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SYSTEMATIC REVIEW

Towards Hyperconnected Zero-Emission Logistics: A Systematic Review of Enabling Technologies within the HOLOGISTICS Project

[version 1; peer review: 1 not approved]

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Abstract

Background

The freight transport system today is undergoing a fundamental transformation driven by decarbonisation, digitalisation, and the imperative of seamless interoperability between different modes, converging on the vision of a hyperconnected, Physical-Internet (PI)-aligned logistics ecosystem. The Horizon Europe HOLOGISTICS project is developing twelve such innovations, spanning modular physical systems, digital-intelligence layers, federated data ecosystems and zero-emission transport. This systematic review synthesises the state of the art underpinning these innovations to identify enabling technologies, cross-cutting gaps and future research priorities.

Methods

This review draws on the reference base compiled for HOLOGISTICS desktop research stage, comprising 171 records retrieved through targeted Scopus and Web of Science searches and curated technical/regulatory sources. Records were grouped into four themes: modular and automated physical systems; digital-intelligence and cyber-physical optimisation; interoperable data ecosystems and governance; and zero-emission, energy-optimised operations. Findings were synthesised narratively within each theme; no quantitative synthesis (meta-analysis) or formal risk-of-bias assessment was conducted.

Results

Open Peer Review

Approval Status ✗

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1. **Valentin Carlan**, University of Antwerp, Antwerp, Belgium

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Across the four themes, the literature shows rapid but uneven progress. Smart containers, automated loading platforms and digital twins are increasingly validated individually, but rarely interoperate across assets, modes or organisations. Federated-data-space concepts (DTLF, EMDS, IDSA) and a substantial body of international standards are technically well developed, yet governance, semantic and trust barriers persist. Electrification, hydrogen propulsion and multi-agent charging optimisation demonstrably reduce emissions, but are seldom coordinated with routing or energy-grid constraints.

Conclusions

Hyperconnected, zero-emission logistics depends on the co-evolution of physical, digital, data-governance and energy layers rather than progress in any one layer alone. HOLOGISTICS's twelve real-world pilots directly target these cross-cutting gaps, offering a practical pathway from fragmented innovation toward system-level, PI-aligned transformation across the TEN-T network.

Keywords
Physical Internet; hyperconnected logistics; digital twins; federated data spaces; zero-emission transport; multimodal freight; systematic review.



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Introduction

Freight transport and logistics are undergoing a profound transformation driven by the combined pressures of decarbonisation, digitalisation, urbanisation and supply-chain resilience. The European Green Deal, the Sustainable and Smart Mobility Strategy, and the ambitions of the Digital Transport and Logistics Forum (DTLF) require logistics systems to become significantly more energy-efficient, multimodal, interoperable and transparent. At the same time, disruptions, from global crises to local bottlenecks, have highlighted the fragility of traditional, siloed freight systems and reinforced the need for more adaptive, connected and resilient transport networks.

Against this framework, research on hyperconnected logistics has accelerated. Concepts such as the Physical Internet (PI) envision a logistics ecosystem characterised by modular, standardised physical units, open and collaborative data flows, and real-time synchromodal orchestration across modes and networks. Parallel advances in Internet-of-Things (IoT), digital twins, AI-based optimisation, and zero-emission transport technologies demonstrate the potential of cyber-physical systems to radically reconfigure freight mobility. Yet despite rapid technological progress, the transition toward fully integrated, PI-compatible logistics remains incomplete. Interoperability gaps persist at multiple levels, including physical interfaces, semantic models, data governance frameworks and operational standards, limiting the scalability and real-world impact of emerging innovations.

The EU-funded project HOLOGISTICS builds upon this evolving landscape by developing twelve innovations that collectively represent the building blocks of a next-generation logistics ecosystem. These innovations span modular physical systems, digital-intelligence layers, federated data ecosystems and zero-emission transport technologies. Through real-world pilots and cross-sector collaboration, HOLOGISTICS seeks to demonstrate how these innovation streams can converge into a functioning, interoperable, multimodal architecture aligned with PI principles and European TEN-T objectives. The project therefore provides an ideal lens through which to examine the state of the art and identify the research challenges that must be addressed to enable scale-up. Despite extensive research across these domains, the literature remains fragmented: studies often focus on isolated technologies, modes or use cases without fully exploring how these elements interact within an integrated logistics architecture. What is missing is a synthesised understanding of the cross-cutting challenges that must be overcome to advance from promising prototypes to system-level transformation.

This paper responds to this need by offering a systematic, PRISMA-guided thematic analysis of recent developments in hyperconnected logistics and by articulating a set of research priorities grounded in both academic evidence and the innovation trajectories of HOLOGISTICS. The contribution of this paper is threefold. First, it consolidates developments across modularisation, cyber-physical optimisation, federated data ecosystems and zero-emission operations into a coherent, evidence-based state-of-the-art overview. Second, it identifies the systemic gaps, technical, organisational and regulatory, that inhibit the emergence of PI-aligned, hyperconnected logistics networks. Third, it outlines a forward-looking research direction that connects these challenges to the real-world innovation agenda of HOLOGISTICS, positioning the project as a catalyst for bridging the divide between technological capability and system-level implementation.

In line with PRISMA 2020 reporting guidance, this systematic review was guided by the following review question: which technologies and mechanisms currently enable, and which gaps currently constrain, the transition toward hyperconnected, zero-emission, Physical-Internet-aligned freight logistics in Europe? The specific objectives were to (i) systematically identify and synthesise literature relevant to this question; (ii) map this evidence onto four cross-cutting themes — modular physical systems, digital-intelligence and cyber-physical optimisation, interoperable data ecosystems and governance, and zero-emission energy-optimised operations; and (iii) identify the technical, organisational and regulatory gaps that must be addressed to advance from isolated technological progress to system-level transformation.

Methods

This review is reported with reference to the PRISMA 2020 statement for systematic reviews, adapted to the scope of a technology and standards evidence base rather than a clinical-outcomes review. The completed PRISMA 2020 checklist and a PRISMA flow diagram (Figure 1) have been deposited in an open-access repository and are cited in full in the Data Availability statement and References below.

Protocol and registration

This review was not prospectively registered. The review's research question and eligibility criteria (below) were defined internally within HOLOGISTICS Task 1.2 (Desktop Research).

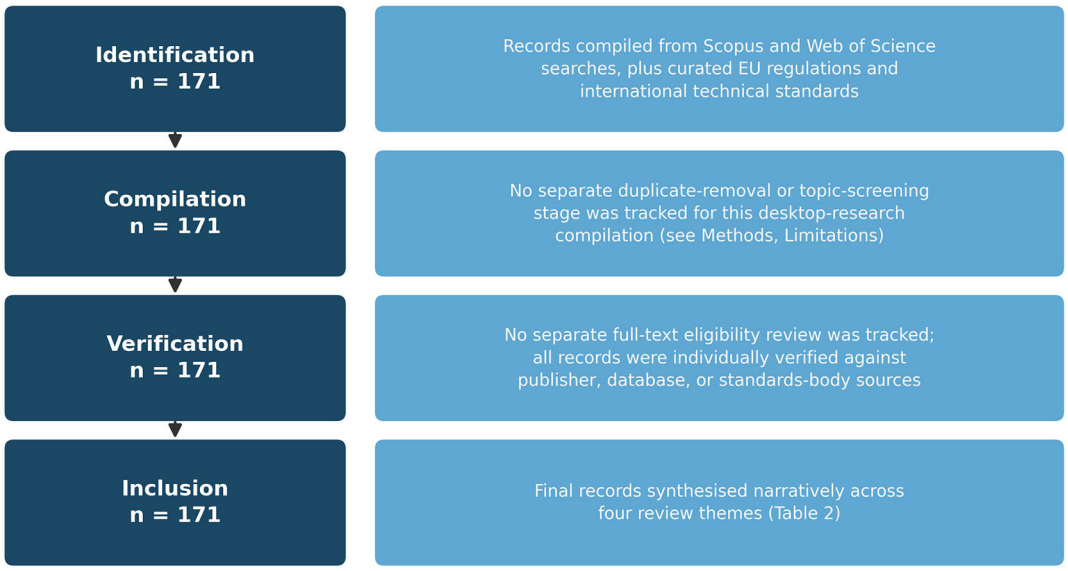


Figure 1. Record-compilation flow diagram for this systematic review. All 171 records in the reference base (References 1–171) were compiled through Scopus and Web of Science searches, supplemented by curated EU regulations and international technical standards, and individually verified against publisher, database, or standards-body sources before inclusion in the narrative synthesis. No formal multi-stage screening/exclusion funnel was tracked for this desktop-research compilation; see Methods – Selection process and Discussion – Limitations. Figure supplied as a separate file (Figure 1_flow.jpg).

Eligibility criteria

Eligible records comprised peer-reviewed journal articles and conference proceedings addressing modular physical logistics systems, digital intelligence and cyber-physical optimisation, interoperable data ecosystems and governance, or zero-emission and energy-optimised transport operations, together with directly relevant EU regulations, international standards (ISO, IEC, ITU, IMO, IACS, IHO) and other official technical or policy documents underpinning these four themes. No language, publication-date, or study-design restriction was applied a priori; in practice, eligible records span 1995–2026, with 85% published from 2020 onward.

Information sources

Records were compiled from the Scopus and Web of Science databases, supplemented by official European Commission, United Nations/UNECE, and international standards-body sources (ISO, IEC, ITU, IMO, IACS, IHO, CESNI, DNV, Bureau Veritas), as part of the desktop-research process underlying HOLOGISTICS Deliverable 1.2.

Search strategy

Database searches combined terminology for each of the four review themes (e.g. “smart container”, “digital twin”, “federated data space”, “zero-emission vessel”) with logistics- and transport-specific qualifiers. Full, database-specific Boolean search strings were not retained in the project records available for this analysis; this is noted as a limitation. Records were supplemented by direct identification of applicable EU legislation and international technical standards relevant to each theme.

Selection process

Records were compiled and screened by the two authors for relevance to the four review themes. Granular, stage-by-stage screening counts (for example, records identified before de-duplication, records excluded at title/abstract versus full-text stage) were not retained in the project documentation available at the time of this analysis; only the final, de-duplicated list of 171 records could be verified and is reported here. This is noted as a limitation, and a full PRISMA flow diagram will be reconstructed if the underlying screening records become available.

Data collection process and data items

For each eligible record, the following data were extracted: authors, publication year, title, and source journal, venue, or issuing body. Records were independently classified by the review team into one of the four review themes based on title

Table 1. Distribution of the 171 records across the four review themes.

Review theme	n	%
A. Modularisation and automated physical systems	31	18.1%
B. Digital intelligence and cyber-physical optimisation	49	28.7%
C. Data ecosystems, interoperability and governance	48	28.1%
D. Zero-emission and energy-optimised operations	43	25.1%
Total	**171**	**100.0%**

and subject matter (Table 1). No formal outcome measures were pre-specified, consistent with a review that synthesises enabling technologies, standards and organisational mechanisms rather than intervention effects.

Study risk of bias assessment

Because the included literature spans conceptual analyses, simulation studies, empirical evaluations, and official standards or regulatory instruments across engineering, computer science, transport-policy and logistics-management traditions, no single validated risk-of-bias or critical-appraisal tool was applied across all records. This is noted as a limitation in the Discussion.

Synthesis methods

Given the heterogeneity of record types, designs and metrics, results were not pooled statistically and no meta-analysis was conducted. Findings were instead grouped into the four review themes (Table 1) and synthesised narratively within each theme (Results). No formal investigation of heterogeneity or sensitivity analyses were conducted, consistent with this narrative-synthesis approach.

Results

Study selection

The desktop-research process underlying HOLOGISTICS Deliverable 1.2 compiled a final, de-duplicated bibliography of 171 records: 26 records discussed directly in the narrative synthesis below with individually verified bibliographic details, and a further 145 records retrieved through database searches and curated regulatory/standards sources. All 171 records were individually checked against publisher, database, or standards-body sources at the time of writing (see Figure 1, supplied as a separate file). Stage-by-stage screening counts preceding this final list (e.g. total records initially retrieved, duplicates removed, records excluded at title/abstract or full-text stage) were not retained in the project documentation available for this analysis; this is noted as a limitation in the Discussion, and Figure 1 (supplied as a separate file; legend at the end of the manuscript) therefore reports record compilation and inclusion only, rather than a full four-stage PRISMA identification/screening/eligibility/inclusion flow.

Study characteristics

The 171 records span 1995 to 2026, with 85% (145 of 171) published from 2020 onward, reflecting the fast-moving nature of the underlying technologies while retaining foundational earlier work and current (2025–2026) standards and regulatory instruments. Table 1 shows the distribution of records across the four review themes. Records were most heavily concentrated in the data-ecosystems, interoperability and governance theme (48 records, 28%), reflecting the breadth of technical standards and EU regulatory instruments underpinning this theme, followed by digital intelligence and cyber-physical optimisation (49 records, 29%), zero-emission and energy-optimised operations (43 records, 25%), and modularisation and automated physical systems (31 records, 18%). The complete bibliographic list of all 171 records is provided in the References section.

Synthesis of results

Findings are synthesised narratively below across the four review themes, consistent with the approach described in Methods. Every one of the 171 records in the reference base is cited at least once below or in the Discussion; see References for full bibliographic details.

Modularisation and automated physical systems

One key area of study for modularisation is the increasing need for interoperable, reusable, and sensor-enabled load units. Smart, reusable and recyclable packaging has been studied extensively in the food sector, where closed-loop container networks, bi-objective packaging network designs, and IoT/RFID-enabled smart packaging systems have been found to

improve traceability, reduce waste, and preserve product integrity across food supply chains.[1,2,3,5,29,30,35,37] Dynamic numbering and identification schemes for modular cargo containers extend this interoperability logic from packaging to the container level itself.[4]

Automation in physical handling processes forms a second strand of this literature. Automated and semi-automated loading platforms, electric railcar and wheel loaders, and hydraulic excavators using positive-flow and load-sensing drive systems have been shown to reduce dwell time, manual handling labour, and energy consumption at rail and terminal facilities.[6,46,47] Rail-specific automation, including automated recognition of railroad infrastructure from LiDAR data and the deployment of autonomous trains, is reported to improve both safety and service network efficiency.[7,27,39] Robotised infrastructure at inland-waterway and port facilities, and industrial robotics more broadly, are similarly linked to efficiency gains and emission reductions,[8,45] while smart stacking and integrated scheduling of handling equipment with bidirectional flows have been shown to raise throughput at automated container terminals.[33,49]

A third strand connects physical modularisation directly to the PI concept and to freight interoperability between modes. Studies frame PI as requiring standardised, modular, and smart containers combined with interconnected hubs; digital-twin-based inbound synchronisation frameworks, smart box-enabled product-service systems, and spatial wireless-sensor-network models for container monitoring have been proposed to operationalise this vision for warehouses and PI-hubs.[38,40,43,44,48] Freight-carriage interoperability between maritime and rail transport modes has been identified as a further precondition for sustainable, modular freight networks.[36] Design of reliable logistics hub networks under disruption, rail-road PI cross-docking hub scheduling that accounts for energy consumption, port digital-twin development explicitly aimed at decarbonisation, and simulation-based studies of rail-borne bulk logistics efficiency further illustrate how physical-layer redesign is increasingly evaluated jointly against efficiency, reliability and environmental criteria.[28,31,42,74] Sector-wide adoption of advanced manufacturing and automation technologies, however, continues to face structural barriers and enablers that shape how quickly such modular, automated systems diffuse in practice,[41] including in energy-intensive settings such as mining load management[34]; technical standards for physical equipment, such as electrical requirements for cargo/carrier cycles, remain an active area of standardisation.[32]

Digital intelligence and cyber-physical optimisation

Digital twins, predictive analytics, and AI-driven optimisation have come to characterise "next generation" logistics. Digital twin use cases for ports/terminals and intermodal facilities cover predictive applications,[9,10,11] and digital twins of vessels and maritime assets more broadly.[64,83] Studies show that integrated digital twin architectures, and predictive maintenance models built on them, can reduce energy consumption, shorten vessel turnaround times, and optimise operational planning.[12] Systematic reviews of digital twin applications in construction, energy efficiency, and oil and gas find consistent gains in predictive accuracy and lifecycle-service quality but persistent challenges around definition, standardisation and cybersecurity of the twin itself.[50,51,52,53,59,70,76,88] Digital-twin-enabled ship routing frameworks that explicitly account for decarbonisation regulatory compliance, IoT-based frameworks for ship-maintenance information exchange, and digital-twin/cybernetic feedback approaches to smart-city logistics extend this concept into operational decarbonisation and urban planning.[60,62,89]

Synchromodal and AI-driven optimisation of freight flows forms a second major strand. Agent-based re-planning, optimisation-simulation approaches, and systematic reviews of synchromodal transportation consistently report improved dynamic re-routing, load balancing and capacity management relative to static planning,[13,14,15,16] while broader surveys of AI in logistics and supply chain management identify route optimisation, demand forecasting and fleet management as the most mature AI application areas to date.[54,58,63,65,67,68,81,87] AI-based hub-location and last-mile optimisation studies, including matheuristic and multi-agent deep-reinforcement-learning approaches to e-commerce logistics and EV charging coordination, report measurable efficiency and cost improvements over conventional heuristics.[56,61,66,72,79,85] The economics of automating public and shared transport operations more broadly is also shown to affect operator cost, travel time and subsidy requirements, extending AI-driven optimisation questions beyond freight into passenger-freight synergies.[86]

A third strand addresses the IoT as the connective layer enabling both digital twins and AI optimisation. Comprehensive surveys of IoT applications in smart logistics report consistent gains in real-time visibility, monitoring and traceability, though interoperability and standardisation gaps between platforms persist,[57,78,84,90] and roadmaps for integrating blockchain with IoT propose decision-making frameworks to secure these data flows.[71,75] Security remains a recurring concern in IoT-enabled digital twins of maritime transportation systems.[73] Enabling technologies for urban smart mobility further illustrate how IoT, AI and digital-twin layers converge at the city scale.[77] Finally, adoption research indicates that organisational, social and governance barriers, rather than the underlying technologies themselves, are

often the binding constraint on AI and Industry 4.0 uptake in logistics and smart-city contexts,[55,69,80,82] a theme that connects directly to the governance literature discussed below.

Data ecosystems, interoperability and governance

Interoperability is one of the most significant challenges to overcome in order to realise the PI vision. Standardisation of data models, use of APIs, and development of federated data spaces have been highly emphasised as areas for fostering interoperability between systems.[17,18,19,95,114] The European Commission's Digital Transport and Logistics Forum (DTLF) has spurred the development of the Common European Mobility Data Space (EMDS) and the eFTI Regulation on electronic freight transport information, which together establish the regulatory basis for standardised, cross-border logistics data exchange within the EU;[99,101,102] the European Blockchain Services Infrastructure (EBSI) extends this basis toward verifiable, decentralised data exchange.[100] Concepts for federated data spaces such as IDSA gain acceptance as governance frameworks for collaboration between multiple organisations,[18] and recent work on data sovereignty formalises the requirements for actors to retain control over shared data within such spaces.[106,131]

A second strand concerns sector-specific data-exchange standards and single-window concepts. The Single Window Concept for international trade, transport and seaports, global data-exchange standards for smart container digital services, business requirements for logistics data sharing identified within the EU-funded FENIX project, and automatic information exchange between interoperable systems at seaport terminals each describe practical mechanisms for consolidating fragmented data flows into interoperable services.[92,94,115,128] Blockchain-enabled IoT logistics systems for tracking high-value shipments, and international standards for tracking and tracing on inland waterways and for electronic consignment notes (eCMR), extend this single-window logic to shipment-level provenance and paperless documentation.[93,129,130] A broader literature review of operational decisions in collaborative supply chains, and a roadmap evaluating the role of data networks and APIs for operational efficiency in small and medium enterprises, situate these data-exchange mechanisms within wider supply-chain collaboration and firm-level adoption questions.[97,118] Maritime- and inland-waterway-specific technical standards, including IHO S-57 hydrographic data, CESNI's River Information Services standard, NMEA 0183 for marine electronics, connected and automated mobility on-board unit standards, and ITU radio-communication standards for automatic identification and VHF data exchange, provide the lower-level technical interoperability layer on which these data-sharing services depend;[96,109,112,113,121,124] IACS cyber-resilience requirements and ISO standards for shipboard machinery data further extend this interoperability layer into cybersecurity and asset-data management.[107,108,111] At the vehicle-to-grid interface, ISO 15118 defines the communication interface enabling electric vehicles to participate in interoperable energy and mobility data exchange.[110] Analytics of European and national standards for data quality, interoperability and safety confirm that this standards landscape remains under active development and harmonisation.[123]

A third strand addresses data governance more broadly. Studies on data governance for trustworthy AI, data sovereignty in information systems, and embedding public-interest values in data governance collectively argue that technical interoperability must be matched by clear governance rules on access, control and accountability if federated data spaces are to be trusted by participants.[116,131,133] EU-level instruments such as the Cybersecurity Act, the rail interoperability technical specification for freight wagons, the inland-waterway technical-requirements Directive, and non-financial reporting obligations under Directive 2014/95/EU illustrate how regulatory and governance frameworks are being built out in parallel with technical standards.[98,103,104,119] Sector analogues from outside freight logistics, including the European Health Data Space and cross-border health-data interoperability projects, offer transferable governance lessons on balancing data sharing with sovereignty and trust.[105,126] Persistent adoption barriers for IoT and secure, cloud-based logistics data-sharing technologies in logistics and smart-city contexts, including IoT-enabled hazardous-goods monitoring applications, are reported consistently across this literature,[91,117,120,122,125,127,132] reinforcing the conclusion from the digital-intelligence theme above that governance and organisational readiness, not technology per se, are the binding constraint on interoperable data ecosystems.

Zero-emission and energy-optimised operations

Studies on transport decarbonisation have pointed to electrification, hydrogen propulsion concepts, and multi-agent energy optimisation as crucial drivers for zero-emission logistics corridors.[20,21,138,148] Battery-electric and hybrid-electric propulsion, as well as fuel-cell power systems, have been shown to already reduce emissions significantly and to improve energy efficiency for inland waterway transport and port-related activities,[20,168] while systematic reviews of Industry 4.0 technologies applied to inland waterway transport identify traffic monitoring, smart navigation, emission reduction, big-data analytics and cybersecurity as the five leading application domains for the sector.[145,161] Impact studies of automation and zero-emission propulsion on small inland cargo vessel design confirm that automation and decarbonisation are increasingly evaluated as joint, rather than separate, design objectives.[135]

Multi-agent reinforcement learning and distributed optimisation strategies have also been found to have significant applications for charging-synchronisation strategies and for fleet management balancing energy scheduling processes, as in.[22,23,24,134,157] Cooperative and hierarchical multi-agent systems for EV charging scheduling across multiple stations, decentralised management of large-scale EV fleets, and distributed convex optimisation for EV aggregators report consistent improvements in charging efficiency, grid congestion and fleet utilisation relative to centralised or myopic scheduling approaches;[158,160,162,163,164,169,170,171] decentralised energy-management strategies for EV charging within islanded microgrids extend these gains to off-grid and resilience-critical settings.[136]

While the integration of logistics route-planning strategies with energy-grid management remains at an early stage, several studies have shown promising interest in this area for future development, including automated electric transportation deployment strategies compared against isolated approaches[144] and policy decision-support frameworks assessing the economic viability of inland waterway transport in sustainable urban areas.[156] Case studies of inland waterway transport development, and of digital information services needed to sustain it, confirm that economic viability and digital readiness must be assessed jointly with environmental performance,[159,165] while sustainability-issue taxonomies for inland waterway transport situate these findings within the wider UN 2030 Agenda.[140] Regional electric-propulsion standardisation efforts, such as policy recommendations for electric passenger ferries on inland waterways in the Philippines, illustrate how this transition is being operationalised outside Europe as well.[166] A substantial body of international standards and regulatory instruments now underpins this transition: IEC and IEC/IEEE standards for electric-vehicle conductive charging, shore-side electrical installation requirements, and high-voltage shore connection in ports,[139,149,150,151,152] the IMO's draft Maritime Autonomous Surface Ships (MASS) Code, DNV rules for autonomous and remotely operated vessels, and Bureau Veritas machinery and electrical requirements collectively govern the safe deployment of automated, zero-emission vessels;[137,141,153] ITU radiotelephone and automatic-identification-system standards provide the communication backbone for these automated maritime operations.[154,155] EU instruments including the Euro 7 emissions and battery-durability regulation and EMSA guidance on battery energy storage systems on board ships extend this regulatory layer to vehicle- and vessel-level emissions and safety,[142,143] while national and international bodies continue to update inland-waterway-specific technical and operational requirements, including Dutch regulations for automated inland shipping experiments and UNECE's harmonised technical recommendations for inland navigation vessels.[146,147,167]

Discussion

Key challenges and future research priorities

A transition towards hyperconnected and emission-free logistics is characterised by a set of interrelated issues that form a clear path for research in the coming years. One key issue is holistic support for PI-compatible modularisation. Although recent breakthroughs in intelligent containers, reusable packaging, and automated loading systems have shown improved performance in terms of efficiency, traceability, and recycling potential,[1,2,4,29,35] today's landscape is far from holistic overall. Current approaches tend to be lock-and-key in nature and emerge in either mode-related or corridor-related domains, depending on heterogeneous design parameters, incompatible proprietary schemas, and differing coupling standards. This creates scalability and interoperability challenges and, therefore, demands a holistic definition and compatibility-testing infrastructure for modular logistics systems.[5,6,41]

The success of digital twins is inextricably linked to developments in federated data environments, which several scholars consider to be the cornerstones of next-generation freight systems.[18] Although rigorous models such as those defined by DTLF, IDSA, and the EMDS are already well established, their application leaves room for improvement. Empirical analyses make clear that reaching agreement on governance rules, and ensuring API compatibility and interoperable semantics among transport entities, remains problematic.[17,19,95,116] Without scalable, trustworthy infrastructure underpinning data exchange, intermodal transport governance today faces limitations in several respects, and further research is required to better understand governance and trust-establishment approaches.

Decarbonisation brings about a further set of structural issues. Optimising emission-free corridors requires the holistic governance of transport and energy networks, whereas traditional optimisation benchmarks still largely treat vehicle routing, dispatch, and energy supply as separate, unrelated problems.[22] Multi-agent predictive optimisation models and frameworks have shown promising potential for charging coordination and depot-scale optimisation, but their interaction with, and responsiveness to, energy networks and market conditions, such as price signals, is not yet satisfactorily addressed in the recent literature.[12,24,162]

A further challenge concerns the governance of human-AI collaboration, as AI-driven decision-making becomes increasingly embedded in logistics operations. Optimisation algorithms and predictive models continue to take on greater operational responsibility, raising questions of explainability, liability and acceptance by human operators.[25]

Research communities stress the importance of auditability and transparency, particularly in systems where automation influences safety-critical or time-sensitive decisions.[26] Future work must advance human-in-the-loop design principles, clarify responsibility distributions, and develop regulatory frameworks that ensure trustworthy integration of autonomous and semi-autonomous systems in logistics.

These challenges collectively form a layered research agenda that mirrors emerging architectures for hyperconnected logistics. At the foundation lies the need for interoperable physical modularisation; above it, digital twins and AI-driven orchestration provide adaptive capabilities; federated data ecosystems serve as the connective tissue enabling cross-actor collaboration; zero-emission energy optimisation ensures environmental alignment; and governance structures ensure transparency, trust and human agency. Progress in any one layer is contingent on advances in the others, reinforcing the need for integrated, multi-layer research capable of advancing logistics toward a fully PI-enabled and zero-emission future.

Interpretation

The synthesis of recent research shows that hyperconnected logistics is emerging from the progressive alignment of several previously separate innovation streams. Modular physical systems, digital twins, federated data architectures and zero-emission technologies are now developing in parallel, yet their integration remains partial and uneven. The literature highlights that although intelligent containers, reusable modular units and automated handling platforms are increasingly available,[1,2,38] their deployment is still constrained by incompatible standards and fragmented operational practices, limiting their contribution to end-to-end multimodal coordination.

Digital twins show similar patterns of progress and fragmentation. Significant advances have been made in modelling maritime operations, port processes and predictive maintenance.[9,11,12] However, these implementations remain largely domain-specific: digital twins rarely interoperate across assets, organisations or modes, and their semantics are not yet standardised.[50,53] This prevents the emergence of "network-level twins" capable of supporting synchromodal planning or corridor-wide optimisation. Scholars increasingly argue that a new generation of digital twin architectures, interconnected, semantically aligned and synchronised with operational data, is needed for predictive and resilient logistics.[52]

The discussion becomes even more complex when considering data governance. Research on data spaces and interoperability frameworks stresses the importance of establishing shared semantics, trusted access mechanisms and governance protocols.[18,19,106,131] Yet empirical studies reveal that logistics actors continue to operate within highly siloed information systems. Even where technical APIs exist, trust, liability and competitive concerns hinder data sharing. This misalignment between digital potential and organisational readiness reinforces the need for robust governance models that enable cross-actor collaboration without undermining data sovereignty.

Decarbonisation pressures further amplify these challenges. Studies on electric and hydrogen propulsion demonstrate clear environmental benefits but also highlight operational vulnerabilities, especially where energy supply, charging logistics and routing decisions interact.[21,168] Only a limited number of works explore integrated planning approaches that coordinate transport operations with energy-system constraints, despite their importance for designing zero-emission multimodal corridors.

Taken together, this body of research exposes a structural gap between technological maturity and systemic maturity. Technologies such as AI, digital twins, IoT, and multi-agent optimisation are advancing rapidly, yet the governance frameworks, standardisation mechanisms and cross-domain integration needed to deploy them at scale are evolving more slowly. This tension reflects a recurring theme in logistics innovation: progress within individual domains does not automatically translate into system-level transformation. In this context, the challenges identified above can be interpreted as elements of a multi-layered transition pathway. Modular physical assets form the base of a PI-compatible ecosystem; above them, digital twins and AI provide the cognitive capabilities for orchestration; federated data ecosystems offer the connective tissue enabling collaboration; energy-optimised infrastructures ensure environmental sustainability; and governance structures anchor the human and regulatory dimensions. The literature suggests that advancing these layers in isolation is insufficient: meaningful progress requires integrated research that simultaneously addresses physical, digital, organisational and regulatory aspects.

Limitations

This review has several limitations that should be considered when interpreting its findings. First, no formal risk-of-bias or critical-appraisal tool was applied to included records, given the heterogeneity of record types (academic studies, EU regulations, and international technical standards) across engineering, computer science, transport-policy and legal traditions; the review therefore cannot report a formal certainty-of-evidence rating. Second, and most importantly, the

stage-by-stage screening counts that preceded the final 171-record bibliography (records initially retrieved, duplicates removed, records excluded at title/abstract or full-text stage) were not retained in the project documentation available for this analysis. Third, the full database-specific Boolean search strings used during the original desktop-research phase were not retained; the terms reported in Methods describe the search approach but are not independently reproducible in their exact original form. Fourth, thematic classification of records into the four review themes was performed by the review team based on title and subject matter rather than a pre-registered, independently verified coding scheme.

Implications for research and practice

Taken together, these findings imply that future research on hyperconnected logistics should treat physical modularisation, digital-intelligence orchestration, data governance and energy optimisation as jointly evolving layers rather than as sequential or independent research programmes. For practitioners piloting individual HOLOGISTICS innovations, the review suggests that interoperability and governance dependencies, rather than the physical or digital technologies in isolation, are likely to determine whether pilot-scale gains translate into system-level, PI-aligned transformation.

Conclusions

This paper has synthesised current developments across modular logistics systems, digital twin technologies, federated data spaces and zero-emission transport, highlighting how these domains collectively underpin the transition toward hyperconnected freight ecosystems. While the literature demonstrates rapid technological progress, particularly in IoT-enabled modular assets, predictive digital twins and multi-agent optimisation, system-level integration remains limited. Fragmented standards, heterogeneous data models and insufficient governance structures continue to hinder the deployment of PI-compatible solutions at scale.[1,9,18] The structured analysis presented here shows that the next stage of innovation depends on the co-evolution of several layers: interoperable physical modularisation, semantically aligned digital twins, trusted and sovereign data-sharing mechanisms, energy-aware optimisation frameworks, and human-centric governance models. Advancing any one layer in isolation is unlikely to unlock meaningful transformation; instead, future work must address their interactions and the institutional, regulatory and organisational conditions that shape them.[19,22,25]

In this regard, the HOLOGISTICS project plays a vital bridging role. By implementing a series of twelve innovations spanning port/intermodal connectivity, zero-emission last-mile distribution, and shared electric vehicles, the project directly tackles many of the structural weaknesses identified above. The pilots realise the Physical Internet principles of modularity, real-time visibility, synchromodality, and open data exchange in concrete real-world corridors aligned with the TEN-T network, moving from theory to practice. HOLOGISTICS also proposes governance and interoperability tools that contribute to overcoming fragmentation in freight logistics within the European context. By using data-exchange models that fall within the framework of the European Mobility Data Space (EMDS), the project creates the preconditions needed for its various actors to interact within a framework of data sovereignty. By merging physical innovations with digital-intelligence layers and governance-interoperability frameworks, HOLOGISTICS exemplifies the possible co-evolution of technological, organisational and regulatory innovations needed to achieve the system-level transformation required to fulfil the PI vision and the EU's decarbonisation ambitions.

The research priorities identified, ranging from standardised modular asset specifications to cross-actor data governance, network-level digital twin orchestration, and integrated energy-transport coordination, provide a roadmap for guiding academic inquiry and innovation policy. In doing so, they support not only the ambitions of HOLOGISTICS but also broader European objectives for decarbonised, interoperable and resilient freight mobility. Continued progress in these areas will be essential for realising the vision of a Physical-Internet-enabled, zero-emission logistics ecosystem capable of meeting future societal and economic demands.

Data availability

Underlying data

Repository name: HOLOGISTICS Deliverable 1.2 Desktop Research Bibliography. https://doi.org/10.5281/zenodo.21957258.[172]

This project contains the following underlying data:

- hologistics_d1.2_reference_list.csv (bibliographic details for all 171 records synthesised in this systematic review: reference number, authors, publication year, title, source journal/venue, DOI, URL where the DOI is not available, and assigned review theme).

Data are available under the terms of the Creative Commons Zero "No rights reserved" data waiver (CC0 1.0 Public domain dedication).

Extended data

Repository name: PRISMA 2020 checklist and flow diagram for 'Towards Hyperconnected Zero-Emission Logistics: A Systematic Review of Enabling Technologies within the HOLOGISTICS Project'. https://doi.org/10.5281/zenodo.21957412.[173]

This project contains the following extended data:

- PRISMA_2020_checklist_for_repository_deposit.docx (completed PRISMA 2020 checklist reporting how each of the 27 checklist items is addressed in this manuscript).
- Figure 1_flow.jpg (record-compilation flow diagram; Figure 1 in this manuscript).

Data are available under the terms of the Creative Commons Zero "No rights reserved" data waiver (CC0 1.0 Public domain dedication).

Reporting guidelines

Repository name: PRISMA 2020 checklist and flow diagram for 'Towards Hyperconnected Zero-Emission Logistics: A Systematic Review of Enabling Technologies within the HOLOGISTICS Project'. https://doi.org/10.5281/zenodo.21957412.[173]

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Software availability

No new software was developed as part of this study.

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✗ **Valentin Carlan**
University of Antwerp, Antwerp, Belgium

The paper addresses a relevant topic and brings together a considerable amount of information. However, the methodological approach, synthesis of the results, and connection between the review findings and the conclusions need to be strengthened substantially. In particular, several conclusions appear to reflect the ambitions of the HOLOGISTICS project rather than findings derived directly from the analysis presented in the paper. I therefore recommend a major revision.

Major comments
Broaden the classification of technological solutions
Although I agree with the conclusion presented in the relevant sentence, its current formulation gives the impression that it is based primarily on smart containers, automated loading platforms, and digital twins. These examples are too narrow to represent the full range of relevant technological developments.
The classification of solutions should therefore be broadened and presented more systematically. For example, “smart assets” should include not only smart containers but also other connected vehicles, equipment, cargo units, and infrastructure. Similarly, automation extends beyond loading platforms and includes developments in handling, planning, dispatching, monitoring, and administrative processes.
The authors should revise the typology and demonstrate how the broader categories of smart assets, automation, digital platforms, and digital twins contribute to the conclusions.
Reframe the conclusion in the abstract concerning electrification and hydrogen
Electrified and hydrogen-powered transport currently represent only a limited share of freight transport when measured in tonne-kilometres. Consequently, integrating these technologies into planning systems may currently produce relatively limited system-wide benefits compared with the effort required for such integration.
Nevertheless, the underlying issue identified by the authors is relevant. I suggest generalising the conclusion by stating that planning and optimisation tools need to accommodate heterogeneous or mixed-fuel fleets. Such tools should be able to consider differences in range, refueling or recharging requirements, infrastructure availability, operating costs, emissions, and operational constraints.

If the authors retain a specific conclusion about electrification and hydrogen, they should support it with evidence regarding their current scale and operational relevance.
Avoid conclusions that are not derived from the analysis
The following statement appears to be based more on the ambitions formulated during the project-proposal stage than on the analytical results presented in the paper:
“HOLOGISTICS’s twelve real-world pilots directly target these cross-cutting gaps, offering a practical pathway from fragmented innovation toward system-level, PI-aligned transformation across the TEN-T network.”
The paper’s current methodology does not demonstrate how this conclusion was reached. The authors should either: provide an explicit analysis connecting each pilot to the gaps identified in the literature review; or replace this statement with a conclusion that follows directly from the results of the method applied in the paper. The distinction between evidence-based findings, the authors’ interpretation, and the expected future contribution of the project should remain clear throughout the paper.

Clarify the sampling and article-selection process
The methodological description seems to indicate that all identified articles were included in the analysis. If this is the case, the purpose of applying a selection procedure is unclear.

If no articles were excluded, this should be stated explicitly and justified. The authors should also explain what methodological value the screening or selection stage added.

Describe the analytical method, not only the literature search
It remains unclear whether an additional analytical method was applied after the articles were collected to really argument that the new innovation cases contribute to a gap or not.
The methodology should be presented as a reproducible sequence of steps. The description should be sufficiently precise for another researcher to repeat the same procedure and reasonably arrive at comparable findings.
Provide a more structured synthesis of the results
The results contain a substantial amount of relevant information, but they are currently presented in a dispersed manner. This makes it difficult to identify the main findings, compare transport modes, and understand how the shortcomings were derived.
I recommend adding a synthesis subsection for each transport mode. Each subsection could summarise the findings across the review themes and identify: the technologies currently available or in use; their level of implementation or maturity; the degree of integration with other systems and actors; the main operational and organisational limitations; governance and interoperability challenges; and the remaining research and implementation gaps. A final cross-modal synthesis table would make it easier to compare the modes and develop a substantiated roadmap. The roadmap should emerge from the analysis rather than being introduced only in the discussion or conclusion.

Reconsider the interpretation of technological and systemic maturity
The paper identifies a gap between “technological maturity” and “systemic maturity.” I agree that an important gap exists, but I am not convinced that the current wording accurately describes it. It appears that the paper compares the maturity of currently implemented technologies with the aspirational objective of fully hyperconnected logistics. However, it is not clear whether achieving hyperconnected logistics was ever an explicit objective of the technologies or initiatives included in the review. If systemic maturity is assessed against an ideal future state while technological

maturity is assessed on the basis of current implementation, the two concepts are not being measured against comparable benchmarks.
The authors should therefore define both concepts more precisely. They should clarify: what constitutes technological maturity; what constitutes systemic maturity; how each type of maturity is assessed; what reference point or desired end state is used; and whether the identified gap concerns maturity, alignment, integration, or distance from the vision of hyperconnected logistics.
If systemic maturity is treated as a separate dimension involving governance, interoperability, coordination, data sharing, and cross-organisational integration, these elements should be operationalised and assessed explicitly. Otherwise, it may be more accurate to conclude that both technological and systemic developments remain insufficiently aligned with the objectives of hyperconnected logistics.

Use consistent terminology
The terminology should be standardised throughout the manuscript. Expressions such as “hyperconnected logistics,” “hyperconnected logistics ecosystems,” and related variants appear to refer to the same concept.
The authors should select one principal term, define it clearly, and use it consistently. If the terms represent different concepts or levels of analysis, these differences should be explained explicitly.
Thoroughly revise the conclusion
The weaknesses described in the review of the abstract are particularly visible in the conclusion, where several statements appear without a sufficiently transparent analytical basis.
The conclusion should be rewritten so that every principal claim can be traced back to the results. It should clearly distinguish between: findings derived from the literature review; gaps identified through the analysis; interpretations proposed by the authors;
If the authors wish to conclude that the twelve HOLOGISTICS pilots address the identified gaps, this relationship should be analysed explicitly within the paper. A mapping table could show, for each pilot: the transport mode or modes addressed etc.
Without such an analysis, the claims concerning the project’s contribution should be presented as expected or intended contributions rather than as demonstrated research findings.

Are the rationale for, and objectives of, the Systematic Review clearly stated?
Partly

Are sufficient details of the methods and analysis provided to allow replication by others?
No

Is the statistical analysis and its interpretation appropriate?
No

Are the conclusions drawn adequately supported by the results presented in the review?
No

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: My research focuses on digitalisation and innovation in freight transport, logistics, and ports. This includes the economic and organisational assessment of technologies such as artificial intelligence, automation, blockchain, digital platforms, and digital twins. My work

also addresses multimodal transport operations, data sharing, governance, business models, and coordination between actors in logistics ecosystems.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to state that I do not consider it to be of an acceptable scientific standard, for reasons outlined above.