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DIGITAL TWINS AS A CATALYST FOR SUSTAINABLE CONSTRUCTION TRANSPORT POLICIES? A CRITICAL REVIEW

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ABSTRACT

The construction industry plays a critical role in shaping urban freight systems while contributing to environmental impacts through material transport and on-site activities. These activities exacerbate congestion, noise and air pollution, particularly due to inefficient planning and limited coordination of material flows. As Europe advances toward climate-neutral urban freight targets, the sector faces a major challenge: absence of integrated systems planning to support sustainable transport policies. Despite isolated examples of logistics control such as cross-site material consolidation, there remains a lack of scalable and data-driven approaches to manage construction logistics sustainably. This study critically reviews how digital twins (DT) can act as catalysts for zero-emission construction logistics planning. Drawing on an analysis of literature, EU policies and expert interviews, it identifies key gaps in current practices. The results translate into DT requirements for measurable, coordinated and policy-relevant construction transport planning capable of supporting life cycle emissions accounting based on logistics and on-site activity. By synthesizing knowledge across construction, logistics, digitalization and sustainability domains, this study proposes a strategic framework showing how DTs act as a catalyst for sustainable construction transport and informing policy innovation.

KEYWORDS

Digital twin, governance, sustainability, construction transport, policy innovation.

INTRODUCTION

Construction transport accounts for a significant portion of a project's total emissions; around 10% of CO_2 emissions in housebuilding projects (Sezer & Fredriksson, 2020), and represents a significant share of urban freight traffic (Brusselaers et al., 2020, 2023b). Thus, the sector is increasingly pressured to reduce the environmental footprint of material and waste transport while remaining efficient and competitive. At the same time, construction logistics flows are rarely rigorously planned, leading to avoidable vehicle kilometers associated environmental impacts and urban disturbances (Brusselaers et al., 2023a; Eriksson & Fredriksson, 2025).

The implementation of digital twin (DT) systems can greatly improve productivity, precision and sustainability in construction, resulting in more efficient and well-managed projects aligning on- and off-site flows (Sacks et al., 2020; Tetik et al., 2025; Valinejadshoubi

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et al., 2025). While DTs have primarily been discussed in relation to asset management and project level optimization, their potential role in supporting planning, governance and policymaking across construction logistics systems remains underexplored. Particularly, DTs and digitalized operations may offer a means to better understand and coordinate construction transport flows at the urban scale, thereby supporting more evidence-based and sustainable policy interventions. Despite growing awareness of the environmental impacts of construction transport, current practices remain fragmented, reactive and poorly coordinated, and weakly integrated into urban mobility and logistics planning.

Drawing on expert interviews, document analysis and literature review, this paper critically investigates the role of DTs in informing policy development and governance in the transition towards sustainable construction logistics and transport systems. The central argument of the study is that a structural gap persists between (i) strategic ambitions in EU climate/transport policy where data-driven planning, monitoring and digitalization are positioned as enablers, and (ii) operational realities in construction logistics, where planning remains ad hoc, data is fragmented and accountability diffuse. Hence, this study aims to synthesize DT requirements and a governance framework that can translate sustainable policy ambition into implementable construction transport practices at the urban scale.

LITERATURE REVIEW

This study's background comprises: a) Sustainable construction transports, b) Digital twin technologies in construction and c) EU policy frameworks and climate-neutral transport.

SUSTAINABLE CONSTRUCTION LOGISTICS AND TRANSPORT

In this study, construction transport refers to off-site freight movements to- and from sites that interact with the urban logistics flows and municipal governance. Construction logistics is used as the broader term for planning and coordinating material and information flows across the supply chain, including on-site handling. The study focuses on construction transport, using logistics concepts where they enable improved coordination, measurement and governance.

Inefficient logistics planning and execution causes increased greenhouse gas (GHG) emissions due to unnecessary transports, idling and fragmented logistics operations (Dhawan et al., 2024). Common inefficiencies such as unnecessary equipment idling, queuing during material and waste transport and poor planning contribute to excessive emissions (Tetik & Fredriksson, 2026). Recent work shows that transport-related emissions can be reduced through logistics reconfiguration, such as supplier-led distribution, integrated warehousing, and early supplier involvement, while municipal requirements for logistics plans may help bridge policy and practice gaps (Dhawan et al., 2026).

A systematic review of circular economy strategies in the built environment highlights that most studies focus on isolated parts of the construction supply chain rather than integrated approaches (Timm et al., 2023). Limited data availability for Life Cycle Assessment (LCA) phases and Environmental Product Declarations (EPD) hinders a comprehensive understanding of actual emissions from the processes, affecting the ability to make effective, sustainable decisions in construction production and transportation (Tetik et al., 2025b).

From a lean perspective, inefficiencies in construction transport can be understood not merely as isolated operational problems, but as systemic failures in flow coordination across fragmented actors, interfaces and temporary supply chains (Dhawan et al., 2024). Unnecessary trips, vehicle queueing, idling, waiting times and poorly synchronized deliveries represent forms of waste that undermine both production performance and environmental sustainability. In this sense, construction transport is not only a logistics issue but also a flow management problem shaped by how information, responsibilities and timing are coordinated across projects and urban actors (Eriksson & Fredriksson, 2025). Lean construction has long emphasized

reliable workflows, transparency, inter-organizational coordination and continuous improvement, all of which are directly relevant to transport planning and execution (Tetik et al., 2024). While lean provides a valuable lens for understanding such inefficiencies, existing studies offer limited insight into how coordination challenges in construction transport can be addressed at the urban and governance level (Haag & Jünger, 2023).

DIGITAL TWIN TECHNOLOGIES IN CONSTRUCTION

Digital twins are the digital representations of physical systems that integrate real-time and historical data to support monitoring, analysis, and decision-making across building life cycle. DTs can optimize construction transport by providing a real-time, integrated view of logistics capacity and material flows (Tetik et al., 2025a). A systematic review highlights the essential technologies such as IoT, BIM, AI, and data integration for effective DT deployment, while pointing out gaps in data interoperability and real-time visualization (Tuhaise et al., 2023).

DTs can help mitigate traffic, congestion and emissions by enabling smarter logistics planning, real-time monitoring and coordinated delivery schedules. They support optimization of resource use, waste reduction and improved energy efficiency which are critical for sustainable construction (Zahedi et al., 2024). By simulating and optimizing the flow of materials and equipment, DTs can reduce unnecessary transport movements, thereby lowering emissions and improving urban accessibility and livability (Faiad et al., 2023). Despite growing interest in DT applications at the project and asset level, limited attention has been given to their role in supporting urban scale governance and policymaking for construction transport systems. In particular, how DTs can act as catalysts for coordinating construction logistics flows across multiple projects and stakeholders remains insufficiently understood.

EU POLICY AND CLIMATE-NEUTRAL TRANSPORT IN CONSTRUCTION

The European Union (EU) has undertaken to climate neutrality by 2050 through the European Green Deal as formalized in the European Climate Law (European Commission, n.d.). Recognizing that transport generates nearly one-quarter of EU emissions, the EU has singled out the transport sector for significant decarbonization (Climate Action, n.d.). The 'Greener Transport strategy includes a target to reduce emissions by 90% by 2050, supported by legislative packages such as Fit for 55 and Sustainable and Smart Mobility Strategy (Council of the European Union, 2025; European Parliament, 2025). The EU Policy Roadmap for Climate-Neutral Buildings and Construction emphasizes the need to address embodied emissions from transporting materials and equipment (World Green Building Council, 2022).

Despite these ambitions, implementation of climate-neutral transport in construction remains challenging. Integrated policies combining technological, infrastructural and behavioral changes are needed (Falanga et al., 2025). The major barriers freight include limited availability of electric trucks and infrastructure, high upfront costs and financing challenges for SMEs besides constraints such as range and payload (Ragon & Rodríguez, 2022).

As a result, there is a growing gap between high level policy objectives and the practical ability to plan, measure, coordinate and govern construction transport in urban contexts, i.e., the sector lacks operational data and cross-actor coordination mechanisms that would make policy targets actionable. Addressing this gap requires not only technological transitions in vehicle fleets, but also improved understanding of system, data integration, and coordination across projects and stakeholders. In this context, digital tools such as DTs may play a complementary role by supporting evidence-based policy development and governance, enabling authorities and industry actors to better understand construction transport dynamics and assess the implications of alternative policy measures.

METHOD

This study adopts a qualitative, multi-method critical review combining (i) a systematic literature review (SLR), (ii) an integrative literature review including policy document analysis, and (iii) expert interviews. The aim is to examine how DT technologies are positioned regarding construction transport governance and identify gaps between academic knowledge, policy ambitions, and practical implementation.

SYSTEMATIC LITERATURE REVIEW

To identify and assess the existing body of research at the intersection of DTs, construction logistics and transport governance, a systematic literature review (SLR) was conducted. The review followed guidelines for synthesis in management studies (Tranfield et al., 2003) that comprised three stages: (i) planning the review by defining the scope, keywords and inclusion criteria; (ii) conducting the review through structured searches in Scopus and screening of titles and abstracts; and (iii) synthesizing the findings to identify common themes and research gaps related to DTs and construction transport governance. Database was searched with keyword combinations related to "digital twin", "construction logistics", "construction transport", "urban freight", and "governance". It was conducted on 15.12.25 yielding 67 records. It included English language peer reviewed journal and conference papers. Studies focusing on unrelated sectors or on technical applications without relevance to transport, logistics, or governance were excluded. After title and abstract screening, remaining papers were assessed in full text for topical relevance. Only four articles were identified as partially relevant to the intersection of DTs, construction transport, and urban/policy governance. Some of these studies address DTs in construction logistics at the project/site level, such as construction site logistics and material dispatch/replenishment applications, rather than governance or urban policy (Greif et al., 2020; Xiao et al., 2024). Similarly, Jiang et al. (2023) propose a DT enabled optimization mechanism for synchronizing material logistics and on-site assembly in fit-out construction, though this remains focused on operational logistics rather than urban transport governance. Vrijhoef (2025) moves closer to a governance perspective with a multilevel DT approach for modelling urban construction logistics and visualizing transport and environmental effects, enabling municipalities to assess traffic impacts in advance, yet stopping short of integrating DTs within a broader construction transport policy framework. No studies were found explicitly integrating DTs with construction transport governance at urban or policy level. Construction DT research remains largely confined to project or asset level, while urban DT studies largely exclude construction logistics. This gap motivates the integrative review and interview analysis.

INTEGRATIVE LITERATURE REVIEW

An integrative literature review which is a research approach that brings together prior academic studies and policy documents in a structured manner to generate new conceptual perspectives and theoretical insights (Torraco, 2005) was used. This extended beyond the corpus of DT studies to include literature on sustainable construction logistics, lean perspectives on flow and coordination and digitalization in the built environment. The review focused on information and material flows both on-site and off-site, enabling the identification of systemic inefficiencies and opportunities for DT applications beyond project optimization. The integrative review served to synthesize insights across disciplinary boundaries and to develop a conceptual understanding of DTs as potential enablers of governance and coordination rather than as standalone technological solutions.

To complement the literature, a thematic analysis (TA) of policy and governance documents was conducted focusing on EU strategies, regulations and policy roadmaps on climate-neutral transport and construction. Key documents included the European Green Deal, the European Climate Law, the Sustainable and Smart Mobility Strategy and sector-specific roadmaps

addressing embodied emissions in construction. Documents were analyzed to identify how construction transport is framed, governed or omitted, and to assess the extent to which digital tools and data-driven approaches are recognized as enablers for policy implementation.

EXPERT INTERVIEWS

The empirical component involved semi-structured interviews (Brinkmann, 2014) allowing for flexibility while covering key themes: sustainability strategies, transport planning, DT applications and barriers. Participants included logistics experts and construction managers with direct involvement in urban construction logistics and digital innovation projects. A purposive sampling strategy was used to select interviewees with different roles across the construction ecosystem, including contractor, developer, consultancy, logistics service, equipment rental, and waste management perspectives, to capture both strategic and operational viewpoints. Data was collected through in-person and online interviews, which were recorded with consent and transcribed for thematic analysis. Coding was performed using NVivo software to identify recurring patterns and contradictions. To improve coding reliability, the coding structure was developed iteratively and refined through repeated reviews of the material and emerging themes. The range of perspectives provided by the diverse set of experts provided rich insights into both strategic and operational dimensions of construction logistics and digitalization. Data collection was concluded when additional interviews provided largely recurring insights and no major new thematic categories emerged, indicating sufficient thematic saturation for the scope of this exploratory study. The interview details are listed in Table 1.

Table 1: Details about the expert interviews

Interviewee	Company, country	Date
Construction industry expert, founder	Developer, Finland	18.08.25, Helsinki
Material flow specialist	Logistics consultancy, Finland	26.08.25, online
Head of business area (logistics)	Equipment rental and logistics service provider, Sweden	05.09.25, online
Project manager	Contractor, Estonia	02.08.25, online
CEO	Logistics company, Finland	15.10.25, online
CEO	Waste and recycling management, Finland	01.05.25, online

FINDINGS

FINDINGS FROM LITERATURE AND POLICY ANALYSIS

While LCA standards account for transport emissions in the construction phase, most studies do not explicitly analyze them as a distinct component, and limited work explores its intersection with broader construction sustainability. Construction transport, however, represents a highly specific case, as it involves the movement of large volumes of bulk materials, specialized equipment and oversized components. This makes it both a major contributor to emissions and a critical area for digital innovation where integrated DTs could align construction management with sustainable transport strategies. EU climate strategies set ambitious emission targets but embed construction transport and logistics within broader building and transport policy instruments rather than dedicated governance frameworks

(European Green Deal, 2019). Moreover, emerging requirements for life cycle disclosure shift practical responsibility for generating construction phase emissions data to actors controlling logistics and on-site operations (Directorate-General for Energy, 2015). This places contractors at the center of data production, underscoring the role of DT-enabled logistics systems as enabling infrastructures for verifiable and policy-relevant emissions accounting.

The SLR revealed a near absence of studies that explicitly combine DTs, construction and transport or logistics. Across the screened literature, DTs are framed as project-level or organizational tools; construction transport is absent. Very few studies explicitly address DTs in the context of construction logistics, and existing work is largely confined to project or site level operational applications, such as material dispatch and replenishment systems (Greif et al., 2020; Xiao et al., 2024).

Urban DT research has focused on city-scale planning and infrastructure management through GIS-BIM integration with limited consideration of construction phase or transport flows (Xia et al., 2022). While data-driven approaches and DTs are increasingly explored for managing public traffic disruptions during infrastructure construction (Gu et al., 2025), comparable approaches remain largely absent for construction transport and logistics systems.

Policies emphasize ambitious decarbonization targets and data-driven implementation, yet construction transport remains weakly defined as a governable domain with clear mechanisms for measurement, coordination, and accountability. This creates a gap between policy ambition and operational execution, visible in ad hoc routing, limited emissions tracking, and fragmented procurement and data ownership.

FINDINGS FROM THE EXPERT INTERVIEW ANALYSIS

The analyses reveal that coordination remains a major challenge in construction transport with significant implications for sustainability. Daily truck trips are often made with non-full loads and uncertainty around material storage locations leads to inefficiencies and increased environmental impact. The relatively low cost of fossil fuels makes truck transport appear inexpensive which discourages precise calculation of material quantities, while consolidation centers are viewed as costly and underutilized. Geographical constraints are frequently overlooked during procurement, further exacerbating transport inefficiencies.

Emission tracking for construction transport remains in its infancy and is largely limited to pilot initiatives, partly due to the absence of dedicated logistics engineers and fragmented delivery practices where subcontractors supply materials without centralized oversight. Centralized procurement of materials and labor was identified as a key enabler of coordination, while route planning remains ad hoc and unoptimized, leading to excessive truck movements. For heavy materials such as concrete elements, procurement decisions are driven primarily by price rather than transport distance or truck capacity. Although emission tracking regulations are anticipated, they are not yet in place. Interviewees emphasized the need to track material quantities, truck loads, distances, weights, and dimensions, noting that planning currently relies on manual processes and professional experience rather than digital simulation.

One interviewee noted that a key limitation of current digital tools for sustainable construction logistics is their limited adaptability to site specific conditions. Unlike standardized industrial environments, construction sites vary widely in layout, processes, and constraints which makes it difficult for logistics software to provide tailored solutions and often result in generic functionalities that fail to support site specific sustainability goals.

While an interviewee was not formally familiar with DT technologies, they described using a logistics calendar to simulate material flows and site operations, including transport schedules, arrival gates, terminals, loading and unloading areas, cranes, heavy hauling machinery, and lifts. However, they emphasized that this approach relies on traditional methods grounded in

personal experience rather than digital simulation, highlighting a gap between advanced DT solutions and current practice in construction material delivery and handling.

An interviewee emphasized that implementing a DT for construction logistics requires comprehensive, well-structured data that is currently fragmented across actors, contracts, and project phases. Unlike building information, logistics data; truck loads, delivery timing, routing constraints, crane availability, and site access, is rarely standardized or centrally owned, limiting reuse across projects. The core barrier is therefore not data availability but the absence of shared data structures and governance mechanisms defining ownership and accountability across organizational boundaries. Key data elements include timelines, material types and quantities, transport routes, loading and unloading locations, and available human and machinery resources. Successful implementation also requires interdisciplinary collaboration among software designers with logistics experience, logistics managers, foremen, and workers, ensuring DT systems are technically robust and practically relevant. Table 2 summarizes the findings by key areas through which DTs can contribute to sustainable construction transport.

Table 2: Contributions of digital twins in sustainable construction transports

Key area	DT contributions to sustainable construction transports
Coordination and planning	Simulate complex logistics scenarios including material flows, arrival gates, terminals, loading/unloading zones, cranes, hauling teams and transport schedules that support coordination across multiple actors and phases of construction that can reduce inefficiencies
	Enables stakeholder alignment and proactive planning.
Responsiveness and risk management	Visualize, quantify delays, congestion and delivery issues' impacts
	Real-time monitoring and scenario analysis, proactive responses to disruptions and minimizing timeline extensions and cost overruns
	Can support predictive maintenance and dynamic rerouting
Knowledge transfer and standardization	A means to codify expert knowledge into reusable digital models, supporting standardization and scalability across projects
Transparency and decision support	Can make hidden costs visible supporting more informed decision making
Sustainability monitoring	Help avoid empty truck runs and optimize fleet operations
	Tracking emissions and equipment usage in real time
	Automating waste bin collection times from sites

One interviewee expressed frustration with the industry's tendency to treat every project as unique causing resistance to standardization. While DTs are not yet widely used to challenge this mindset, their ability to model repeatable logistics processes and enable workflow reuse across projects suggests a shift toward more industrialized and data-driven practices.

DIGITAL TWIN PRACTICES AS CATALYSTS FOR POLICY INNOVATION IN SUSTAINABLE CONSTRUCTION TRANSPORT

The results indicate that DT use can be interpreted across two governance levels. At the strategic level, EU climate-neutrality ambitions require measurable progress and scalable implementation mechanisms. At the operational level, construction transport is shaped by

temporary supply chains, fragmented procurement and locally constrained urban access: conditions that currently prevent systematic measurement and coordinated action. DTs can bridge these levels by translating project logistics data into urban-scale indicators and decision support that authorities and industry can jointly use. While policy calls for coordinated and data-driven freight transitions, transport is still managed as a project-by-project problem. Table 3 summarizes this strategic–operational gap and the DT implications.

Table 3: EU policy ambition vs. construction transport reality, and DT implications

Dimension	Strategic expectation	Operational reality	DT direction
Measurement and reporting	Progress requires measurable emissions and accountability	Emission tracking is at pilot cases and it is not standardized	Emission data model, automated reporting
Coordination	System level coordination across actors and urban constraints	Ad hoc routing, non-full loads, unclear storage or access	Shared logistics calendar, simulation, multi actor coordination
Planning	Evidence-based planning and evaluation of measures	Manual planning, experience-based decisions	Scenario testing; consolidation, delivery windows, routing
Governance and responsibility	Clear mechanisms to implement targets	Data ownership fragmented, no central logistics oversight	Governance layer for data roles, access rights, accountability
Procurement	Incentives should support low-emission choices	Procurement based on item price; distance ignored	DT-informed procurement KPIs such as distance, load factor, emission

Figure 1 shows the relationship between DTs with policies. DTs can be used as a catalyst which informs policy for more sustainable construction transport practices. The framework integrates data infrastructure, coordination mechanisms and observed practices to show how DTs can translate fragmented project logistics into policy relevant sustainability outcomes.

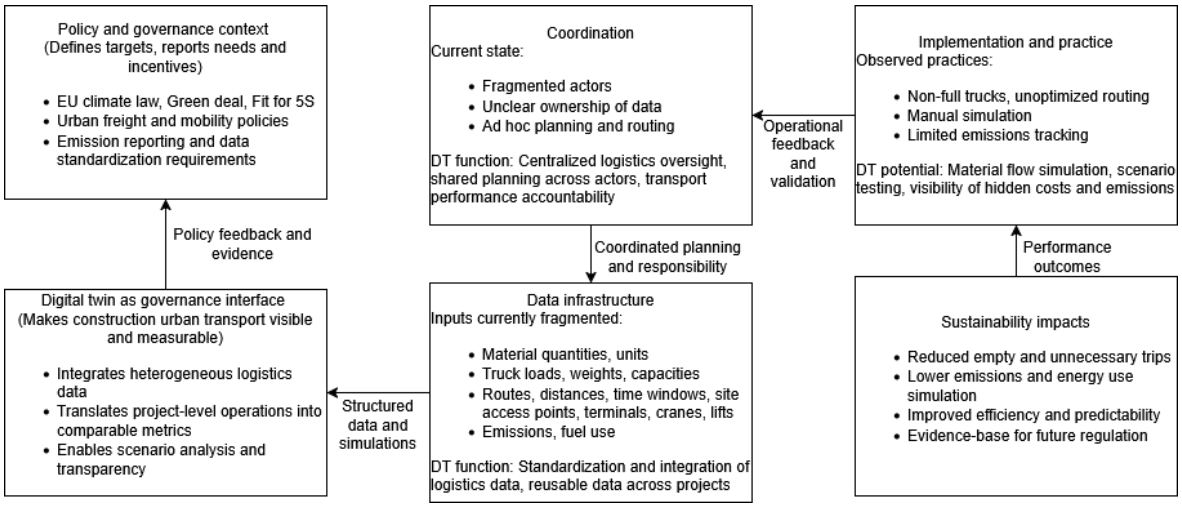

Figure 1: Sustainable construction transport governance framework enabled through DT

The policy value of DTs depends on their maturity and integration across data, coordination, and governance, not on technology deployment alone. While some DTs support only basic tracking and visualization, more integrated systems enable simulation, predictive analytics, and cross-actor coordination, making them more useful for policy development.

DTs are positioned in the framework as an enabling governance interface and supporting infrastructure for coordination and data integration. As a governance interface, DTs make construction urban transport visible and measurable by integrating heterogeneous logistics data, translating project-level operations into comparable metrics, and enabling scenario analysis and transparency. At the same time, DTs strengthen coordination by supporting centralized logistics oversight, shared planning across actors, and transport performance accountability, while also improving the data infrastructure through the standardization and integration of fragmented logistics data such as material quantities, truck loads, routes, access points, and emissions information. The framework also emphasizes feedback loops, where operational results and policy evidence can inform both project practices and broader governance development.

DISCUSSION

While DTs primarily enhance coordination and monitoring, their contribution to emission reduction is largely indirect: by improving flow and coordination, efficiency gains and decision making. The most substantial emissions reductions, however, stem from the transition to low-emission energy sources such as electrification and hydrogen. In this sense, DTs should be understood as complementary enablers that support planning, coordination and accountability for low-carbon transitions rather than as primary decarbonization solutions.

Recent EU policy developments require life cycle GHG emissions of buildings to be calculated using harmonized methodologies that increasingly rely on construction-phase data, including transport and on-site activities (Directorate-General for Energy, 2015). While lifecycle global warming potential (GWP) is disclosed at the building level, the underlying data must be generated during construction operations, highlighting the need for systematic, data-driven approaches to managing construction logistics.

The interviewees described capabilities such as simulating material flows, arrival gates, terminals, loading and unloading zones, cranes, heavy machinery, transport teams, and arrival timing. These show how DTs can make urban construction logistics flows explicit and analyzable, which is a prerequisite for operational improvement and policy intervention. From a lean perspective, such visibility is important because it supports improved flow, coordination and the reduction of waste associated with waiting, queuing and poorly synchronized deliveries. Beyond planning and visualization, a true DT compares simulated states with real-time data, enabling anomaly detection and identification of their causes (Sacks et al., 2020).

The idea of managing all construction operations through an updated digital model is not new (Tetik et al., 2019). Yet, extending this explicitly to urban construction logistics highlights a domain that has remained largely peripheral in digital construction research and sustainability policy. Extending it to construction transport, DTs can provide real-time visibility in material flows, vehicle operations and logistics processes, thereby aligning with decarbonization in planning and efficiency improvements across supply chains. In lean terms, it means supporting more reliable flow across project interfaces and reducing waste in transport operations.

The findings align with prior construction transport sustainability research calling for unified frameworks to address fragmentation between construction management and transport (Dhawan et al., 2022). This study extends this by showing that barriers are not solely technical but also stem from organizational and governance factors including fragmented data ownership, weak coordination, and limited regulatory incentives.

CONCLUSION

This study shows that sustainable construction logistics is constrained less by a lack of isolated tools and more by a governance and systems-planning gap: construction transport remains weakly coordinated, measured, and connected to urban freight planning, even as EU climate-neutral mobility ambitions demand accountable implementation. DTs can help bridge this strategic-operational disconnection by functioning as (i) coordination infrastructure, (ii) measurement infrastructure, and (iii) policy learning infrastructure.

This study critically reviews DT solutions as enablers of sustainable construction transport policy, drawing on systematic and integrative literature analyses, EU policy frameworks and expert interviews. The review reveals a near absence of DT research addressing construction transport, while policy analysis shows that transport emissions are embedded within aggregated lifecycle stages rather than governed as a distinct domain. For policymakers, this implies a need to recognize construction transport as a dedicated intervention domain within climate, mobility, and urban logistics strategies, supported by clearer responsibilities, interoperable data governance, and measurable indicators. For industry stakeholders, findings highlight the importance of integrating transport planning, monitoring, and cross-actor coordination with DTs into logistics practices rather than treating transport as a disconnected downstream activity.

The results may not reflect the full range of practices present across all regions or project types. Future research should explore the quantitative impact of DTs on emissions reduction, transport efficiency and cost savings. Longitudinal studies could assess how DT adoption evolves over time and interacts with emerging regulatory frameworks.

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