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RESEARCH

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Digital twins in logistics: a comprehensive bibliometric analysis for advancing smart cities and sustainable development

Andrii Galkin[1,2,3*], Ganna Samchuk[2*], Denys Kopytkov[2] and Russell G. Thompson[3]

*Correspondence:
Andrii Galkin
andrii.galkin@uantwerpen.be
Ganna Samchuk
ganna.samchuk@kname.edu.ua
[1]University of Antwerp, Prinsstraat 13, 2000 Antwerp, Belgium
[2]O. M. Beketov National University of Urban Economy in Kharkiv, 17, Chornoglazivska Street, Kharkiv 61002, Ukraine
[3]The University of Melbourne, Grattan Street, Parkville, VIC 3010, Australia

Abstract

Purpose This study aims to provide a comprehensive analysis of the evolving research landscape of digital twins (DTs) in logistics. It investigates emerging technological and operational trends, examines how DT applications vary across different implementation scales, and assesses the alignment of current research with the United Nations Sustainable Development Goals (SDGs).

Methodology A systematic bibliometric analysis was conducted on a curated dataset of 389 publications from the Scopus database (2017–2025). 2017 is effectively when digital twin research in logistics began to proliferate. The methodology integrates citation analysis, keyword co-occurrence mapping, and thematic clustering to identify the intellectual structure, thematic evolution, and collaborative patterns within the field.

Originality/value This paper's originality is threefold. First, it offers a more robust justification for digitalisation by mapping the complex pressures driving DT adoption. Second, it introduces a novel scale-based taxonomy (object, infrastructure, system) that provides a new framework for classifying and understanding the maturity of DT applications in logistics. Third, unlike previous reviews, it systematically connects the functions and impacts of DTs to specific SDGs, thereby bridging a critical gap between technological innovation and sustainability governance.

Findings The analysis reveals a rapid maturation of the field, with research shifting from a narrow focus on simulation toward broader themes of sustainability, resilience, and AI-driven optimisation. Key findings indicate a significant gap between the conceptual potential of DTs and their practical implementation, particularly concerning system-level integration and data interoperability. While DT applications show a strong conceptual alignment with SDG 9 (Infrastructure), SDG 11 (Sustainable Cities), and SDG 12 (Responsible Consumption), there is a notable lack of empirical evidence and quantifiable metrics to validate their real-world sustainability impacts.

Implications The findings provide strategic insights for managers and policymakers to guide the adoption of DTs for enhanced operational efficiency and sustainability. For academics, this study clarifies the current state of knowledge, highlights critical research gaps, such as the need for quantitative impact assessments and cross-sectoral

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studies, and proposes future research directions focused on developing integrated frameworks for digital sustainability governance in logistics.

Keywords Digital twin, Logistics, Bibliometric analysis, Supply chains, Sustainable development goals (SDG)

1 Introduction

The global logistics sector is undergoing a forced and rapid transformation. Intense pressures from escalating e-commerce, stringent decarbonisation targets, and persistent geopolitical disruptions have rendered traditional operational models inadequate [77, 92]. This complex environment creates a clear mandate for profound digitalisation. The pressure is not only operational but also institutional. Stakeholders, from consumers to investors, now demand greater transparency, resilience, and sustainability. Concurrently, regulatory bodies such as the EU Digital Transport and Logistics Forum and the International Maritime Organization (IMO) are establishing frameworks that require machine-readable, interoperable data across the supply chain. Consequently, logistics firms face an urgent need to re-engineer both their physical assets and information flows, moving beyond incremental IT upgrades toward a more integrated, intelligent infrastructure.

In response to these pressures, the digital twin has emerged as a leading technological paradigm. A digital twin is a virtual construct of a physical system that is dynamically updated with real-world data, enabling sophisticated analysis, prediction, and optimisation [65]. Unlike passive simulations, a digital twin maintains a live, bidirectional link with its physical counterpart, allowing for continuous diagnosis and control [13]. While mature in manufacturing, digital twin applications in logistics are now scaling rapidly. Key use cases include enhancing end-to-end visibility in container tracking [84], optimising warehouse orchestration [34, 52], and improving multimodal routing [53]. These applications promise to deliver the auditable metrics and rapid scenario-testing capabilities required in the modern logistics landscape.

The existing body of literature confirms the significant potential of digital twins. Research highlights numerous benefits, including simulation for risk assessment [79], resource optimisation [2, 98], sustainability and emission reduction [7]. However, the integration of digital twins with other key technologies like the Internet of Things (IoT), Artificial Intelligence (AI), and blockchain introduces significant hurdles. Critical challenges remain in achieving data interoperability, ensuring cybersecurity, and developing scalable infrastructure capable of managing vast and heterogeneous data streams [50, 60].

While earlier reviews concede that Digital Twins could foster sustainability, they usually treat any environmental benefit as a convenient spill-over of process optimisation. We diverge from that techno-centric view by casting the Digital Twin as a purpose-built instrument of sustainability governance and accountability. Its real novelty in logistics lies in its ability to transmute high-level commitments, such as the UN Sustainable Development Goals (SDGs), into auditable, real-time performance metrics. A live, bidirectional data bridge between physical operations and their social-environmental footprints transforms the supply chain from an opaque cost centre into a transparent, evidence-based ecosystem. Consequently, the Digital Twin acts as a digital monitoring tool, enabling companies to transparently show their adherence to sustainability goals rather than merely stating it.

Escalating stakeholder scrutiny and ever finer-grained sustainability regulations mean that marginal efficiency gains are no longer sufficient. Regulators and investors increasingly demand proof of impact at the level of specific SDG targets. DTs supply the missing architecture for that proof. For example, fusing real-time tail-pipe emissions from fleet telematics with adaptive routing algorithms operationalises SDG 11.6 (urban environmental impact) and SDG 12.5 (waste reduction) in one continuous feedback loop. Yet, as our bibliometric scan shows, prior studies seldom map DT functionalities to concrete SDG indicators or examine the governance implications of such mappings. By offering a scale-based taxonomy (object → infrastructure → system) tied to explicit, verifiable SDG metrics, we close that gap and position the DT as a dynamic capability that fuses operational agility with institutional legitimacy, advancing both practice and theory on digital sustainability governance.

This study addresses these gaps through a comprehensive bibliometric analysis of 389 publications. Its contribution is threefold. First, it maps the technological and organisational trends driving digital twin adoption, providing a robust justification for digitalisation in logistics. Second, it proposes a scale-based taxonomy (object, infrastructure, system) to clarify how the benefits and challenges of digital twins evolve with their scope. Third, it connects digital twin research to the SDGs, identifying where empirical evidence is needed most. Accordingly, this investigation is guided by three research questions:

RQ1: What are the emerging trends in logistics digitalisation—specifically technological (e.g., integration with IoT, AI, Blockchain), operational (e.g., real-time process optimisation, inventory control), and sustainability-related trends (e.g., carbon reduction, closed-loop supply chains)—as revealed by the bibliometric analysis?

RQ2: How do the applications and impacts of digital twins vary across different scales in logistics (e.g., object-level, process-level, and system-level)?

RQ3: How can the development and integration of digital twin technologies advance sustainable development in logistics, specifically in alignment with the strategic priorities of the SDGs?

To answer these questions, this study analyses publications retrieved from Scopus in March 2025. By mapping citation networks, co-author collaborations, and keyword clusters, our analysis highlights the intersection of digital twin technology with key logistical objectives. Following this introduction, Sect. 2 outlines the methodology, including the selection criteria and bibliometric techniques employed. Section 3 presents the main results, structured to reflect each RQ. Section 4 discusses the implications of our findings, emphasising gaps in current research and opportunities for interdisciplinary collaboration. Finally, Sect. 5 concludes by summarising key takeaways and suggesting directions for future inquiries into digital twins in logistics.

2 Materials and methods

This section details the methodological approach of the study, including data collection (2.1) and data processing (2.2). These subsections describe stages of the paper selection process and bibliometric analysis techniques to be employed in addressing each RQ.

2.1 Data collection

This study employs a bibliometric analysis framework to systematically examine the research landscape on digital twins in logistics. The methodological approach is designed to address the research questions, ensuring a structured and comprehensive evaluation of trends, scholarly impact, and collaborative structures. By integrating citation analysis, keyword co-occurrence analysis, co-authorship analysis, and thematic clustering, this study enables a nuanced exploration of the intellectual foundations, research evolution, and alignment of digital twin applications with the SDGs.

The data collection process commenced with a comprehensive search in the Scopus database, chosen for its extensive coverage of peer-reviewed literature. A three-stage filtering process was applied to the dataset to ensure methodological robustness. The first stage involved database selection and query design, where data was retrieved from Scopus, focusing on documents published until March 2025. The second stage applied exclusion criteria, eliminating studies that lacked a direct focus on digital twins in logistics or supply chain management. The third stage involved a review and validation of the final dataset, ensuring thematic relevance, methodological soundness, and alignment with the study's research objectives.

In this study, our primary scope is how digital twins function in distribution, warehousing, transport, and broader supply chain contexts for ensuring sustainable development. When searching for scientific articles, we did not include a specific formulation of the Sustainable Development Goals in the keywords. The reason is that a test search with, for example, "Sustainable Development Goals" OR “SDG” significantly narrowed the results. The system initially returned 18 relevant publications, and after applying additional filters, only 7 remained. Such a narrow result could limit the completeness of the analysis.

We focused our content search on the topics of "digital twin", "logistics", and "supply chain" to cover a broader range of studies and effectively address all three research questions, including how digital twin technologies contribute to the implementation of the Sustainable Development Goals, even if these goals are not always explicitly mentioned.

The initial search employed a combination of keywords—*Digital twin*, *Digital Replica*, *Virtual Twin*, *Logistics*, *Supply Chain*, and *Warehousing*—resulting in a preliminary pool of 1068 publications in March 2025. The dataset was refined by applying specific selection criteria. Inclusion criteria focused on subject area, document type, and language to enhance the quality and relevance of the dataset. Specifying the subject area ensures that articles directly match the research topic and avoids unrelated disciplines that may dilute the analysis. Document type is prioritised for peer-reviewed articles and book chapters, which typically offer more rigorous and reliable evidence. Language is also an important factor, as choosing articles in a common language such as English helps maintain consistency, improves interpretability, and allows for accurate analysis and comparison of all sources. At the same time, exclusion criteria helped to eliminate documents that were not relevant to the study objectives. These combined measures ensured that the dataset was both relevant for further analysis.

The database search revealed that the initial articles matching the “digital twin + logistics/supply chain” combination were only published in 2017.The paper selection process is presented in Fig. 1.

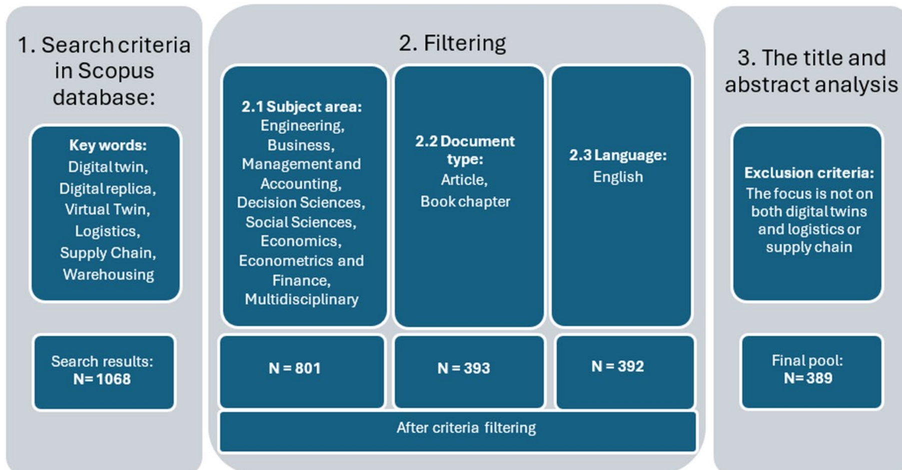

Fig. 1 Paper selection process

After applying these filters, the dataset was narrowed to 392 publications. We have revised titles and abstracts to overcome the shortcomings of keyword search. The final dataset comprises 389 studies, ensuring a robust and focused basis for bibliometric analysis. To provide an answer for RQ3, the final pool of papers was then analysed to reveal a connection between digital twins and logistics through the SDGS.

2.2 Data processing

To systematically analyse the academic landscape on digital twins in logistics, we employed an integrated suite of bibliometric techniques designed to address our three research questions (RQ1, RQ2, and RQ3). Our approach combined citation analysis, VOSviewer-based keyword clustering, and co-authorship network mapping, following preliminary data cleaning and metadata standardisation to ensure a robust dataset.

The selection of these bibliometric techniques is grounded in their capacity to deliver nuanced insights into the evolving landscape of digital twins in logistics. Citation analysis provides a quantitative measure of research influence, which is essential for understanding the boundaries of the field [14]. Co-authorship analysis offers a lens into the collaborative dynamics that drive innovation and identifies gaps where further research is needed [43, 89]. Keyword co-occurrence analysis, on the other hand, uncovers the thematic evolution of the field, providing a forward-looking perspective on where the research is headed [17, 27].

Collectively, these methods enabled a comprehensive exploration of the research landscape, addressing each RQ with a depth of analysis that is both rigorous and informative. The findings from these analyses were instrumental in guiding future research efforts [4, 29], fostering greater collaboration [12], and informing policy and industry practices in the realm of digital twin technology in logistics [88].

For RQ1, which seeks to identify emerging technological, operational, and sustainability trends, we conducted a citation analysis that calculated total, minimum, maximum, and average citations per paper across publication years. This analysis traced the evolution of digital twin research and identified key influential studies. For instance, the work by Ivanov and Dolgui [35] on digital supply chain twin for managing the disruption risks and resilience has been highly influential, setting a foundation for subsequent research [35]. The analysis [66] also revealed how the academic impact of these works has evolved, providing a historical perspective on the development of the field.

Keyword co-occurrence analysis was utilised to address this. This technique involved analysing the frequency and co-occurrence of keywords within the dataset to identify emerging research themes and trends. By categorising papers based on their keywords and assessing the frequency and impact of these categories, the study provided insights into the specific areas within digital twin technology and logistics that are gaining traction. For example, recent studies such as those by Wu et al. [93] on digital twin-enabled spatial–temporal knowledge graphs indicated a growing interest in the integration of the IoT with digital twins. Keyword co-occurrence analysis was performed using VOSviewer. By applying the association strength measure, we clustered keywords into thematic networks that uncovered dominant domains such as real-time monitoring, process optimisation, AI integration, and sustainability. These clusters not only mapped the conceptual structure of digital twin research but also highlighted underexplored areas, such as high-fidelity visualisation and system-level integration, that emerged in our comparative synthesis. The analysis [55] ultimately informed recommendations for future research directions, particularly in areas where the integration of digital twins with other emerging technologies is underrepresented.

Addressing RQ2, which explores the variation in digital twin applications across different logistical scales, the keyword clustering facilitated the categorisation of studies based on their implementation at the object-level, process-level, and system-level. This classification revealed distinct roles and challenges associated with each scale, further emphasizing the gap between academic prototypes and holistic, end-to-end solutions.

For RQ3, which investigates the role of digital twins in advancing sustainable development, we performed a co-authorship and collaboration network analysis. This method mapped global research partnerships and institutional affiliations, shedding light on interdisciplinary and geographic collaboration patterns. Such insights are critical for understanding how digital twin initiatives align with sustainability priorities, including those outlined in the SDG strategic framework.

3 Results

This section presents the findings of the bibliometric analysis, structured to directly address the study's three research questions. The results first identify major research trends (3.1) by examining publication growth, citation impact, and thematic clusters. Subsequently, key technological and operational applications of digital twins in logistics (3.2) are analysed. Finally, the role of digital twins in achieving sustainable logistics (3.3) is explored, assessing their alignment with SDGs.

3.1 Identifying research trends in digital twins for logistics

The study first examines the evolution of research output, citation impact, and dominant thematic areas. The results indicate a clear upward trajectory in digital twin research for logistics, particularly since 2018, with more than 60% of publications appearing in the last two years (2022–2024). Figure 2 provides a detailed breakdown of citation trends by year. The most influential period (2019–2021) coincides with the integration of digital twins in Industry 4.0, predictive analytics, and global logistics optimisation. In 2021, the increasing number of publications about digital twins was noted, which consolidated

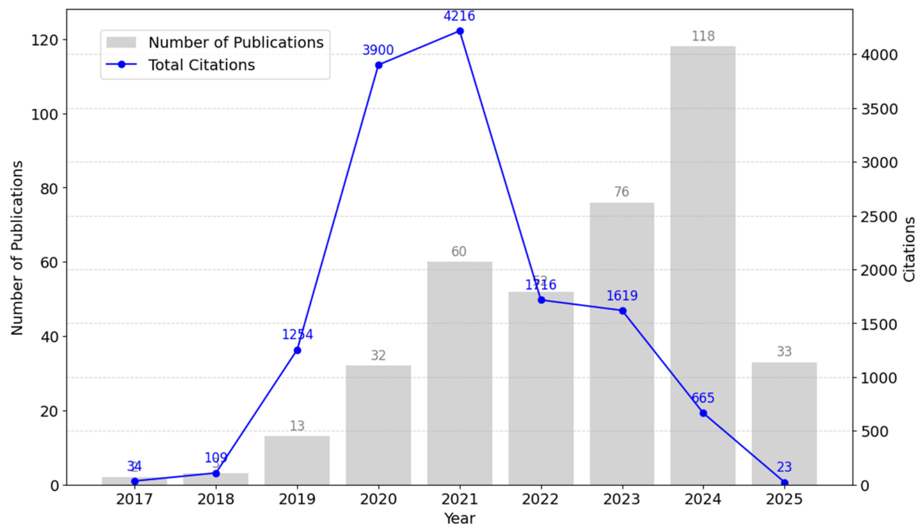

Fig. 2 Citations and publications over the years

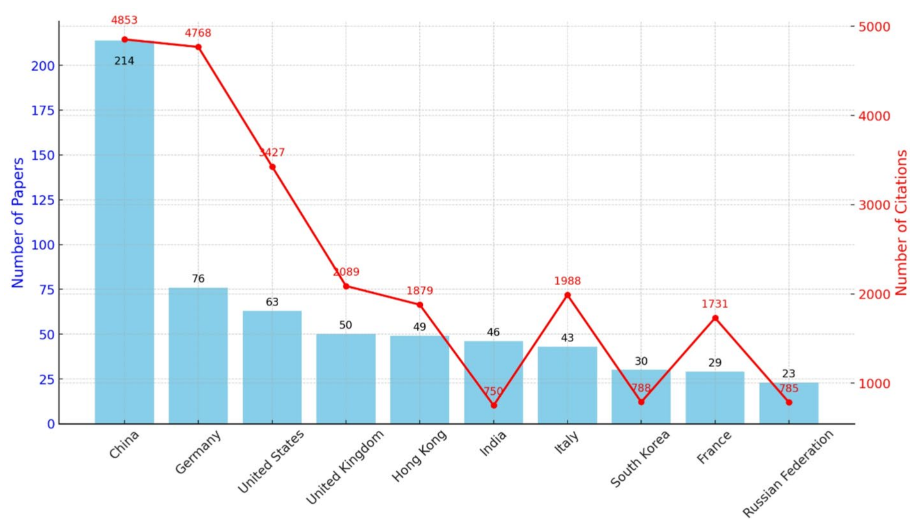

Fig. 3 Publications and citations per country/territory

previous knowledge and stimulated further research at the intersection of digital transformation and logistics. The surge in publications and citations can be attributed to technological and global factors. By then, advances in IoT, cloud computing, and AI made digital twin implementation feasible, while the COVID-19 pandemic highlighted the need for resilient, real-time solutions [15, 35, 69]. More recent papers (2022–2024) show a lower citation count, reflecting the time lag in citation accumulation rather than a decline in research quality or relevance.

The final pool is representatives from 50 countries, but the majority of publications are presented by scholars from China, Germany, the United States, the United Kingdom, Hong Kong, India, and Italy (Fig. 3). However, the underrepresentation of other regions, such as Africa and South America, indicates potential geographical gaps in research focus.

Almost half of the studies are conceptual and contain theoretical material, mainly proposals for conceptual clarification, digital twin architecture, and digital twin framework.

The final pool of papers contains literature reviews and bibliometric analysis, focusing on different aspects of digital twins in the supply chain and logistics. Through a literature review, [33] analysed the potential of digital twin applications in the food supply chain, highlighting their focus on monitoring and prediction. Kajba et al. [39] discussed the implementation of digital twins in logistics for sustainability purposes. In the paper by Yi et al. [94], frontier trends in production logistics are analysed, and a digital twin-enabled synchronised decision-making framework is introduced. The study by Aretoulaki, Ponis, Plakas, and Tzanetou [3] outlines analyses on implementing discrete event simulation and digital twins in warehouse logistics. In addition, an overview of digital twin technology and its usefulness in freight logistics is provided by Sura et al. [82].

Although a growing number of literature reviews have mapped the digital twin landscape in logistics and supply chains (summarised in Table 1), their integration with sustainability frameworks remains limited. For example, Nguyen et al. [66] conducted a systematic review of 518 papers on digital twins and the Physical Internet, offering comprehensive knowledge mapping across multiple platforms (Scopus, Web of Science, EBSCOhost). While their work highlights technological and operational developments, it lacks an explicit analytical framework for assessing how these innovations support SDG-related goals such as emissions reduction or supply chain circularity. Similarly, Lam et al. [53] carried out a large-scale bibliometric study of 2.652 documents from Web of Science and effectively identified publication trends, research clusters, and influential authors. However, the review remains narrowly focused on citation metrics and thematic clustering, offering little insight into the societal or environmental implications of digital twin adoption. Gerlach et al. [30] contribute a conceptual clarification of digital supply chain twins and present various use cases. While insightful from a systems and architecture standpoint, their analysis does not explore how these models contribute to sustainable development or address risks such as carbon emissions or resource inefficiency. Finally, Le and Fan [54] provide a framework that synthesises digital twin research in logistics and supply chains using 48 publications, yet their discussion of sustainability is general and primarily conceptual, without anchoring to specific SDG targets or metrics. Across all four reviews, SDGs are mentioned only peripherally—often as contextual motivation rather than as analytical or evaluative criteria. As a result, these works fall short of capturing the strategic role digital twins could play in advancing SDG 9 (Industry, Innovation, and Infrastructure), SDG 11 (Sustainable Cities and Communities), or

Table 1 Literature review papers on digital twins in supply chains with a general focus

Authors/references	Year	Country	Number of papers	Database	Period	Focus
Nguyen et al. [66]	2022	UK, China	518	Scopus, Web of Science, EBSCOhost	2013–2021	Digital twin and physical internet in supply chain management
Lam et al. [53]	2023	Malaysia	2652	Web of Science	2014–2023	Bibliometric analysis of digital twin in the supply chain
Gerlach et al. [30]	2021	Germany	66	Web of Science, EBCSO, IEEE	2016–2021	Conceptual clarification of digital supply chain twins
Le and Fan [54]	2024	USA	48	Google Scholar, Web of Science	2018–2023 (Jan.–Apr.)	Conceptual framework of digital twins for logistics and supply chain systems

SDG 12 (Responsible Consumption and Production). This paper addresses that gap by critically linking bibliometric insights with SDG alignment, providing a more holistic perspective on how digital twin technologies can support both smart logistics and sustainable development.

For keyword co-occurrence analysis, the words that have close meaning or have different ways of writing were merged to enhance clustering accuracy and improve the reliability of visualisation results, for example, terms such as *supply chain*, *supply chains*, and *supply chain management*. It is noteworthy that keywords with similar meanings, such as *real-time*, *real-time systems*, and *real-time systems,* are frequently used in these studies, with their prevalence growing in recent research. So, we set the minimum number of occurrences of any keyword as 6 (Fig. 4). Of 3174 keywords, 72 meet the threshold. The chosen keywords were automatically divided into six clusters using the method of association strength (Table 2).

As shown in Fig. 4, *digital twin* is the dominant keyword, signifying its central role across multiple domains, including *supply chains, decision-making, logistics*, and *smart manufacturing.* The strong interconnections between digital twin and industry 4.0, artificial intelligence, blockchain, and data analytics indicate its integration with advanced technologies to drive automation, optimisation, and intelligent decision-making. Also, earlier studies (2021–2022) focused more on simulation, artificial intelligence, and optimisation, while recent research vector (2022–2023) has shifted toward *sustainability, resilience,* and *environmental* impact, reflecting an increasing interest in leveraging *digital twins* for *sustainable* and *adaptive supply chain management.* Additionally, emerging trends include *machine learning* and *e-learning*, indicating a growing emphasis on training, simulation, and predictive analytics within *digital twin* applications. The connections between digital twin and visibility, information management, and decision-making reinforce its increasing role in ensuring efficiency, transparency, and automation across industries.

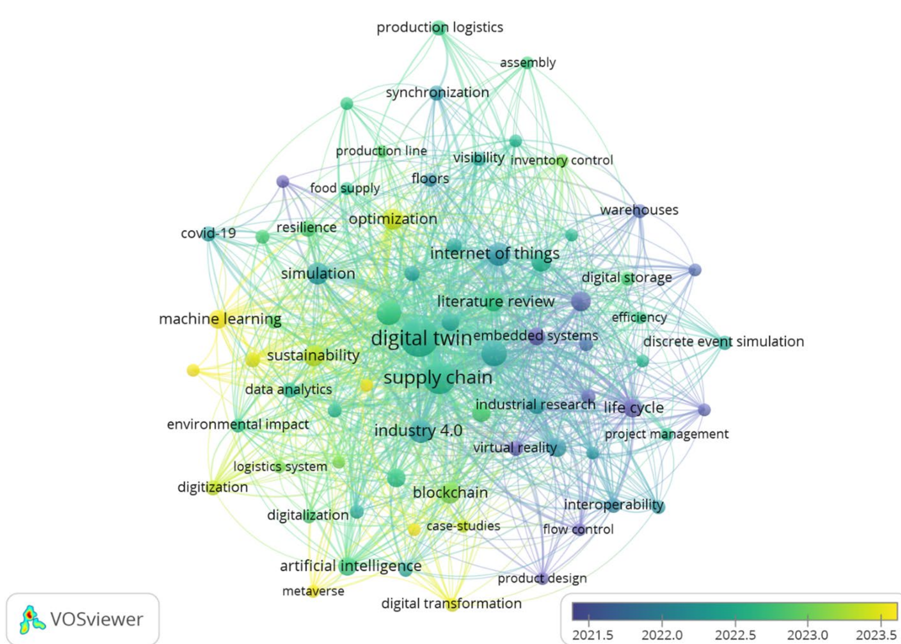

Fig. 4 Keyword co-occurrence

Table 2 Description of clusters

Cluster	General name	Keywords	References
Cluster 1	Data Infrastructure, Interoperability and Visualisation	Big data, Building information modelling, Construction industry, Data visualisation, Design/methodology/approach, Digital storage, Efficiency, Industrial research, Information management, Interoperability, Life cycle, Product design, Project management, Semantics, Sustainable development, Transparency, Virtual reality	Lee and Lee [55], Kümpel et al. [51], Klar et al. [44], Hu et al. [34], Marmolejo-Saucedo et al. [61]
Cluster 2	Cyber-Physical Production Systems and Smart Manufacturing	Assembly, Cloud computing, Cyber physical system, Digital twin, Embedded systems, Floors, Flow control, IoT, Manufacturing, Production control, Production line, Production logistics, Production system, Synchronisation, Visibility	Park et al. [70], Leung et al. [57], Pan et al. [69], Tang et al. [83], Zhao et al. [98], Yi et al. [94]
Cluster 3	Risk, Sustainability and Socioeconomic Impact	Competition, Covid-19, Data analytics, Digitisation, Economic and social effect, Environmental impact, Food supply, Process control, Resilience, Risk assessment, Risk management, Simulation, Supply chain, Sustainability	Singh et al. [80], Burgos and Ivanov [15], Guidani et al. [32], Ivanov and Dolgui [35], Binsfeld and Gerlach [10]
Cluster 4	AI-Driven Industrial Innovation and Learning	Case studies, Deep learning, Digitalisation, E-learning, Industry 4.0, Industry 5.0, Logistics system, Machine learning, Production process, Reinforcement learning	Corsini et al. [21], Zdolsek Draksler et al. [95], Lam et al. [53], Zhan et al. [96]
Cluster 5	Human-Centric Systems and Operational Intelligence	Automation, Discrete event simulation, Human factor, Human-in-loop, Inventory control, Literature review, Optimisation, Real-time systems, Warehouses	Aretoulaki et al. [3], Battini et al. [8], An et al. [2], Nguyen et al. [66], Bányai et al. [7]
Cluster 6	Digital Strategy, Blockchain and Transformation	Artificial intelligence, Blockchain, Decision making, Digital transformation, Logistic operations, Logistics, Metaverse	Le and Fan [54], Sura et al. [82], Rauscher et al. [75], Coelho et al. [19], Greif et al. [31]

Table 2 categorises the research landscape into four key clusters to further explore these thematic connections. Each cluster encapsulates a distinct yet interconnected aspect of digital twin applications, ranging from data-driven sustainability and analytics to cyber-physical systems and smart manufacturing. These classifications provide a clearer view of how digital twins support decision-making, system optimisation, and industrial transformation, shaping the future of logistics and manufacturing.

Data Infrastructure, Interoperability & Visualisation cluster centres around the foundational digital infrastructure necessary for managing, visualising, and integrating large-scale data systems across industrial and construction environments. Topics such as big data, building information modelling, and data visualisation are critical enablers of smarter construction, digital planning, and lifecycle tracking of assets. Emphasis is placed on interoperability and information management, showcasing the growing need for seamless integration between systems and platforms. Virtual reality and semantics introduce immersive and cognitive layers to digital ecosystems, enriching both design and stakeholder communication. The inclusion of project management, product design, and sustainable development indicates a multi-disciplinary approach aimed at optimising performance, reducing waste, and supporting long-term industrial innovation. Researchers in this cluster explore ways to bridge digital design methodologies with operational efficiency and transparent governance [34, 44, 51, 55, 61].

The Cyber-Physical Production Systems & Smart Manufacturing cluster represents the integration of physical and digital realms within the manufacturing sector. It focuses on technologies such as digital twins, cyber-physical systems, and embedded systems, which support intelligent automation and production synchronisation. This research area highlights how IoT and cloud computing facilitate real-time communication between devices and systems, enabling enhanced visibility, predictive maintenance, and automated logistics flows. Studies in this cluster often address production control, floor-level optimisation, and smart assembly, showcasing the role of digital technologies in streamlining operations and reducing waste. The keywords signal a deep interest in applying these tools for high-precision, scalable manufacturing environments, aligning with both Industry 4.0 and Industry 5.0 paradigms. This cluster contributes significantly to the evolution of digitalised production and logistics infrastructure, offering insights into how data-rich, connected systems can drive operational resilience and industrial agility [57, 69, 70, 83, 94, 98].

Risk, Sustainability & Socioeconomic Impact cluster captures the growing emphasis on supply chain resilience, environmental responsibility, and societal impacts in logistics systems. Anchored by themes such as Covid-19, risk management, and sustainability, this research domain examines how digital twin technologies can mitigate disruptions, manage volatility, and support adaptive logistics strategies. Researchers utilise data analytics, simulation, and digitisation to model socio-economic scenarios and evaluate logistics systems' responsiveness under stress. Topics such as food supply and environmental impact reflect an acute awareness of the real-world stakes associated with global supply chain dynamics. This cluster aligns strongly with SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action), advocating for logistics systems that are both efficient and ethically accountable. Scholars argue for multi-level resilience frameworks, from local logistics hubs to global networks, integrating predictive capabilities with socio-environmental foresight [10, 15, 32, 35, 80].

The AI-Driven Industrial Innovation & Learning cluster explores the role of artificial intelligence, machine learning, and deep learning in transforming logistics operations and production processes. Research in this domain emphasises adaptive decision-making, predictive analytics, and reinforcement learning techniques that allow logistics systems to evolve in response to shifting demands and operational conditions. The inclusion of e-learning and digitalisation indicates that workforce education and digital competency are vital for effective AI implementation, bridging human expertise with algorithmic efficiency. Case studies within this cluster illustrate practical applications of AI in production planning, inventory optimisation, and supply chain forecasting. Researchers also investigate the fusion of Industry 4.0 and Industry 5.0, positioning this cluster at the forefront of intelligent, autonomous, and human-integrated industrial ecosystems. The transformative nature of these technologies is reflected in their potential to drive innovation, reduce waste, and enable self-optimising logistics networks [21, 53, 95, 96].

The Human-Centric Systems & Operational Intelligence cluster emphasises the interface between human agents and digital logistics systems, advocating for collaborative models that blend automation with human oversight. Topics such as human-in-loop systems, discrete event simulation, and real-time systems reflect an operational focus on enhancing workflow efficiency while maintaining adaptability and safety. Researchers leverage literature reviews, inventory control models, and warehouse simulations to refine decision-making processes, improve ergonomics, and align operations with human capacities. This cluster underscores the importance of maintaining cognitive trust, user-centred design, and operational transparency in logistics automation. It contributes to designing responsive and ethical logistics systems that respect human variability while enhancing system intelligence and responsiveness. This research is vital for achieving operational excellence in logistics networks without compromising human well-being and organisational adaptability [2, 3, 7, 8, 66].

The Digital Strategy, Blockchain & Transformation cluster focuses on strategic enablers of digital transformation in logistics, particularly through the deployment of blockchain, AI-driven decision support, and metaverse-based simulation environments. The cluster investigates how digital technologies can provide secure, transparent, and traceable logistics operations, overcoming issues of trust, data silos, and fraud. Digital transformation is conceptualized here as a holistic reconfiguration of business models and supply chain interactions, not merely a technology upgrade. Blockchain integration supports decentralised information flows and audit trails, while AI systems facilitate dynamic scenario modelling and strategic decision-making. The inclusion of logistics operations and decision-making frameworks reveals a shift from operational tools to strategic assets, enabling firms to predict disruptions, manage uncertainty, and align logistics activities with long-term goals. This cluster contributes to the theoretical framing of logistics as a system of interconnected, intelligent, and secure processes, capable of autonomous operation and high-level adaptability [19, 31, 54, 75, 82].

The application of digital twins in smart cities presents significant opportunities for enhancing urban infrastructure, sustainability, and decision-making [16]. Digitalisation and smart technologies are essential for enhancing the sustainability of modern cities [28, 41]. As cities evolve into more complex, data-driven environments, the integration of digital twins with urban systems can provide a multitude of benefits across various domains. Diaz-Sarachaga [25] focuses on Urban Digital Twins (UDTs) and their role in urban planning and governance and develops an assessment framework for evaluating governance in smart cities through UDTs. The paper by Diaz-Sarachaga [24] examines the role of UDTs in achieving sustainable urban development goals, specifically within Spain's New Urban Agenda.

Digital twins enable real-time monitoring, predictive analytics, and simulation-based optimizations, allowing city planners and policymakers to manage traffic flows, energy consumption, and urban logistics more efficiently [9, 18, 20, 23, 44, 45, 47, 56, 58, 59, 68, 71, 73, 78, 81, 90]. For instance, Cognitive Digital Twins (CDTs) improve freight parking management in last-mile delivery, optimising urban resource allocation and logistics efficiency through enhanced semantic capabilities [59]. In ports, digital twins serve as interoperable platforms, breaking physical boundaries and enabling the joint optimization of city, port, and supply chain operations to improve energy use and operational efficiency [44, 45]. Additionally, digital twins support city logistics and urban hubs by balancing energy supply and demand, integrating renewable sources, and reducing emissions [9, 16, 18, 57, 58, 81, 90].

However, despite their transformative potential, digital twins were not explicitly clustered in the analysis, likely due to limited keyword recall and fragmented research across these diverse urban applications.

3.2 Digital twin scale analyses

To address RQ2, this section dissects digital twins across three scales, object-level, infrastructure-level, and system-level, each driving logistics efficiency, resilience, and strategic decision-making. Figure 5 categorises these levels, while Table 3 outlines their benefits, challenges, and real-world applications.

Complexity increases as digital twins scale from individual assets to interconnected logistics ecosystems. Object- and infrastructure-level twins are widely deployed, optimising operations, but system-level twins remain underutilised due to integration bottlenecks and unquantified sustainability potential:

I. Object-Level Digital Twins. At the object level, digital twins represent specific assets or items, such as machinery or individual goods. For instance, Maersk employs digital twins to individual shipping containers, tracking their location, temperature, and humidity to ensure the safe transport of perishable goods, particularly in cold chain logistics [84]. These object-level applications demonstrate the utility of digital twins in maintaining the quality and integrity of high-value goods.

II. Infrastructure-Level Digital Twins. Process-level digital twins focus on optimising specific workflows or operational processes. A notable example is DHL, which uses digital twins to simulate warehouse operations, including inventory control, order picking, and packing [52]. By modelling these processes, DHL has optimised warehouse layouts and improved efficiency, reducing costs and order processing times. Another example is Siemens' use of digital twins in manufacturing processes to simulate production lines and identify bottlenecks, ensuring efficient resource utilisation [42].

III. System-Level Digital Twins. At the system level, digital twins simulate complex ecosystems involving multiple interconnected processes and entities. For instance, Singapore has developed a city-wide digital twin called "Virtual Singapore", which models the entire urban environment to support infrastructure planning, disaster management, and traffic optimisation [76]. In logistics, UPS (via its ORION software) reportedly saves 10 million gallons of fuel annually, reducing about 100,000 metric tons of CO_2 through AI-driven route optimisation and digital twin–based visibility [87]. Meanwhile, Maersk leverages container-level digital twins to monitor temperature and humidity, cutting product spoilage by 15–20% in cold chain logistics [84]. In warehouse operations, DHL's digital twin simulations sometimes yield 10–15% throughput increases and up to 20% faster order processing [52].

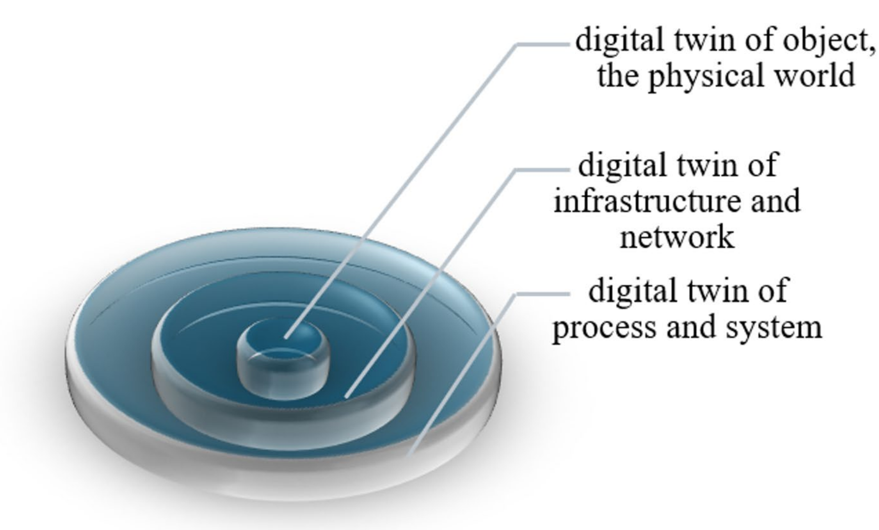

Fig. 5 Categorisation of digital twins according to scale

Table 3 Digital twin scale analyses

Level	Benefits	Challenges	Scale	Examples	References
Highest level or System-Level digital twins	End-to-end visibility of the supply chain	High complexity in building and managing system-wide models with interconnected components	Digital twin of process and system	Smart cities	Liu et al. [59], Klar et al. [45], Klar et al. [44]
	Strategic decision-making through scenario simulation (e.g., disaster preparedness, demand-surge management)	Scalability issues when handling large datasets from multiple sources		Supply chain and logistics	Sura et al. [82], Coelho et al. [19], Zdolsek Draksler et al. [95], Pan et al. [69], Tasche et al. [85], Binsfeld and Gerlach [10], Marmolejo-Saucedo et al. [61]
	Increased operational efficiency by optimizing transportation routes and reducing congestion (e.g., ports, global logistics)	Dependence on accurate and timely data from diverse sources (e.g., weather, traffic, supplier systems)			
	Enhanced sustainability by reducing waste, emissions, and energy consumption	Ethical concerns, including data privacy and ownership across global networks		System, service platform	An et al. [2], Borangiu and Răileanu [11], Jiang et al. [37], Nicoletti and Appolloni [67], Tufano [86], Miao and Lan [62], Krajcovic et al. [48]
Middle level or Infrastructure-Level digital twins	Optimization of specific workflows (e.g., inventory management, warehousing)	Integration of digital twins with legacy systems and software	Digital twin of network	Temporal graph network, logistics network	Zheng et al. [99]
	Improved productivity through simulation of scenarios (e.g., peak demand forecasting)	Resistance to adopting new technologies by operational staff			
	Reduction in lead times and operational costs (e.g., robotic operations in warehouses)	Cybersecurity risks due to increased reliance on IoT devices	Digital twin of infrastructure	Factory, plants	Rauscher et al. [75], Qiu et al. [74]
	Enhanced predictive maintenance, reducing equipment downtime	Limited expertise in developing and maintaining process-specific digital twins		Warehouses	Hu et al. [34], Petković et al. [72]
Low level or Object-Level digital twins	Real-time monitoring of individual assets	High initial investment in sensors and IoT devices for each item	Digital twin of objects, the physical world	Workshop, assembly work centre	Wu et al. [91], Park et al. [70]
	Improved quality control (e.g., temperature-sensitive goods)	Data overload from tracking numerous individual items			
	Early detection of anomalies, reducing losses	Ensuring consistent and accurate calibration of devices		Material flow, tags, gateways, trolleys assets, products, bulk silos	Wu et al. [93], Zhan et al. [96], Bányai et al. [7], Baalsrud Hauge et al. [5], Greif et al. [31], Jeschke and Grassmann [36], Knapp et al. [46]
	Enhanced customer trust through traceability (e.g., pharmaceuticals, food supply)	Complex logistics for integrating IoT with existing systems			

These examples underscore the transformative potential of digital twins across scales, from monitoring individual assets to optimising entire ecosystems. By contextualising these applications, stakeholders can better understand the scalability and versatility of digital twins in logistics and beyond.

Table 4 Digital twin contribution to SDG

Aspect	References	Key Statistics
SDG 9: Industry, innovation, and infrastructure	Lam et al. [53], Zhang et al. [97], Nasir et al. [64], Singh et al. [80], Klar et al. [44], Tao et al. [84], Montreuil [63]	Focus on the integration of advanced technologies (IoT, artificial intelligence, blockchain) for sustainable industrial practices
SDG 11: Sustainable cities and communities	Leung et al. [57], Badakhshan and Ball [6], Caprari et al. [18], Schrotter and Hürzeler [76]	Emphasises the reduction of congestion and carbon emissions in urban logistics
SDG 12: Responsible consumption and production	Nguyen et al. [66], Nasir et al. [64], Singh et al. [80], Kuo and Choi [52]	Highlights the optimisation of resources and the reduction of environmental footprint in supply chains

3.3 Digital twin development and its role in sustainable logistics

RQ3 requires a focused examination of how digital twins contribute to sustainable logistics, specifically through their alignment with the strategic priorities. While digital twins are often positioned as enablers of operational efficiency, their role in achieving sustainability objectives remains underexplored. The bibliometric analysis reveals some examples of conceptual links between digital twins and SDG 9, SDG 11, and SDG 12. However, the extent of their practical impact on emissions reduction, resource efficiency, and supply chain resilience remains uncertain. Table 4 summarises these connections, highlighting how digital twins align with key sustainability initiatives.

The application of digital twins to industrial infrastructure and logistics suggests alignment with SDG 9. Studies [53] highlight their role in integrating IoT, AI, and blockchain, enabling logistics providers to enhance efficiency while minimising externalities. Research shows how digital twins facilitate real-time monitoring, predictive analytics, and decision-making, reducing production and transport network inefficiencies [97]. For instance, Siemens has developed digital twin platforms to optimise factory layouts, resource usage, and energy consumption [22, 63]. At the same time, Maersk uses digital twins to monitor shipping containers in real-time, improving handling processes and minimising spoilage in cold chain logistics [84]. Despite these advances, quantitative data on the overall reduction of emissions and energy consumption remains scarce, underscoring the need for more empirical research.

At the urban level, the connection to SDG 11 focuses on reducing congestion and optimising logistics flows. Digital twins enable real-time modelling of traffic management, freight distribution, and multimodal transport integration, which has the potential to lower carbon emissions [6, 18]. In line with the Physical Internet paradigm [57], some cities aim for seamlessly connected transport systems that dynamically reroute shipments for maximum efficiency. "Virtual Singapore," a large-scale digital twin project, optimises traffic flow, monitors energy consumption, and supports disaster preparedness through data-driven urban planning [76]. Although these initiatives hold promise, there is limited empirical evidence of large-scale emissions reductions, reflecting a persistent gap between concept and widespread implementation.

The relationship with SDG 12 is grounded in resource optimisation within supply chains, where digital twins enhance inventory management, minimise overproduction, and reduce waste. Studies emphasise that digital twins enable lean logistics by optimising material flow and curbing excess stock [64, 66, 80]. DHL has piloted warehouse digital twins that streamline receiving, picking, and packing processes, significantly reducing operational waste and overproduction [52]. While localised applications demonstrate tangible gains, the broader implications for circular economy models remain underexplored. Current research tends to focus on incremental efficiency improvements rather than transformative changes in production and consumption patterns.

Although digital twins align with sustainability goals, such as zero-emission logistics and resilient supply chains, robust, large-scale evidence of their impact remains limited [35, 57]. The Port of Rotterdam provides a noteworthy example, deploying a digital twin to optimize multimodal freight flows, reduce congestion, and curb emissions through AI-driven route adjustments [1]. Similarly, Amazon employs digital twin modelling across its fulfilment network to manage warehouse operations and transportation routes in real-time, improving overall efficiency while cutting down on waste [38]. Despite these successes, comprehensive data-driven assessments of long-term emissions reductions and energy savings are still rare, highlighting the need for ongoing investigation into the true sustainability potential of digital twins.

4 Discussion

This section synthesises the results by contextualising them within existing research on digital twins in logistics, ensuring a critical evaluation of their significance. The discussion is structured around the responses to the three research questions, emphasising how this study expands the understanding of emerging trends in sustainability and SDG impact, while also advancing the conceptualisation of digital twin scales and their broader ecosystem applications.

4.1 Research trends in digital twins for logistics (RQ1)

The bibliometric analysis in Sect. 3.1 reveals a rapidly maturing research landscape around digital twins in logistics, characterised by increasing thematic diversification and methodological depth. Three major patterns emerge: the elevation of digital infrastructure and interoperability as standalone research domains; the mainstreaming of sustainability and resilience as core priorities; and the convergence of artificial intelligence, human–machine interaction, and adaptive decision-making in digital twin innovation.

Digital infrastructure and interoperability have evolved from enabling tools to foundational pillars in digital twin ecosystems. Clusters associated with big data, BIM, visualisation, and semantic integration indicate that successful digital twin deployment relies not only on modelling accuracy but also on robust data governance and cross-platform connectivity [34, 55, 61]. This shift suggests a conceptual evolution—from digital twins as static digital replicas to dynamic, interconnected decision-support systems that span the lifecycle of assets and processes [5, 31].

At the same time, resilience and sustainability have moved to the forefront of logistics-related digital twin research. Terms like risk management, environmental impact, and adaptive systems appear prominently in keyword clusters, reflecting growing concern with climate-related disruptions, global supply chain shocks, and regulatory demands [35, 64, 66, 80, 93, 96, 98]. These findings echo broader literature trends and point to a systemic reconfiguration of digital twins as strategic instruments for sustainability governance, especially in the context of post-COVID recovery and climate adaptation strategies.

Moreover, the analysis highlights a shift from simulation-focused research toward real-time synchronisation and orchestration. The prevalence of keywords such as real-time systems, cloud computing, and synchronisation signals a move toward live-data-enabled logistics platforms capable of dynamic adjustment based on supply and demand fluctuations [49, 67, 69].

A forward-looking development is the integration of AI and human-in-the-loop systems, indicating a hybrid model of decision-making. Clusters referencing reinforcement learning, e-learning, and human-centred design point to a future where digital twins evolve into cognitive systems that interact with and augment human operators [95, 96]. These trends also underline the need for digital competency development within logistics workforces, ensuring that AI-enhanced digital twins support rather than replace human judgment.

As detailed in Sect. 3.3, digital twins demonstrate potential alignment with SDG 9, 11, and 12, particularly in terms of emissions reduction, logistics optimisation, and smart infrastructure planning. This section builds on those findings to frame their conceptual and governance relevance, rather than repeating implementation cases or individual project data.

While UDT applications, such as in city planning, traffic optimisation, and port logistics, offer a compelling extension of logistics-focused digital twins, the bibliometric clustering suggests this research remains fragmented. Despite numerous real-world examples, these urban applications do not yet coalesce into a distinct research cluster, indicating an opportunity for more integrated cross-sector studies that bridge smart cities and logistics innovation [9, 16, 25, 44, 45, 57, 59, 81].

Finally, although this study reveals a rich conceptual landscape, the current literature often lacks critical case-based evaluation. Future bibliometric reviews should triangulate trends with in-depth case analyses to assess where digital twins have succeeded or failed in operational environments. This cross-validation is essential for distinguishing between academic popularity and practical effectiveness in logistics innovation.

4.2 Digital twin applications across scales (RQ2)

Digital twin research has traditionally concentrated on lower-level applications, such as asset-level monitoring, warehouse automation, and predictive maintenance within confined operational settings [72, 93, 96]. While valuable, this narrow focus has limited the theoretical exploration of digital twins as comprehensive logistics ecosystem enablers. This study proposes a broader scale-based framework, categorising digital twin applications at three levels: object, infrastructure, and system.

By introducing this multi-scale classification, this study expands the conceptual understanding of digital twins beyond isolated logistics functions toward an ecosystem-oriented perspective. The dominance of infrastructure-level applications in prior research reflects a historical focus on efficiency gains within factories, warehouses, and transport hubs. However, as logistics operations grow in complexity, system-wide digital twin integration becomes essential for achieving cross-sectoral interoperability, data-driven decision-making, and real-time adaptability [5, 7, 31, 36, 69, 75, 96].

This study's findings emphasise the critical need for scalable digital twin models that extend beyond isolated operational nodes to system-wide applications, including multimodal transport networks, urban logistics planning, and circular economy models. The proposed framework advances theoretical discussions on digital twin scalability, positioning it as a key driver of future logistics innovation.

4.3 Digital twins and sustainable logistics (RQ3)

Research on digital twins has progressed rapidly, yet their specific contribution to sustainability goals in logistics still needs sharper definition. By moving beyond conceptual projections, this study identifies the concrete sustainability functions of digital twins across diverse logistical settings.

A unique contribution of this study is the identification of distinct sustainability use cases of digital twins in real-world logistics applications. These include: (i) Urban traffic management and last-mile delivery coordination, where digital twins model congestion patterns and optimize route selection to reduce emissions [53, 87],(ii) Simulation of circular economy logistics models, helping firms minimise waste and recycle materials within supply chains [64, 80],(iii) Monitoring and reducing carbon footprints of freight operations through energy usage analytics and predictive scenario testing [40, 80].

Our findings contribute to theoretical understanding by repositioning Digital Twins within institutional and legitimacy frameworks. These perspectives remain largely unexplored within logistics research but have gained traction in foundational works such as Di Vaio et al. [26]. Traditionally, literature approaches Digital Twins from a resource-based view, emphasising their potential for operational efficiency and competitive advantage. However, our analysis uncovers a more transformative role: Digital Twins as tools for achieving organizational legitimacy amid heightened scrutiny from regulators, investors, and consumers. By transparently mapping real-time environmental and social performance to specific Sustainable Development Goals (SDGs), notably SDG 9.4 (sustainable industrial infrastructure) and SDG 12.6 (integration of sustainability into corporate reporting), Digital Twins externalize internal sustainability processes. This transparency bolsters firms' credibility, solidifying their social license to operate.

Moreover, our study introduces resilience theory as a valuable interpretive lens for understanding Digital Twins beyond crisis management. While prior studies have predominantly characterised Digital Twins as tools for operational resilience against immediate disruptions [64, 84], our research extends this perspective, highlighting their proactive governance capabilities against long-term systemic sustainability challenges, such as climate change and resource depletion. Our object–infrastructure–system taxonomy demonstrates the Digital Twin's capacity to simulate and manage chronic environmental and regulatory pressures proactively. For instance, at the system level, Digital Twins can evaluate long-term sustainability impacts, such as the influence of rising sea levels on port infrastructure, directly aligning with SDG 13.1 (strengthening resilience to climate-related hazards). This proactive governance capability signifies a theoretical advancement, bridging resilience theory with sustainability governance.

This study highlights that digital twins are central to aligning logistics with broader sustainable development goals by enabling system- and city-level transparency and data-driven optimisation across supply chains. In urban contexts, digital twins help manage last-mile delivery more efficiently, reducing traffic congestion and emissions, and promoting sustainable urban consumption patterns. The conducted literature analysis reveals that digital twins allow predictive analytics for logistics, optimising routes and transport modes, thereby reducing fuel use and carbon emissions. This promotes cleaner logistics operations.

The practical implications of this theoretical reframing are considerable. For managerial decision-makers, Digital Twins transform from mere technological assets into strategic governance platforms for sustainability risk management and brand reputation enhancement. They provide executives with actionable insights through real-time dashboards that align business objectives with sustainability mandates. For policymakers, Digital Twins at a system or city level offer novel tools for evidence-based collaborative governance, enabling precise and data-driven formulation and testing of interventions, such as low-emission zones or circular economy initiatives, before large-scale implementation (i.e. a logistics twin of Rotterdam port already informs congestion fees and route-optimisation incentives that cut emissions in real time). For executives, a twin becomes a strategic risk-and-reputation asset that links profit metrics to purpose metrics through a live sustainability dashboard. These examples illustrate how digital twins facilitate collaborative governance, allowing public and private actors to co-design and stress-test sustainability interventions before large-scale roll-out.

5 Conclusions

This bibliometric analysis maps the evolving landscape of Digital Twin research in logistics, confirming a significant shift from isolated, production-oriented applications toward integrated, system-level solutions focused on sustainability and resilience. Our key findings reveal a field that is rapidly maturing, yet a persistent gap remains between the conceptual potential of Digital Twins and their evidence-backed implementation. While our scale-based taxonomy (object, infrastructure, system) provides a framework for understanding this evolution, the analysis underscores that most progress remains at the lower scales, with system-wide integration and quantifiable sustainability impacts being the next major frontiers. In this respect, our work lays the empirical groundwork for scholars and practitioners to calibrate expectations, allocate resources, and benchmark progress along a clearly articulated maturity curve.

Theoretical implications of the results are presented in three statements: First, the study extends resource-based and dynamic-capability views by positioning digital twins as *legitimacy-generating assets*. Beyond enabling efficiency, digital twins externalise real-time ESG performance, reinforcing the social licence to operate and aligning firms with SDG-linked institutional pressures. Second, by integrating resilience theory, we recast digital twins not merely as tools for shock absorption but as instruments for *proactive sustainability governance* capable of modelling chronic, long-horizon risks such as climate change and resource scarcity. Finally, the object–infrastructure–system taxonomy enriches digital-twin theory by clarifying boundary conditions and scaling laws that determine when benefits plateau or when new coordination mechanisms become necessary.

Theoretical implications of the results can be distilled into three, now broader, statements. First, by viewing digital twins as legitimacy-generating assets, we extend both the resource-based and dynamic-capability perspectives. Digital twins do more than enhance internal efficiencies; they externalise real-time ESG signals to regulators, investors, and civil-society watchdogs. Such transparency embeds firms within the broader institutional logic of sustainable development, allowing them to anticipate audits, tap green-finance instruments, and pre-empt reputational harm. This mechanism is especially salient in logistics—an industry often accused of opacity—because twin-driven dashboards can stream carbon intensities, labour-hour footprints, and congestion metrics directly into public or investor portals. Second, by integrating resilience theory, we recast digital twins from passive shock absorbers into proactive sustainability-governance engines. They can simulate slow-burn crises—sea-level rise on port assets, multistage carbon taxation scenarios, or lithium-supply volatility—allowing firms and cities to pivot long before disruptions crystalise. Third, the object–infrastructure–system taxonomy enriches digital-twin theory by illuminating the scaling laws, coordination thresholds, and data-governance inflection points at which incremental benefits plateau and collective orchestration or new governance protocols become imperative. For instance, performance gains from warehouse twins often saturate at ~ 15% throughput improvement; crossing that ceiling requires meshing multiple nodes into a corridor-wide or city-wide twin where network effects and policy levers (e.g., dynamic road-pricing) unlock fresh value.

Managerial implications can now be elaborated into a three-step operational playbook accompanied by enabling practices. (1) Phased rollout and capability scaffolding. Begin with limited-scope twins—say, cold-chain container tracking or AGV scheduling—to create “data exhaust” and refine data stewardship, then layer twins horizontally across facilities before finally connecting them into an end-to-end supply-network mirror. Along the way, appoint a cross-functional twin-governance team that blends IT architects, operations analysts, ESG officers, and legal-compliance specialists. (2) Bilateral KPI architecture. Populate twin dashboards with paired operational and sustainability metrics: delivery-lead-time vs. NOx emissions, inventory-turnover vs. Scope-3 carbon intensity, dock-throughput vs. occupational-safety incidents. Such pairing underwrites capital-budget requests because every euro of efficiency gain is coupled to a verifiable externality reduction. (3) Continuous-learning loops and workforce reskilling. Treat each twin as evolving infrastructure, not a frozen snapshot. Schedule quarterly “twin sprints” in which the model ingests fresh sensor feeds or policy assumptions, and establish micro-credential programmes so warehouse supervisors or fleet dispatchers can interpret twin insights without relying exclusively on data scientists. Firms that close this sociotechnical loop are more likely to harvest dynamic efficiencies and sustain executive sponsorship.

Policy recommendations now broaden into a four-pillar agenda aimed at accelerating responsible twin diffusion. (i) Regulatory sandboxes with sunset clauses: National transport ministries or city governments should grant time-bound derogations from data-localisation or procurement rules so innovators can trial multi-modal twins, provided they submit post-pilot impact reports. (ii) Open, machine-readable logistics-data standards: Build on initiatives such as e-CMR and Digital Transport & Logistics Forum (DTLF) by mandating canonical ontologies for shipment IDs, carbon factors, and congestion levels. This ensures twin interoperability across modes and borders, thereby nurturing network externalities. (iii) Public twin infrastructure as a digital commons: Just as roads and ports are natural monopolies, city-scale twins that integrate freight, passenger movement, and land-use plans should be co-financed through blended public–private models. SMEs could then consume twin micro-services—demand forecasts, curb-side slot reservations—without footing full development costs. (iv) Outcome-linked incentives: Green-finance tax credits or preferential toll rates should hinge on documented, twin-validated emissions savings, pushing firms to elevate twin transparency from voluntary disclosure to revenue-relevant compliance.

Study limitations merit a fuller discussion. First, relying on Scopus excludes trade magazines, standards-body white papers, and start-up blogs where cutting-edge prototypes are unveiled. Future meta-analyses should triangulate across academic, industry, and patent databases to temper citation bias with practice realism. Second, despite an exhaustive keyword-harmonisation routine, synonyms such as "virtual clone," "synthetic environment," or domain-specific labels like "port twin" may have escaped detection, potentially undercounting niche sub-fields. Third, bibliometrics privilege academic influence over operational fidelity; a highly cited conceptual article might describe a non-deployable architecture, whereas a low-citation industry case could reveal hard-won lessons about sensor drift or union push-back. Fourth, publication cut-off at March 2025 means rapidly unfolding twin pilots, especially in EU Fit-for-55 corridors and US CHIPS-Act-funded supply chains, remain un-captured.

Future research directions proliferate. 1) Longitudinal field experiments with quasi-control groups should track twin interventions over multi-year horizons, capturing rebound effects such as induced demand or data-privacy backlash. 2) Open-source middleware and semantic ontologies must be developed, perhaps under Eclipse Foundation governance, to let heterogeneous twins exchange event messages in near real time. 3) Socio-technical and ethical inquiry should pair ethnographic ride-alongs with large-scale log-file analysis to uncover how algorithmic route choices intersect with driver fatigue, urban equity, and algorithmic bias. 4) Cross-pollination between logistics and Urban Digital Twins invites modeling of freight–passenger trade-offs under congestion pricing or zero-emission zones, offering holistic smart-city governance levers. 5) Life-cycle assessment–enabled twins could embed cradle-to-grave carbon factors, making it possible to simulate not only operational but also embodied-emission savings from modal shifts or packaging redesign. 6) Twin-in-the-loop policy simulation—using digital-microcosm "serious games" where regulators, carriers, and citizens co-design measures—could democratise infrastructure planning and build societal trust.

Author contributions

Andrii Galkin: Conceptualisation, Methodology, Data curation, Supervision. Ganna Samchuk: Conceptualisation, Investigation, Writing—original draft, Writing—review & editing. Denys Kopytkov: Writing—original draft, Visualisation. Russell G. Thompson: Methodology, Writing—review & editing, Supervision.

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Data availability

Data available on request from the authors.

Declarations

Ethics approval and consent to participate

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Consent for publication

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The authors declare no competing interests.

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