability	Responsiveness	Agility	Cost	Asset management efficiency	Simulation	Optimisation
Baruffaldi, Accorsi, and Manzini 2019				✓				✓					✓	✓	
Cavalcante et al. 2019		✓		✓				✓	✓		✓			✓	✓
Mandolla et al. 2019				✓			✓		✓	✓		✓		✓	
Toro, Seif, and Akhtar 2020				✓									✓	✓	
Ciano et al. 2020	✓			✓										✓	✓ ...
Ivanov and Dolgui 2020				✓							✓			✓	
Marmolejo-Saucedo 2020				✓										✓	
Pan et al. 2020				✓				✓	✓	✓			✓	✓	✓
Park, Woo, and Choi 2020				✓		✓		✓					✓	✓	
Park, Son, and Noh 2020				✓		✓		✓	✓	✓		✓	✓	✓	
Wang and Wu 2020				✓		✓		✓						✓	✓
Wang, Zhang, and Zhong 2020				✓		✓		✓					✓	✓	✓
Zhang et al. 2020				✓		✓		✓			✓		✓	✓	
Bai, You, and Lee 2021				✓		✓							✓	✓	
Burgos and Ivanov 2021				✓	✓	✓			✓	✓		✓	✓	✓	
dos Santos et al. 2021				✓		✓				✓			✓	✓	
Guo, Li, Ling et al. 2021				✓	✓	✓		✓	✓	✓			✓	✓	✓
Guo, Zhong et al. 2021				✓	✓	✓		✓	✓	✓			✓	✓	✓
Hauge et al. 2021				✓		✓							✓	✓	
Liu, Cao et al. 2021				✓		✓	✓		✓	✓	✓		✓	✓	✓
Pan et al. 2021				✓	✓	✓		✓				✓	✓	✓	
Shoji et al. 2021				✓		✓							✓	✓	
Wang et al. 2021			✓	✓					✓		✓		✓	✓	
Badakhshan and Ball 2022				✓			✓				✓	✓	✓	✓	✓
Kombaya Touckia, Hamani, and Kermad 2022				✓		✓							✓	✓	
Leung, Lee, and Ouyang 2022				✓	✓			✓					✓	✓	✓
Rahmanzadeh, Pishvae, and Govindan 2023				✓		✓		✓				✓	✓	✓	✓
Tang et al. 2022				✓				✓	✓				✓	✓	✓
Wang et al. 2022	✓			✓									✓	✓	
Wu et al. 2022				✓	✓	✓		✓		✓			✓	✓	
Xia et al. 2022				✓		✓	✓		✓				✓	✓	
Zhang et al. 2022				✓		✓						✓	✓	✓	
Zhao et al. 2022				✓			✓						✓	✓	✓

practices associated with lean. Therefore, organisations can identify cost-saving opportunities and optimise their supply chain costs effectively by leveraging the digital twin capabilities.

- **Method:** After careful examination of the 33 studies, we observe a pattern that all of them exhibit a combination of the digital twin and simulation methodologies. However, it is crucial to note that only 13 studies out of this pool explicitly presented the utilisation of both the digital twin and simulation techniques in conjunction with optimisation strategies, with a focus on the application of digital twins for supply chain management. This is not surprising, as the concept of the digital twin was initially treated as an extension of simulation with a high-fidelity digital counterpart in manufacturing and logistics studies (Agalinos et al. 2020; Boschert and Rosen 2016; Glaessgen and Stargel 2012; Schluse and Rossmann 2016). With a higher level of data integration between the physical and digital counterparts, interaction and optimisation can be achieved by combining digital twins with big data, operations research and artificial intelligence techniques (Kritzing et al. 2018; Qi et al. 2021; Rathore et al. 2021).

After careful analysis of the role of the digital twin in lean supply chain management, in addition to boosting the eight pillars in lean supply chain management, the studies also indicate the roles of digital twins in enhancing (1) supply chain integration, coordination, and collaboration (Guo, Zhong et al. 2021; Leung, Lee, and Ouyang 2022; Marmolejo-Saucedo 2020; Pan et al. 2020; Pan et al. 2021; Park, Woo, and Choi 2020; Rahmanzadeh, Pishvaei, and Govindan 2023; Tang et al. 2022; Wang et al. 2022; Xia et al. 2022; Zhang et al. 2020; Zhang et al. 2022), and (2) supply chain flexibility, resilience, and adaptability (Badakhshan and Ball 2022; Burgos and Ivanov 2021; Cavalcante et al. 2019; Guo, Zhong et al. 2021; Kombaya Touckia, Hamani, and Kermad 2022; Marmolejo-Saucedo 2020; Wang et al. 2022). Despite these two pillars not being explicitly explored in the eight pillars framework (Jasti and Kodali 2015b), these topics have received increasing attention in the lean supply chain field in the context of industry 4.0 (Manavalan and Jayakrishna 2019; Núñez-Merino et al. 2020; Qader et al. 2022; Reyes, Mula, and Díaz-Madroño 2023). Particularly, the recent COVID-19 pandemic and geopolitical influences (e.g. US–China tensions and Russia–Ukraine war) threatened supply chains domestically and globally with demand volatility, supply shortages, sourcing limitations, transportation and logistics constraints, and shift to e-commerce, reshaping global supply chain management practices and emphasising the importance of

coordination, collaboration, resilience, and adaptability in preparing for future disruptions (Handfield, Graham, and Burns 2020; Ivanov 2021, 2022; Praharsi et al. 2021; Pujawan and Bah 2022; Remko 2020).

5. Discussion

In this section, we address the research questions posed in this paper and provide a summary of our findings.

5.1. Key findings from the review

5.1.1. RQ1: what is the current state of the digital twin application in supply chain management?

Digital twin applications in supply chain management have been explored across various industry sectors, including pharmaceuticals, health care providers & services, chemicals, machinery, electrical equipment, automobiles, automobile components, food products, commercial services & supplies, textiles, apparel & luxury goods, consumer staples distribution & retail, technology hardware, storage & peripherals, and building products. The concept of the digital twin is being utilised in different supply chain processes based on SCOR framework, with a focus on plan, make, and delivery processes, as reported in numerous studies. However, the application of digital twins in source and return processes has received relatively less exploration, with only a limited number of studies reporting on it. By digitally mapping physical entities, digital twins enhance supply chain connectivity, optimisation, and collaboration among multiple stakeholders and echelons. This enables them to address real-world problems and achieve successful implementation in authentic industry settings in many cases. However, some studies remain at the proof-of-concept stage or have been implemented solely in simulation or laboratory environments.

5.1.2. RQ2: what is the role of the digital twin in enhancing lean management and improving supply chain performance?

The reviewed papers collectively affirm the significance of the digital twin in enhancing lean management and improving supply chain performance. We analysed them through eight major pillars of lean supply chain management, and the digital twin has been found to contribute to all of these pillars. It enables the streamlined flow of information, waste elimination, optimises logistics management, facilitates JIT production, and promotes continuous improvement. Limited but significant studies emphasise the importance of digital twins in

enhancing top management commitment, supplier relationship management, and customer relationship management for lean supply chain management. Besides, the digital twin has been found to go beyond enhancing the recognised eight pillars of lean supply chain management. It also contributes to two additional areas: supply chain integration, coordination, and collaboration, as well as supply chain flexibility, resilience, and adaptability. These aspects have gained attention in the context of Industry 4.0, especially due to disruptions like the COVID-19 pandemic and geopolitical influences (Handfield, Graham, and Burns 2020; Ivanov 2021, 2022; Manavalan and Jayakrishna 2019; Núñez-Merino et al. 2020; Praharsi et al. 2021; Pujawan and Bah 2022; Qader et al. 2022; Remko 2020; Reyes, Mula, and Díaz-Madroñero 2023). The digital twin enables seamless information flow and interaction among supply chain partners while empowering organisations to effectively respond to changes and disruptions in the business environment. Furthermore, the digital twin has been instrumental in improving SCOR-based supply chain performance metrics. It enhances asset management efficiency, reliability, responsiveness, agility, and cost optimisation. By utilising digital twins, organisations can improve their utilisation of resources, fulfil orders on time, reduce lead time, and manage risks more effectively.

5.2. Future research directions

5.2.1. RQ3: what are the research directions and future research agenda for leveraging the digital twin in lean supply chain management?

The findings of this review have important implications for future research. Despite the extensive discussion on digital twin applications in supply chain management across various industries, there is still no unified understanding of the composition and subsequent usage of digital twins for lean supply chain management. Recently, prominent scholars have identified seven major elements of a digital twin in the supply chain and operations management: scope, technology, people, organisation, modelling, management, and task, which provides a conceptual framework for further structuring the knowledge on the utilisation of digital twins in supply chain management (Ivanov 2024). Moreover, a four-layered digital twin reference architecture has been introduced to structure digital twin perception, interaction, cognition, and application capabilities, which has been successfully adopted in the real-world manufacturing industry to support cost-efficient and scalable digital transformation (Guo et al. 2023). These works lay the groundwork by providing both a theoretical foundation and practical guidance for leveraging the potential of digital twins

within the context of lean supply chain management in the future. Building upon the seven-element supply chain and operations management (SCOM) digital twin framework and the four-layered digital twin reference architecture outlined in recent literature (Guo et al. 2023; Ivanov 2024), as illustrated in Figure 6, this section introduces an open and innovative framework designed for digital twin-driven smart lean supply chain management, by integrating digital twin capabilities into lean supply chain management.

The proposed framework incorporates seven major elements of scope, technology, organisation, people, modelling, management, and task into four layers: the supply chain digital twins (SCDT) mapping & convergence layer, SCDT interaction layer, SCDT cognition layer, and SCDT service layer. Based on the four-layered digital twin reference architecture, the SCDT mapping & convergence layer acts as the technical infrastructure of the framework, focusing on real-time perception and mapping of a physical supply chain into a digital twin while maintaining convergence between them. The SCDT interaction layer supports real-time interaction between the SCDT and its physical counterpart. The SCDT cognition layer acts as the brain of the framework by offering digital twin-driven insights from prescriptive and predictive analytics. The SCDT service layer augments the capabilities of lean task & management for enhancing supply chain performance metrics such as reliability, responsiveness, agility, cost, and asset management efficiency.

Below are the main challenges and opportunities from the aspects of SCDT mapping & convergence, SCDT interaction, SCDT cognition, and SCDT service emerging from this framework:

- SCDT mapping & convergence:** This layer encompasses major elements of scope, technology, organisation, focusing on real-time mapping and convergence between the SCDT and its equivalent physical supply chain, as well as how it innovates business and organisational models. The scope of the supply chain processes covers plan, source, make, deliver, and return from the aspects of the SCOR framework. With the rapid application and integration of emerging technologies, such as the Internet of Things (IoT), data visualisation, big data analytics, cloud computing, 5G, WIFI, blockchain, and many other related technologies, it is possible to build an SCDT that includes a physical supply chain in the real space, a virtual supply chain with appropriate sets of information in the virtual space, and connections of data and information that connect and synchronise them at an appropriate frequency. With static data that maps

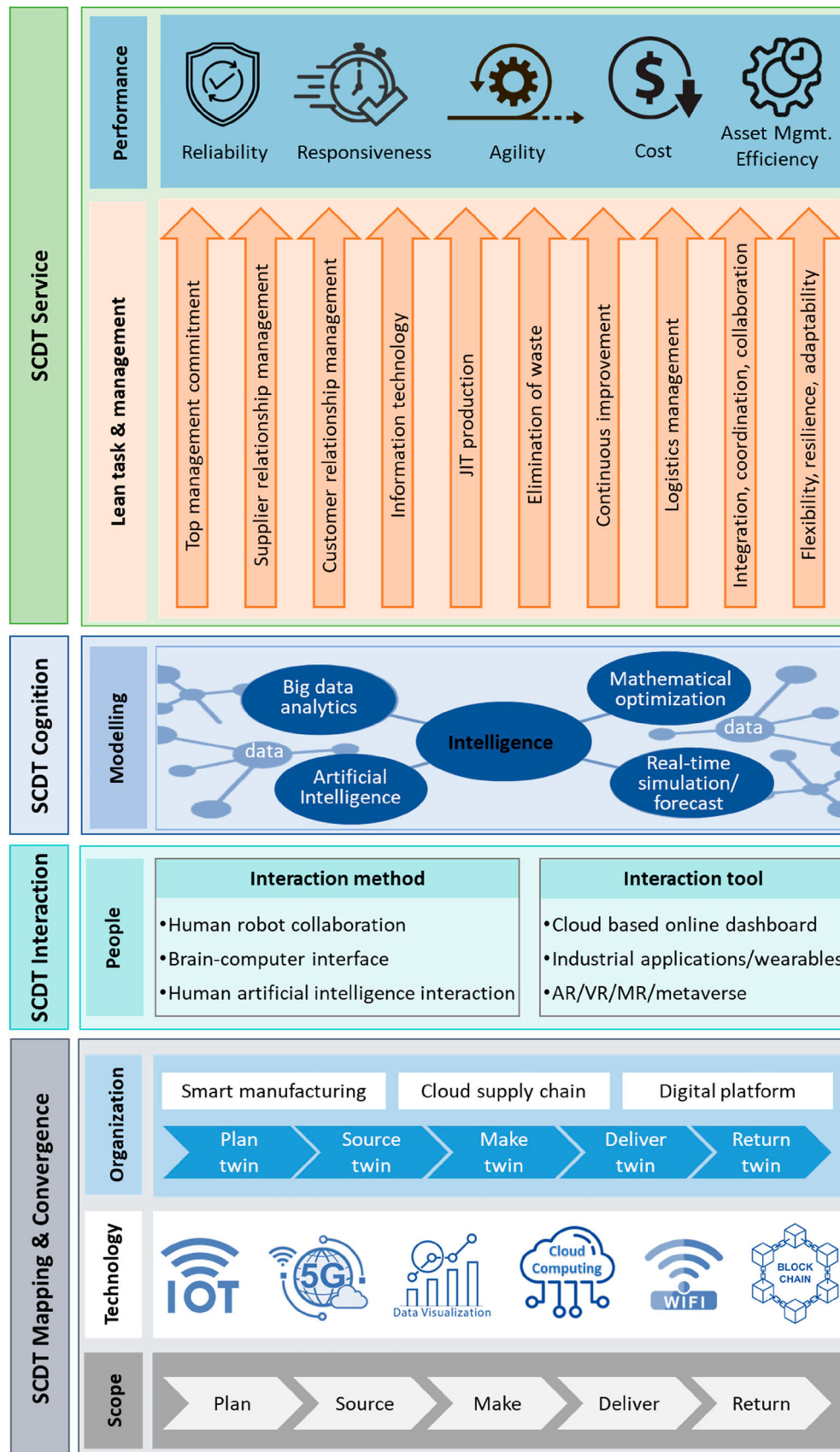


Figure 6. A framework of digital twin-driven smart lean supply chain management (developed on the basis of the four-layered digital twin reference architecture (Guo et al. 2023) and the seven-element digital twin framework (Ivanov 2024)). Notes: A framework of digital twin-driven smart lean supply chain management that incorporates seven major elements of scope, technology, organisation, people, modelling management and task into four layers including the supply chain digital twins (SCDT) mapping & convergence layer, SCDT interaction layer, SCDT cognition layer and SCDT service layer.

the structure and properties of the physical supply chain and real-time dynamic data that synchronise the behaviours, states and processes between physical and digital spaces, real-time mapping and convergence between the SCDT and its equivalent physical supply chain can be achieved (Barykin et al. 2020; Ivanov 2023; Ivanov and Dolgui 2020; Wang et al. 2022). This facilitates the realisation of various conceptual constructs, namely, the plan digital twin, source digital twin, make digital twin, delivery digital twin, and return digital twin, thereby engendering new business and organisational paradigms, such as smart manufacturing (Tao, Qi et al., 2018), cloud supply chain (Ivanov, Dolgui, and Sokolov 2022), and digital platforms (De Reuver, Sørensen, and Basole 2018). However, digital twins in supply chains lag behind their counterparts in production. Important issues related to SCDT mapping & convergence are for example: How to efficiently map a physical supply chain into an appropriate SCDT while maintaining high fidelity? How to achieve interoperability among individual digital twins (e.g. plan, source, make, deliver, and return digital twins) to ensure seamless communication and data exchange? How to ensure convergence and synchronisation between the SCDT and its equivalent physical supply chain at an appropriate frequency? How to effectively handle the legal considerations, security concerns, and privacy issues that arise when multiple stakeholders collaboratively create and use an SCDT?

- **SCDT interaction:** This layer pertains to the interaction between an SCDT within the virtual realm and its corresponding physical supply chain in the real-world domain. SCDTs are developed and used by people, and concurrently, they transform the manner in which supply chain managers and on-site operators engage with related resources and activities with enhanced visibility. This facilitates interaction and collaboration among people, machines, and materials by providing a real-time digital navigation environment. For example, production operations could be organised in an agile, resilient, and cost-efficient manner with spatiotemporal synchronisation of men, machines, and materials by utilising cyber-physical visibility and traceability (Guo et al. 2021). However, this requires innovative interaction methods like human-robot collaboration (Hjorth and Chrysostomou 2022), brain-computer interface (Liu, Wang, and Gao 2024), and human-artificial intelligence interface (Adobor, Awudu, and Norbis 2023). In addition, new interaction tools such as cloud-based dashboards, AR/VR/MR/Metaverse, industrial applications and industrial wearables are needed to enhance real-time

communication, interaction and collaboration (Dolgui and Ivanov 2023; Ivanov, Dolgui, and Sokolov 2022; Queiroz et al. 2023).

- **SCDT cognition:** This layer acts as the brain of the framework by offering digital twin-driven insights from prescriptive and predictive analytics. Real-time mapping and interaction between the SCDT and its physical counterpart provide a transparent and real-time view of supply chain operations, such as order progress, supplier performance, inventory levels, production and logistics monitoring, quality control, and workforce management. By feeding the digital twin-driven historical and real-time data to sophisticated modelling technologies such as big data analytics, artificial intelligence (AI), mathematical optimisation, and real-time simulation and forecasting, stakeholders actively engaged in the supply chain can access and scrutinise contemporaneous information pertaining to their assets, operational processes, and performance metrics (Bhandal et al. 2022; van der Valk et al. 2022; Wang et al. 2022). This empowers stakeholders within the supply chain to make informed decisions, react promptly to dynamic shifts, and enhance processes through the invaluable support of intelligent decision-making. Nonetheless, relying solely on data-driven modelling approaches may inadvertently neglect the qualitative and contextual insights crucial for comprehending intricate supply chain dynamics (Schniederjans, Curado, and Khalajhedayati 2020). In this context, the integration of domain expertise and data-driven insights stands as a pivotal focus for future research in the realm of digital supply chain management (Jahani, Jain, and Ivanov 2023). Additionally, the integration of Generative AI and supply chain management is a promising area that deserves further investigation (Castañé et al. 2023; Jackson, Jesus Saenz, and Ivanov 2024; Wamba et al. 2023).
- **SCDT service:** This layer pertains to the SCDT service, which augments the capabilities of lean task & management for enhancing supply chain performance metrics such as reliability, responsiveness, agility, cost, and asset management efficiency. The introduction of SCDT effectively expands the operational scope from the physical realm into the digital domain with the digital twin-driven insights, which extends two additional pillars: supply chain integration, coordination, and collaboration, as well as supply chain flexibility, resilience, and adaptability identified from reviewing the application of digital twins in supply chain management. Together with the other eight pillars identified in the literature (Jasti and Kodali 2015b), this expansion results in ten pillars of lean supply chain

task and management. Lean supply chain initiatives are essential in the digital era to leverage the capabilities of digital technologies, drive efficiency, enhance agility, and deliver customer value. This has been evidenced even in turbulent times with the Covid-19 pandemic and other recent disruptions (Choi et al. 2023). However, in practice, supply chain-focused lean initiatives are often undertaken without a clear conceptualisation and a systematic thinking process, which results in the variety of lean supply chain management definitions, multiple conceptual frameworks, and an absence of standardised constructs found in the current literature (Cusumano et al. 2021; Jasti and Kodali 2015b). It becomes crucial to have a clear understanding of the concepts underlying digital twins' disruptions and lean supply chain management if we want to offer efficient lean task and management services in the digital era (Cifone et al. 2021; Naranjo, Menor, and Johnson 2023). Future research in lean digital supply chain management should focus on a generic conceptual framework, standardised constructs and methods that integrate systematic lean thinking and emerging technologies to address the evolving needs and complexities of future supply chains.

6. Conclusions

In this paper, we investigated the role of digital twins in lean supply chain management to provide insights into their applications and potential contributions. We performed a systematic literature review and selected 33 papers for final inclusion in descriptive and thematic analysis. Our descriptive analysis shows that the studies of digital twins in supply chain are mainly associated with simulation and design at the current stage, and the topic is attracting cross-disciplinary studies from engineering, management science, operations research, economics and computer science, with the number of research studies and associated citations experiencing a rapid increase since 2019. We explored digital twin applications in supply chain management across various industry sectors. By digitally mapping physical entities, the digital twin enhance supply chain connectivity, optimisation, and collaboration among multiple stakeholders. By utilising digital twins, organisations can improve their utilisation of resources, fulfil orders on time, reduce lead time, and manage risks more effectively. Our analysis revealed that the digital twin has the potential to enhance lean management and improve supply chain performance. Below, we summarise our key findings and contributions:

- Classification of digital twin applications:** Based on the SCOR framework, we classified the digital twin applications into various supply chain processes, including plan, make, delivery, and return. Digital twins are being utilised across all supply chain processes, with a focus on plan, make, and delivery processes, as reported in numerous studies. However, the application of digital twins in source and return processes has received relatively less exploration, with only a limited number of studies reported. We sorted the studies by their application sectors and observed that the machinery industry had the highest prevalence of digital twin applications. Additionally, half of the studies claimed their digital twin applications in real-world settings, while the rest were either proof-of-concept demonstrations or limited to simulations or laboratories.
- Digital twins improve supply chain performance:** Our analysis reveals that the implementation of digital twins has resulted in significant advancements in SCOR-based supply chain performance. The studies highlighted improved asset management efficiency, including improved utilisation of materials, machines, and manpower. Reliability improvements were also observed, particularly in areas such as order fulfillment, on-time delivery, and product preservation. The positive impact of digital twins on responsiveness was evident through reduced lead time and cycle time, contributing to a more agile and responsive supply chain. Additionally, digital twins were found to enhance agility, adaptability, resilience, and risk management. The potential for cost optimisation was acknowledged, with organisations able to identify cost-saving opportunities and optimise their supply chain costs. By leveraging the capabilities of digital twins, organisations can enhance their operational performance and improve customer satisfaction.
- Digital twins enhance lean supply chain management:** Following the widely recognised lean supply chain management framework, the digital twin enables efficient information flow, waste elimination, optimised logistics management, JIT production, and continuous improvement. Notably, limited but significant research emphasises its impact on top management commitment, supplier relationship management, and customer relationship management. Furthermore, the digital twin extends its influence to two additional areas: enhancing supply chain integration, coordination, and collaboration, and bolstering supply chain flexibility and resilience, particularly in response to recent disruptions such as the COVID-19 pandemic and geopolitical influences. These findings underscore the transformative potential of the digital

twin in advancing lean supply chain practices, promoting operational efficiency, and fostering strategic collaboration in a rapidly changing business landscape.

- **Framework and research directions:** We also proposed a digital twin-driven framework to achieve smart lean supply chain management (Figure 6). This framework is built upon the recent seven-element digital twin framework and the four-layered digital twin reference architecture, which serves as a guide to improve supply chain performances of reliability, responsiveness, agility, cost, and asset management efficiency by integrating lean supply chain management and SCDT. Additionally, we outlined future research directions from four research clusters including the SCDT mapping & convergence, SCDT interaction, SCDT cognition and SCDT service.

While we ensured the reliability and inclusivity of our research, our study is constrained by its exclusive reliance on peer-reviewed material sourced from Scopus, Web of Science, and ABI Inform databases. Although these repositories offer extensive and up-to-date scholarly works, it is possible that our review might have overlooked studies published in alternative outlets and industry reports. To address this limitation, future research should consider incorporating non-academic publications and a wider range of academic articles, thereby broadening the scope and depth of the literature review. Additionally, upcoming research will delve into an examination of how various technologies contributing to the digital twin concept can offer advantages to the different stages of the supply chain. Furthermore, the exploration on using the proposed open framework of digital twin-driven smart supply chain management to enhance supply chain viability in the context of disruptions such as the COVID-19 pandemic and geopolitical influences deserves further investigation (Ivanov et al. 2023).

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Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article [and/or] its supplementary materials.

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Appendix

Table A1. The summary of the application of the digital twin in supply chain management.

Reference	Industry application (according to GICS)		Major processes as per SCOR					Digital twin application	Development degree
			Plan	Source	Make	Deliver	Return		
Baruffaldi, Accorsi, and Manzini 2019	351020	Health Care Providers & Services	✓			✓		An original decision-support tool that behaves as a digital twin to improve warehousing operation performance with the support of what-if multi-scenario simulation and optimisation	Medium
Cavalcante et al. 2019	N/A	Not mentioned	✓	✓				Machine learning and simulation can be combined to create digital supply chain twins, and through these twins improve supply chain resilience	Medium
Mandolla et al. 2019	201010	Aerospace & Defense			✓			Reinforces the concept of 'digital twin for additive manufacturing supply chains', which proposes a digital twin for additive manufacturing in the aircraft industry through the exploitation of Blockchain solutions	Low
Toro et al., 2019	201060	Machinery			✓			Create Asset Administrative Shells as digital twins for enhancing connectivity in Mini Factories	Low
Ciano et al. 2020	201040	Electrical Equipment			✓			Share information and simulate different maintenance solutions in a safe condition to forecast future maintenance with digital twin simulation	Low
Ivanov and Dolgui 2020	N/A	Not mentioned	✓	✓	✓	✓		Improve supply chain resilience with digital twin-based visibility as well as model-based and data-driven decision-making	Low
Marmolejo-Saucedo 2020	352020	Pharmaceuticals	✓		✓	✓		Improve on time delivery and reduce lead time by integrating digital twin-enabled real-time information visibility and what-if multi-scenario simulation	High
Pan et al. 2020	N/A	Not mentioned	✓			✓		Improve overall performance (vehicle utilisation, delivery reliability and cost) through a digital twin-driven decision-making information architecture and coordinated control mechanism	Medium
Park, Woo, and Choi 2020	251020	Automobiles	✓		✓			Facilitate factory design, analysis and manage factory performance optimisation with a cloud-based digital twin manufacturing system	High
Park, Son, and Noh 2020	251020	Automobiles	✓		✓			Improve supply chain planning performance by alleviating the bullwhip and ripple effects with the support of digital twin-enabled multi-level information-sharing	High
Wang and Wu 2020	201060	Machinery	✓		✓			Improve production scheduling performance by reducing wasted waiting with the support of real-time synergy between the information and logistics flows enabled by digital twin	High
Wang, Zhang, and Zhong 2020	251010	Automobile Components	✓		✓	✓		Reduce the total nonvalue-added energy consumption of manufacturing resources and optimise the routes of smart trolleys with the support of shop-floor digital twin	High
Zhang et al. 2020	151010	Chemicals	✓		✓	✓		Improve total profit by combining digital twin-based real-time information visibility and opti-state control-based optimal decision-making	High

(continued)

Table A1. Continued

Reference	Industry application (according to GICS)		Major processes as per SCOR					Digital twin application	Development degree
			Plan	Source	Make	Deliver	Return		
Bai, You, and Lee 2021	N/A	Not mentioned	✓		✓	✓		Improve efficiency and accuracy of lean production method with digital twin factory simulation and optimisation	Low
Burgos and Ivanov 2021	302020	Food Products	✓	✓	✓	✓		Improve supply chain resilience and overall performance with digital twin-based end-to-end visibility along with resilient demand, inventory, and capacity management	High
dos Santos et al. 2021	252030	Textiles, Apparel & Luxury Goods	✓					Improve operational efficiency and reduce lead time with a digital twin that was composed of a discrete event simulation model, an artificial Intelligence model, and a decision dashboard	High
Guo, Li, Ling et al. 2021	201060	Machinery	✓		✓			Improve responsiveness and cost-efficiency by reconfiguring production systems with optimal allocating production resources and activities through the integration of digital twin-enabled real-time visibility and reconfiguration mechanism	High
Guo, Zhong et al. 2021	201060	Machinery	✓		✓	✓		Improve overall performance of integrated production and logistics with the support of digital twin-based synchronised information-sharing, decision-making and operations	High
Hauge et al. 2021	N/A	Not mentioned	✓		✓			Improve equipment (e.g. AGV, robot and forklift) utilisation by creating and utilising digital twin-based real-time visibility	Low
Liu, Cao et al. 2021	201060	Machinery			✓			Towards traceability and dynamic control for processing quality with high-fidelity multi-scale and multi-dimensional digital twin simulation	Medium
Pan et al. 2021	151010	Chemicals	✓		✓	✓		Reduce production and warehousing cost by coordinating production and logistics operations with the support of digital twin-enabled real-time monitor, decision and control	High
Shoji et al. 2021	302020	Food Products				✓		Improve product quality and reduce waste through real-time monitoring and simulations with the with the fruit digital twins	High
Wang et al. 2021	201060	Machinery	✓		✓	✓		Incorporation of digital twin into the paradigm of existing data-driven smart customisation will make the process more responsive, adaptable and predictive	Low
Badakhshan and Ball 2022	N/A	Not mentioned	✓		✓	✓		Minimise the impact of the physical and financial disruptions on supply chain performance by using the supply chain digital twin framework that integrates machine learning and simulation to identify the inventory and cash replenishment policies	Medium
Kombaya Touckia, Hamani, and Kermad 2022	202010	Commercial Services & Supplies	✓		✓			Make production more efficient and intelligent with a digital twin design and simulation for reconfigurable manufacturing systems	Low

(continued)

Table A1. Continued

Reference	Industry application (according to GLCS)		Major processes as per SCOR					Digital twin application	Development degree
			Plan	Source	Make	Deliver	Return		
Leung, Lee, and Ouyang 2022	N/A	Not mentioned	✓			✓		Improve delivery performance through coordination of picking-replenishment operations with the support of digital twin enabled real-time information-sharing	Medium
Rahmanzadeh, Pishvaei, and Govindan 2023	252030	Textiles, Apparel & Luxury Goods	✓	✓	✓	✓		Reduce supply chain cost by integrating design and production system with the support of digital twin-enabled information-sharing	Medium
Tang et al. 2022	252030	Textiles, Apparel & Luxury Goods	✓			✓		Improve on-time delivery by integrating demand forecasting, inventory optimisation and digital twin-based real-time information visibility	Medium
Wang et al. 2022	301010	Consumer Staples Distribution & Retail	✓	✓	✓	✓	✓	Enable the supply chain to operate with better performance and higher efficiency based on the concept of digital twin-driven smart supply chain	Low
Wu et al. 2022	452020	Technology Hardware, Storage & Peripherals			✓			Shortening the order lead time and improving the service level with digital twin-enabled real-time tracking and tracing of finished goods logistics	High
Xia et al. 2022	201060	Machinery	✓		✓			Reduce work-in-progress inventory, and advance of delivery time within a digital twin manufacturing ecosystem that includes a factory digital twin, a product digital twin and a supply chain digital twin	High
Zhang et al. 2022	201060	Machinery	✓		✓			Improve efficiency and reduce cost by integrating design, manufacturing, and service based on digital twin	High
Zhao et al. 2022	201020	Building Products	✓		✓	✓		improve resource utilisation of production logistics based on digital twin-enabled dynamic spatial-temporal knowledge graph model	High

Low degree of development: the work primarily focuses on presenting a conceptual framework or a proof-of-concept demonstration without any substantial qualitative results; Medium degree of development: the work primarily focuses on presenting qualitative and quantitative studies that have been implemented in a simulation or a lab environment; High degree of development: the work primarily focuses on presenting qualitative and quantitative studies that have been implemented in a real industry environment. N/A means not applicable.