

Systematic Review

A CIMO-Based Systematic Review and Synthesis of the Physical Internet and IoT: Mechanisms for Triple-Performance Optimization in Logistics 4.0

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Abstract

Background: The confluence of the Internet of Things (IoT) and the Physical Internet (PI) is a major accelerant of Logistics 4.0, which can provide significant upsides to supply chain performance. While prior reviews mainly concentrated on technological advancement and applications, limited consideration has been given to the mechanisms through which the PI-IoT system integration generates benefits, namely operational, economic, and environmental benefits. **Methods:** To fill this gap, this study undertakes a systematic literature review of 43 peer-reviewed studies guided by PRISMA. This study uses the Context, Intervention, Mechanism, Outcome (CIMO) framework to automatically conduct a mechanism-based synthesis of PI-IoT integration, unlike previous reviews. **Results:** The results show that enhanced operational and economic efficiency, as well as environmentally sustainable performance, can be achieved by using real-time visibility, predictive decision-making, collaborative resource optimization, intelligent automation, and adaptive system responsiveness. **Conclusion:** This review also proposes a conceptual framework, linking contextual conditions, technological interventions, mechanisms, and outcomes, while also identifying important research gaps and future research directions. This study offers essential findings that offer practical insights for researchers, logistics managers, and policymakers intending to implement collaborative, data-driven, and sustainable PI-IoT-enabled logistics systems.

Keywords: Physical Internet; Internet of Things; Logistics 4.0; supply chain optimization; sustainable logistics; CIMO framework



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1. Introduction

There is a growing emphasis on the need for logistics systems that are operationally efficient, economically competitive, and environmentally sustainable through the design of global supply chains. Organizations are forced to rethink models of logistics. In order to meet changing consumer expectations, rapidly shifting market conditions, urban congestion, resource scarcity, and greater environmental concerns. Within this context, Logistics

4.0 has emerged as a strategic paradigm that leverages digital technologies to improve visibility, coordination, and decision-making across supply chain networks.

According to [1–3], Logistics 4.0 is the digital transformation of logistics systems through cyber–physical systems, artificial intelligence, cloud computing, big data analytics, blockchain, digital twins, and the Internet of Things. These technologies enhance interconnectivity, interoperability, automation, and intelligence in networks and their data and processes within the supply chain.

The Physical Internet (PI) and the Internet of Things (IoT) are somewhat interesting technologies associated with Logistics 4.0 because of their complementarity. According to [4], the Physical Internet recommends a radical change to the logistics systems, using standardised, modular, and interoperable logistics units that can flow through open and shared logistics networks. PI adopts an approach similar to that of the Internet, which aims to maximise the use of resources, minimise empty runs, and allow for joint logistical operations across companies [5–7].

While PI lays the groundwork for collaborative logistics, IoT delivers the information systems to enable real-time coordination and intelligent decision-making. IoT enables the continuous monitoring of products as well as vehicles, containers, and logistics infrastructures through connected sensors, RFID technologies, cyber-physical systems, and smart devices [8–11]. This enhanced visibility allows for dynamic rerouting, forecasting, synchronizing stock levels, and improving responding to disruptions.

The rise of PI and IoT has been increasingly recognised as a key enabler of logistics transformation. PI sets the basic physical and organizational conditions for resource sharing and interoperability between networks. Also, the collective IoT will allow gathering the necessary real-time data for coordinating those distributed logistics activities. The potential economic benefits of these technologies are immediately apparent. At first glance, the promising capabilities of the Physical Internet, artificial intelligence, blockchain, and IoT technologies are clear. Together, these technologies can yield potential improvements in environmental performance, operational performance, and economic performance.

Despite this growing interest, the existing knowledge is still broken. Initially, several studies on the Physical Internet and Internet of Things technologies are conducted separately and not on their joint effect on logistics performance. Similarly, the literature contains a very heterogeneous set of technological perspective, which includes optimization models, digital twins, and blockchain architecture, cybersecurity frameworks, cloud–fog computing, and artificial intelligence. Although such technologies could serve to support logistics transportation, they are not always analytically relevant to PI-IoT integration [12–14].

Because of this heterogeneity, the repeated identification of mechanisms becomes more complicated and reported outcomes are less comparable. Another limitation relates to the type of evidence available. The literature is dominated by concepts, simulation models, and technology-driven architectures, while large-scale empirical validations remain relatively limited. Also, the quantitative improvements, such as in costs, leadtime, or environmental performance, are often stated in isolation. Thus, it becomes difficult to relate logistics with technologies in the form of causality.

Existing reviews have given good insight into Logistics 4.0 technologies, the creation of sustainable supply chains, and digital transformation initiatives. Yet, most of the reviews remain predominantly descriptive and tech oriented. The technologies, applications, and performance indicators are catalogued, but it is not clear how they can bring performance improvements. Therefore, the links between these technology interventions and operational, economic, and environmental outcomes are poorly understood.

Although both the Physical Internet and the Internet of Things have been abundantly researched in the Logistics 4.0 literature, they are mostly analysed separately as techno-

logical domains or application-oriented perspectives. The impact of Logistics 4.0 will not be due to a separate deployment of these technologies but due to their strong linkage. The Physical Internet provides us with the logistics architecture that is standardised and collaborative, on the other hand IoT gives the real-time sensing and connectivity that are necessary. The architecture would then be operated dynamically through the intelligent decisions that IoT enables. Therefore, studying these technologies in isolation leads to an incomplete understanding of digital logistics transformation. Moreover, the previous literature reviews do not highlight the mechanisms for how their integration translates technical capabilities into performance increases.

With a view to resolving these limitations, this article performs a systematic literature review of 43 documents published in Scopus between 2020 and 2025 and draws a mechanism-based synthesis of PI-IoT integration using the Context, Intervention, Mechanism, Outcome (CIMO) framework. In contrast to traditional reviews that emphasise technology, our study takes a causal approach by investigating how specific interventions act to create mechanisms that increase logistics performance.

This review has three interrelated objectives of research. To begin with, it studies the contribution of PI and IoT to the improvement of environmental, operational, and economic performance in logistics and supply chain management. Secondly, the mechanisms through which they generate value resource pooling, interoperability, real-time visibility, adaptive coordination, and intelligent decision-making. Third, it highlights the methodological, technological, and organizational barriers which hamper large-scale implementation.

In order to achieve these aims, the review corpus presented in Table A1 in Appendix A is structured according to different levels of analytical relevance. Specifically, we distinguish core studies that directly address the PI-IoT-enabled logistics optimisation from supporting and contextual studies. This methodology enhances the analytical coherence of this review and allows for the synthesis to remain focused on the most pertinent evidence while taking account of the broader Logistics 4.0 ecosystem.

Accordingly, this study addresses the following research questions:

RQ1. How does the integration of the Physical Internet and the Internet of Things contribute to environmental, operational, and economic performance improvements in logistics systems?

RQ2. Through which mechanisms do PI and IoT generate these performance improvements under different logistics contexts?

RQ3. What technological, organizational, and methodological barriers continue to hinder the large-scale deployment of PI-IoT-enabled logistics systems?

The research has three main contributions. To begin with, it organises and synthesises recent research on PI-IoT integration in logistics and supply chain management. Secondly, it operationalises the CIMO framework as a mechanism-based analytical lens that explains the causal pathways linking technological interventions to logistics outcome. Third, it pinpoints crucial research deficiencies and suggests future strategies that promise to foster the evolution of more sustainable, resilient, and intelligent logistics systems.

The remainder of this paper is organised in the following manner. The theoretical findings on the Physical Internet, Internet of Things, and Logistics 4.0 are presented in Section 2. Section 3 provides the methodology of the systematic review as well as the operationalisation of the CIMO framework. The CIMO-based synthesis and comparative analysis results are presented in Section 4. The main research gaps and future research opportunities are discussed in Section 5. To summarise this paper's theoretical contribution, practical implications, limitations, and future research direction, Section 6 culminates this paper.

2. Conceptual Foundations of PI-IoT-Enabled Logistics Transformation

2.1. Logistics 4.0 and the Need for Triple-Performance Optimization

Supply chain and logistics systems are being transformed digitally with the emergence of Logistics 4.0. Building on the principles of Industry 4.0, Logistics 4.0 plans to improve the efficiency, flexibility, sustainability, and resilience of logistics operations with the help of advanced technology. It is becoming increasingly common for organizations to need to lower operational costs, improve service responsiveness, and minimise environmental footprints. Therefore, the performance of logistics can no longer be assessed only with economic indicators but must also consider operational and environmental indicators.

Due to this multidimensional view, the importance of triple-performance optimization which refers to simultaneous improvement in economic, operational, and environmental performance is increasing. The achievement of these goals gives rise to trade-offs. Policies to enhance delivery times may raise logistics costs while eco-friendly measures may call for additional spending on facilities or equipment. Consequently, there has been growing interest from both researchers and practitioners in digital technologies which can achieve these competing purposes.

The technologies associated with Logistics 4.0, the Physical Internet, and the Internet of Things represent a promising approach for logistics transformation not only due to the individual contributions but also their complementarity.

2.2. Physical Internet as a Structural Logistics Paradigm

The Physical Internet (PI), originally proposed by [4], represents a fundamental rethinking of how physical goods are moved, stored, and coordinated across logistics networks. Inspired by the architecture of the digital Internet, PI promotes the use of standardised, modular, and interoperable logistics units capable of circulating efficiently through shared logistics infrastructures [6,7].

Unlike traditional logistics systems, which often operate through isolated and organization-specific networks, PI encourages collaboration and resource sharing among multiple stakeholders. Through standardised containers, interconnected hubs, and open logistics networks, PI seeks to improve resource utilization while reducing inefficiencies associated with fragmented transportation systems.

The literature noted several benefits that will accrue from PI, including better use of vehicles, fewer empty trips, more flexibility in routing, greater logistics resilience, and less impact on the environment. However, these advantages depend critically on the ability to coordinate information flows across multiple actors and adjust logistics operations in real-time based on changing circumstances. This requirement underlines the need for complementary digital technologies that have real-time visibility and decision-support capacity [15,16].

2.3. Internet of Things as an Information and Coordination Layer

The IoT acts as a framework for information that enables smart and adaptive logistics systems. It enables the ongoing collection and exchanges operational data in the supply chain. This is achieved through connected sensors, RFID devices, cyber-physical systems, and communication technologies [8–11].

The use of IoT technologies in logistics environments enables live tracking and promises better inventory and vehicle monitoring, condition monitoring, and predictive maintenance. These features improve visibility across logistics networks and allow to make quicker and better decisions.

The IoT facilitates the creation of smart coordination mechanisms that respond dynamically to operational disruptions and demand conditions. Real-time information can

help to modify routes, complement inventory, manage congestion, and allocate resources. Therefore, the IoT is an important aspect that helps improve logistics responsiveness and flexibility [17,18].

Even if the IoT improves the availability of information, the efficient utilisation of that information requires the existence of logistics structures. This creates a natural complementarity between the IoT and PI.

2.4. PI-IoT Integration: From Technological Convergence to Logistics Transformation

The literature suggests that the greatest potential for logistics transformation comes not from single technologies but from the use of complementary technologies. The PI and IoT can be considered mutually reinforcing elements within a bigger logistics ecosystem in this context [19–21].

The usages of principles in the Physical Internet are put through a test to validate for collaborative logistics operations through standardised assets, shared infrastructures, and interoperable logistics networks. At the same time, the informational capabilities provided by IoT technologies help ensure real-time surveillance, coordination, and control of these distributed systems.

Combining both technologies provides several advanced logistics features, namely visibility in real-time facilitates routing dynamics and transport consolidation, and standardised logistics units enable automatic identification and tracking. Through the use of data, shared logistics infrastructures become more efficient. These capabilities enhance service performance, resource use efficiency, and environmental sustainability.

Nonetheless, the existing literature does show that adopting technologies does not automatically lead to better performance. The same technologies often produce vastly different outcomes based on different circumstances. Understanding logistics transformation, therefore, requires a shift from the technology driven perspective to a more analytical framework.

Despite the fact that the PI and IoT facilitate collaborative logistics through real-time information sharing and distributed decision-making, their effective deployment will also depend on secure and trusted digital infrastructures. In order to make large-scale logistics cooperation possible, organizations will have to carry out operational data exchanges across organisational boundaries. This gives rise to cyber security issues, data privacy issues, authentication issues, and trust issues [22,23]. If suitable security mechanisms do not exist, stakeholders may not join shared logistics ecosystems, thus reducing the effectiveness of PI-IoT integration. As a result, blockchain, secure authentication protocols, encryption mechanisms, and trusted communication architectures are important enabling layers that support interoperability and collaborative logistics.

In addition to technical interoperability, a robust and secure data sharing mechanism is necessary for the deployment of PI-IoT ecosystems with multiple stakeholders. Therefore, organizations must supplement digital transformation initiatives with a strong cybersecurity framework, privacy-preserving data governance, and trust-building framework that facilitates collaborative logistics without compromising sensitive operational information [23].

In theoretical terms, the complementarity between the PI and IoT can be interpreted in line with the Dynamic Capabilities Theory, whereby organizations continuously sense changes in their environment, seize new opportunities, and reconfigure resources to maintain competitive advantage. Within PI-IoT-enabled Logistics Systems, the IoT facilitates monitoring that embeds real-time data acquisition and visibility, while PI enables resource reconfiguration that proceeds through standardised, inter-connected, and collaborative logistics operations. This view grants a more potent theoretical rationale that illustrates

how the integration of technology facilitates adaptive logistics capabilities which enhances operational performance, environmental performance, and economic performance.

In order to summarise the complementary functions of the Physical Internet and the Internet of Things in Logistics 4.0, Table 1 describes their main functions, advantages, and drawbacks and the additional value that is added when they are integrated.

Table 1. PI-IoT integration summary.

Aspect	Physical Internet (PI)	Internet of Things (IoT)	PI-IoT Integration
Primary role	Standardised and interconnected logistics architecture	Real-time sensing, communication, and data collection	Intelligent, collaborative logistics ecosystem
Main objective	Resource sharing and logistics network optimization	Visibility, monitoring, and decision support	End-to-end coordination and adaptive logistics management
Key technologies	Modular containers, open logistics hubs, and standardised interfaces	Sensors, RFID, CPS, wireless communication, and cloud connectivity	Integrated physical and digital infrastructure
Main benefits	Higher resource utilization, reduced empty trips, and collaborative transportation	Real-time visibility, predictive monitoring, and operational responsiveness	Improved operational efficiency, economic performance, and environmental sustainability
Limitations	Standardization challenges, infrastructure investment, and stakeholder coordination	Data quality, interoperability, cybersecurity, and privacy concerns	Integration complexity, governance, trust, and organizational readiness
Representative mechanisms	Resource pooling; interoperability	Visibility; predictive analytics	Adaptive coordination, predictive decision-making, and intelligent automation
Expected outcomes	Reduced logistics costs and improved asset utilization	Better responsiveness and operational control	Triple-performance optimization (operational, economic, and environmental)

2.5. Towards a Mechanism-Based Understanding of Logistics Performance

Despite many studies showing that the PI and IoT enhance firm performance, few actually explain how the performance improvements emerge. Studies about technology and outcomes are abundant, but there are fewer studies that look at the mechanisms that link them [5].

As per theory, logistics performance improvement does not result from technology intervention. Technologies implement mechanisms that enter operation in particular contexts. For instance, resource sharing using the PI may activate pooling mechanisms for vehicle utilization. IoT visibility can lead to smarter decision-making and quicker response to disruptions. It leads to reduced transport costs, lower lead times, improved service levels, and lower environmental impacts [24].

An analytical mechanism design perspective can make explicit links between logistics context, technological intervention, activated mechanism, and the outcome observed. An approach could provide information that helps to understand what makes some implementations work while giving others limited results.

In the sphere of PI-IoT-enabled logistics, the act of predictive decision-making is defined as futuristic logistics anticipation that is based on past data and real-time data collected through IoT devices. The reliance of the particular application can range from machine learning algorithms to demand forecasting models for products, predictive maintenance models, and digital twins, and optimization models [25,26]. Prescriptive analytics recommends the optimal actions by applying the information from predictive analytics with optimization and decision support models to help with routing, inventory allocation,

and resource sharing among partners. Descriptive analytics, on the other hand, is focused on monitoring and reporting logistics operations' status. All the analytical skills combined support proactive and adaptive logistics management [27].

Consequently, within the proposed CIMO framework, predictive decision-making is conceptualised as the mechanism through which real-time PI-IoT data are transformed into proactive and optimised logistics actions, ultimately contributing to improved operational, economic, and environmental performance.

To handle this challenge, the present study makes use of the Context, Intervention, Mechanism, Outcome (CIMO) framework to make sense of the first two problems. This framework differs from the conceptual models that are often used in Logistics 4.0 research which mainly categorise enabling technologies, implementation factors, or performance outcomes. Instead, it is concerned with the causal relations between contextual conditions, technological intervention, organizational mechanism, and outcome. According to CIMO, specific interventions using digital technologies generate operational, economic, and environmental improvements in certain logistics contexts, but it does not provide a descriptive categorization of digital technologies. The mechanism-based perspective is quite useful in synthesizing the complementary roles of the PI and IoT, whose effectiveness depends not only on technological capabilities but also on the organizational conditions of deployment.

Figure 1 illustrates the proposed CIMO framework, which extends previous descriptive conceptualizations by explicitly modelling the causal relationships between context, intervention, mechanism, and outcome in PI-IoT-enabled logistics systems.

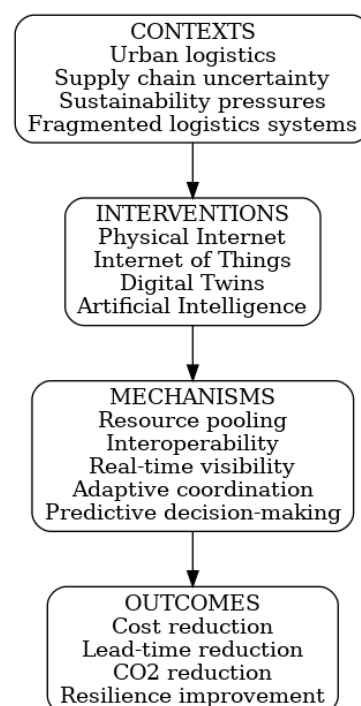


Figure 1. CIMO-based PI—IoT performance framework.

3. Research Methodology

3.1. Research Design

This study employs a Systematic Literature Review (SLR) and a Context–Intervention–Mechanism–Outcome (CIMO) analytical framework to explore how the Physical Internet (PI) and the Internet of Things (IoT) contribute to the enhancement of logistics performance.

This review aims to identify not only the technologies and applications but also to identify the way in which PI-IoT integration is beneficial for the environment, operations,

and economy in Logistics 4.0. After assessing the fragmented literature on this topic, a systematic review approach was chosen to guarantee methodological rigour, transparency, and reproducibility.

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) was used to formulate the review protocol. The research process was divided into different stages:

1. Definition of research questions;
2. Literature identification and retrieval;
3. Screening and eligibility assessment;
4. Data extraction and coding;
5. CIMO-based synthesis and comparative analysis.

The PRISMA screening illustrated in Figure 2 shows the complete methodological workflow.

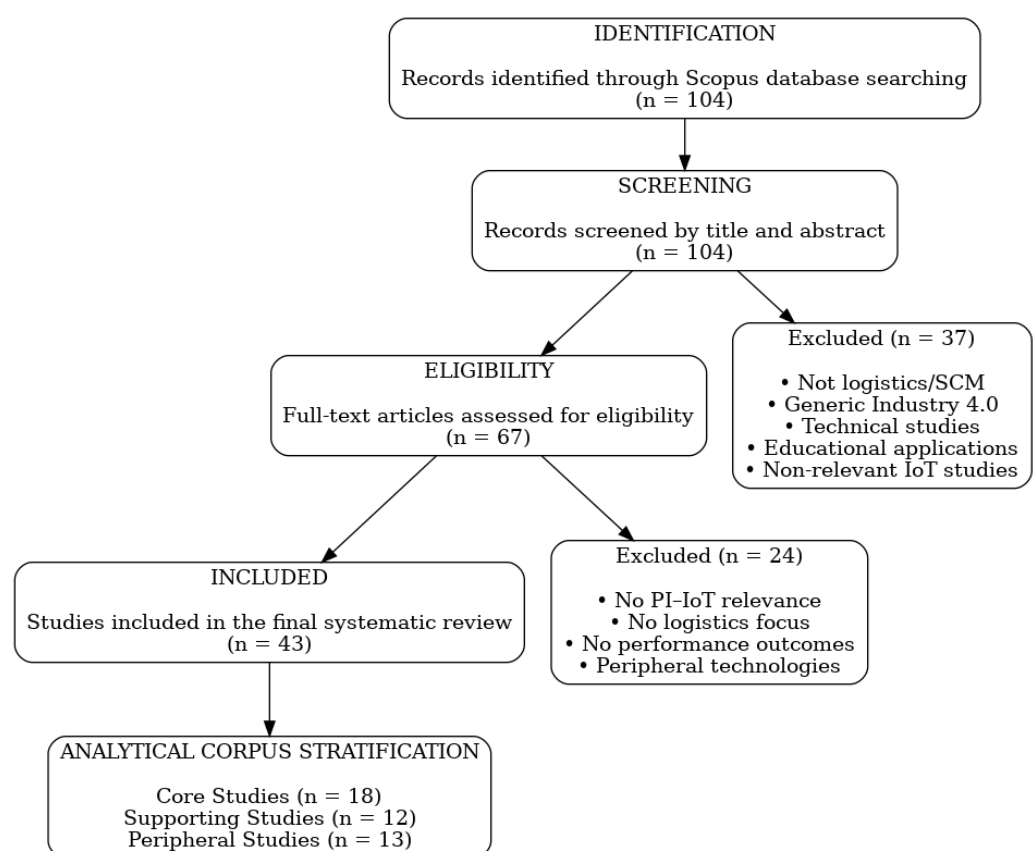


Figure 2. PRISMA screening process.

3.2. Database Selection and Search Strategy

The primary database used for this review was Scopus due to its extensive coverage of peer-reviewed publications in logistics, supply chain management, transportation, operational research, and Industry 4.0. Due to its multidisciplinary and high indexing, it is particularly well suited to investigating emerging technological developments at the logistics and digital transformation intersection.

An iterative search strategy was formulated to balance comprehensiveness and relevance. Initial searches showed that very narrow search queries reduce the number of relevant publications while overly broad searches bring in a lot of clutter. Consequently, the search query adopted was as follows:

("physical internet") AND ("internet of things" OR IoT OR RFID OR sensor)

The search was conducted on article titles, abstracts, and keywords.

The search string did not include forecasting- or prediction-related terms such as “forecasting,” “predictive analytics,” or “machine learning.” Studies that address demand forecasting or predictive maintenance without explicit PI or IoT terminology may therefore fall outside the retrieved set. This is a boundary of the search strategy, not evidence against the mechanism itself.

The following filters were applied ensuring relevance and quality:

- Publication time frame: 2020–2025;
- Language: English;
- Document type: journal articles and conference papers;
- Only published by peer-review.

An initial search generated 104 records.

3.3. Eligibility Criteria and Corpus Delimitation

A major challenge encountered during the review process was the heterogeneity of Logistics 4.0 research. Numerous publications discuss technologies such as artificial intelligence, blockchain, digital twins, cyber–physical Systems, cloud–fog computing, and cybersecurity without explicitly examining their contribution to logistics performance through PI-IoT integration.

To improve analytical coherence, explicit inclusion and exclusion criteria were established prior to full-text assessment.

Inclusion Criteria

Studies were retained if they met the following criteria:

- The application of the Physical Internet and/or Internet of Things within logistics or supply chain management contexts;
- They examined logistics coordination, optimization, visibility, traceability, resource sharing, or decision-making processes;
- They evaluated at least one performance aspect (environmental, operational, or economic);
- The contributions were presented through conceptual, empirical, modelling, simulation, or optimization frameworks;
- This review only focused on published peer-reviewed papers in English. Consequently, there may be publication and language biases due to the exclusion of relevant studies published in other languages. However, these criteria were adopted to ensure the scientific quality and comparability of the reviewed literature;
- The articles or conference papers were peer-reviewed journals.

Exclusion Criteria

Studies were excluded if they met the following criteria:

- Focused exclusively on communication networks, operating systems, cybersecurity protocols, or computing infrastructures without explicit logistics implications;
- Addressed Industry 4.0 technologies generically without clear links to logistics performance;
- Lacked sufficient methodological detail;
- Were editorials, tutorials, notes, or non-peer-reviewed publications;
- Represented duplicate records.

Analytical Corpus Stratification

To enhance analytical coherence and address the heterogeneous nature of Logistics 4.0 research, the composition of the final review corpus represented in Table 2 was based on three levels of analytical relevance.

Classification into the three corpus levels followed the explicitness of the PI-IoT linkage reported in each study. A study was coded as core when it examined the joint deployment of PI and IoT, or closely related technologies such as RFID or cyber-physical systems, and reported at least one quantifiable operational, economic, or environmental outcome. A study was coded as supporting when it addressed the PI or IoT individually, or discussed enabling conditions such as interoperability, resilience, or security, without reporting a direct PI-IoT performance outcome. A study was coded as peripheral when it supplied background technological or conceptual material, for example generic IoT security or cloud–fog infrastructure, without addressing logistics performance directly.

Table 2. Analytical corpus stratification.

Corpus Level	Number of Studies	Role in the Review
Core Studies	18	Primary analytical evidence directly examining PI-IoT-enabled logistics optimisation and performance outcomes
Supporting Studies	12	Contextual and explanatory evidence addressing interoperability, resilience, sustainability, and enabling technologies
Peripheral Studies	13	Background references providing complementary technological or conceptual insights
Total	43	Final structured review corpus

The core studies are the main evidence base for the CIMO-based analysis. They assess the contribution of PI and IoT technologies to logistics performance improvement in a direct way. The other studies provided additional insight on the interoperability, resilience, sustainability, barriers, and technologies that facilitate PI-IoT implementations. The peripheral studies were excluded from the comparative CIMO synthesis but were retained to support the conceptual background, technological landscape, and methodological characterization of the review corpus.

The total of 43 studies reflects the full set of records meeting the systematic inclusion criteria, not the number of studies subjected to CIMO-based comparative analysis. Only the 18 core studies fed into CIMO chain construction (Table 3) and the quantitative evidence synthesis (Table 6). Supporting and peripheral studies ($n = 25$) served only for contextual and thematic interpretation. Their place in the overall count of 43 should not be read as an indication of equal analytical weight to the core studies.

This classification allows identifying studies that have a direct contribution to the research question and studies that provide theoretical or technological support. As a result, the findings of the analysis are essentially reliant on the central corpus, while supporting and peripheral studies are mainly used to give context to results and spotlight principal themes in the Logistics 4.0 ecosystem.

It should also be noted that the 43 studies retained through the systematic review process constitute the analytical corpus used for data extraction, coding, and comparative synthesis. Additional references were incorporated exclusively to support conceptual definitions, theoretical positioning, and contextual discussion. These references were not included in the systematic review dataset and, therefore, were not considered during the comparative analysis of performance outcomes.

3.4. Screening and Selection Procedure

Adopting PRISMA 2020 guidelines, the selection procedure follows a multi-stage screening process.

Record identification occurred initially in 104 records. After reviewing the titles and abstracts, we excluded all the publications which were not related to the application of PI and IoT in logistics supply chain management. The remaining studies went through full-text screening according to the eligibility criteria.

Researchers ensured that selected studies are in accordance with research objectives as well as thematic consistency. We ignore papers that appear to only address educational applicability, technical infrastructure, operating system, or cybersecurity framework or propose a generic Industry 4.0 architecture unless they explicitly mention logistics optimisation.

Following the screening and eligibility assessment phases, the final review corpus compromised 43 studies. The selection process PRISMA flowchart is shown in Figure 2, also see checklist in Table S1.

3.5. Data Extraction and Coding Procedure

A structured coding protocol was developed to ensure consistency and transparency throughout the review process. For each publication, the following information was extracted:

- Bibliographic information;
- Research context and application domain;
- Technologies investigated;
- Methodological approach;
- Performance dimensions addressed;
- Key findings;
- Implementation barriers;
- Future research recommendations.

To reduce interpretive bias, only explicitly reported outcomes were considered during coding.

Performance dimensions were operationalised as follows:

Environmental Performance

Studies that report on improvements in emissions reduction, energy consumption, carbon footprint, sustainability indicators, or environmental efficiency.

Operational Performance

Studies show reduced delivery times, more efficient routing, better processes, and performance reliability.

Economic Performance

Studies claim reduced cost, increased productivity, better resource utilisation, return on investment, or efficiency improvements.

This coding framework allowed for a systematic comparison across studies and facilitated subsequent thematic synthesis.

3.6. Quantitative Evidence Extraction and Synthesis

Alongside thematic coding, quantitative evidence reported in the selected studies was systematically extracted whenever numerical performance indicators were available.

There are essentially three types of indicators that were considered:

- Environmental indicators include CO₂ emissions and energy consumption;

- Operational indicators include lead time, responsiveness, and routing efficiency;
- Economic indicators include cost savings, productivity enhancements, and resource utilisation benefits.

Due to variation in the methodologies of the studies reviewed, which included conceptual analyses, optimisation models, simulations, pilot projects, and empirical case studies, a formal meta-analysis was not considered methodologically appropriate.

A different narrative quantitative synthesis approach was adopted. For each study, documented performance outcomes were recorded along with the logistics context, technological configuration, methodological approach, evaluation metrics, and size of improvement.

As a result, the quantitative values presented in this review should be viewed as context-specific evidence rather than as statistically pooled values. This technique avoids misleading aggregations across fundamentally different research designs while enhancing transparency and traceability.

3.7. CIMO-Based Analytical Framework

The Context Intervention Mechanism Outcome (CIMO) framework was used to analyse studies after data extraction.

The socio-technical aspect of PI-IoT implementation makes this a framework adoption rather than a technology implementation. Traditional literature reviews identify technologies and outcomes but do not explain how they are connected causally.

The CIMO framework facilitates the analysis of logistics contexts, technological interventions, the mechanisms activated, and outcomes rather than being limited to descriptive reporting only. Each selected article was systematically coded according to the four CIMO dimensions. Context captured the logistics environment or application domain, Intervention identified the PI-IoT technologies implemented, Mechanism described the underlying operational processes enabling performance improvements, and Outcome recorded the reported operational, economic, or environmental impacts. This structured coding ensured methodological consistency throughout the synthesis process.

3.8. Thematic and Comparative Analysis

The final stage consisted of thematic and comparative analysis across the selected studies.

The analysis focused on identifying the following:

- Dominant technological configurations;
- Recurring optimisation mechanisms;
- Performance impacts;
- Implementation barriers;
- Methodological tendencies;
- Unresolved research gaps.

Particular attention was paid to repeating patterns rather than isolated findings. The synthesis development based on the mechanism explains how the PI-IoT integration improves logistics performance and also highlights the limitations and contradictions that still restrain deployment.

3.9. Operationalisation of the CIMO Framework

To go beyond describing technologies and applications, the CIMO framework was used as an analytical model to explain mechanisms. Instead of seeing Context, Intervention, Mechanism, and Outcome as discrete analytical categories, the framework was helpful in identifying causal pathways from technological implementation to logistics performance improvements.

The studies reviews deal with the Context (C) which refers to the environmental, operational, and organisational conditions under which logistics systems operate, including supply chain complexity, sustainability requirements, urban freight challenges, resilience concerns, and digitalisation.

Intervention (I) refers to the use of PI principles, IoT technologies, or their combined deployment within logistics operations. Technologies such as digital twins, artificial intelligence, blockchain, cloud–fog computing, and advanced optimisation methods were considered complementary to PI-IoT integration only wherever feasible.

Mechanism (M) stands for underlying processes activated by these interventions. The literature outlines recurring mechanisms such as pooling resources, improving interoperability, real-time visibility, dynamic routing, predictive decision making, adaptive coordination, and collaborative logistics management.

Outcome (O) represents the performance impacts highlighted in the literature. In line with the review objectives, outcomes are assessed across the three dimensions: environmental performance, operational performance, and economic performance.

The objective of analysis is therefore not only to assess whether PI and IoT improve logistics performance, but also to explain how and under which conditions improvements arise. Consequently, this review focuses on the identification of repeating CIMO chains across studies and their effectiveness evaluation. Through the mechanism-based perspective, the explanatory power of this review becomes more robust towards understanding the causal processes in PI-IoT-enabled logistics transformation.

4. Results and Discussion

4.1. CIMO-Based Synthesis of PI-IoT Mechanisms

In order to implement the CIMO framework, and not just a descriptive review of the technologies, the selected studies taken for review were analysed for their ability to develop casual pathways between the logistics contexts, technologies, mechanisms take up, and performance outcomes. In the analysis, rather than looking at technologies in isolation, we focus on using the PI and IoT to create value under specific operational conditions as represented in Table 3 and Figure 3. Several CIMO chains emerged from the literature stream, shedding light on how the improvements materialise as a function of the environment, operation, and economics.

The studies indicate that decreases in costs have been reported between 8% and 35%, reductions in transportation lie between 12% and 40%, and cuts in CO₂ emissions range from 10% to 30%. In contrast, papers focused on fragmented logistics contexts or explicit analyses similarly express potential rather than actual improvements.

The analysis reveals that performance improvements are not generated by technology deployment alone. Rather, outcomes result from the activation of mechanisms such as pooled resources, interoperability, real-time visibility, coordinated adaptability, and prediction. Interventions like PI-IoT-enabled logistics transformation tend to have different outcomes under similar conditions. Therefore, it is important focus on mechanism. The frequency analysis further indicates that real-time visibility was the most frequently identified mechanism (31/43 studies, 72%), followed by predictive decision-making (27/43, 63%), adaptive coordination (24/43, 56%), resource pooling/interoperability (22/43, 51%), and intelligent automation (18/43, 42%).

As noted earlier in this section, the CIMO synthesis yielded several mechanisms that contribute to supply chain resilience. The most central one is predictive decision support, which turns real-time logistics information into pro-active operational actions. Logistics managers can anticipate demand fluctuations, detect potential disruptions, and optimise routing decisions and resource allocation by leveraging IoT-generated information in con-

junction with predictive analytics, machine learning, digital twins, or optimization models. The ability to predict logistical events allows users to manage logistics in anticipation rather than in reaction to operational events happening. In turn, this improves operational responsiveness, decreases costs, and supports more sustainable logistics operations.

Table 3. CIMO-Based Synthesis.

Context (C)	Intervention (I)	Mechanism (M)	Outcome (O)	Representative Studies
Urban freight congestion	PI-enabled collaborative logistics and IoT monitoring	Resource pooling and load consolidation	Reduced transport costs and CO ₂ emissions	[28–30]
Dynamic logistics environments	IoT-enabled tracking systems	Real-time visibility and predictive decision-making	Improved responsiveness and reduced lead times	[17,18]
Hyperconnected supply chains	PI architecture combined with the IoT and digital twins	Adaptive coordination and network synchronisation	Simultaneous operational and economic gains	[19,31]
Sustainable logistics systems	PI resource sharing and IoT-based monitoring	Resource utilisation optimisation	Reduced emissions and improved sustainability performance	[32–34]
Resilient logistics networks	PI-enabled distributed logistics and IoT sensing	Adaptive reconfiguration and resilience enhancement	Improved continuity and service reliability	[35,36]

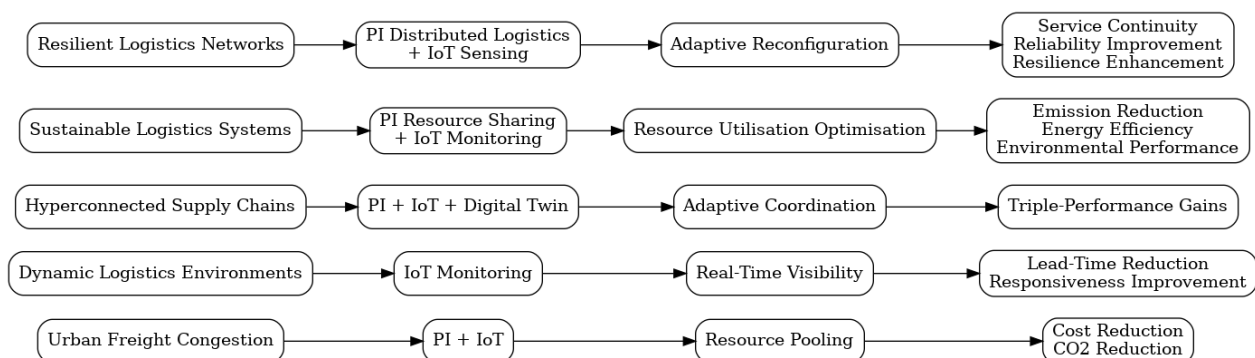


Figure 3. Representative CIMO chains identified in the literature.

Within the reviewed corpus, predictive decision-making designs a mix of computational techniques rather than a single method. Ref. [37] forecasts demand from IoT-generated data using big data streaming and machine learning models. Ref. [38] applies multi-agent reinforcement learning to dynamic container bidding. Ref. [30] combines a multi-objective NSGA-III algorithm with mixed-integer nonlinear programming to optimise production-distribution decisions, while [31] embeds machine learning within a digital twin architecture to synchronise PI hub operations in real time. The technique chosen in each case tracks the granularity and volume of IoT data available, which suggests that “predictive decision-making” functions as an umbrella term covering statistical forecasting, machine learning, metaheuristic optimisation, and reinforcement learning rather than a single analytical approach.

4.2. Thematic Synthesis and Recurring Patterns

Across the literature, three dominant patterns emerged from the data.

To begin, many studies highlight the role of the PI and IoT in improving visibility and coordination in logistics. IoT technologies help in collecting data in real-time, while the PI offers the structure required to make use of that data through collaborative logistics operations.

The use of resource-sharing mechanisms is associated with performance improvements. The utilisation of standardised containers, shared logistics infrastructures, and collaborative transport systems will improve asset deployment and lower operational inefficiencies.

Furthermore, sustainability, increasingly, is becoming a strategic objective and not an outcome. Research proves that operational improvements like route optimisation, transport consolidation, and reduction in empty movements bring about environmental benefits indirectly.

As a whole, the analysis of the literature indicates that the combination of the PI and IoT can help move the fragmented logistics systems towards more integrated and adaptive resource-efficient supply chain systems.

4.3. Key Technologies and Their Roles

The literature reviewed involves a wide range of technologies. Nevertheless, not all technologies provide equal contributions towards the goal of PI-IoT-enabled logistics optimisation. To assess the harmony of analytical constraints, the technologies were classified in accordance with their impact on the alignment of the logistics transformation process as shown in Table 4.

Table 4. Key technologies and their roles.

Technology Category	Technology	Role in Logistics Transformation
Primary Technologies	Physical Internet (PI)	The PI constitutes the structural foundation of logistics transformation by promoting standardisation, interoperability, resource sharing, and collaborative logistics networks.
	Internet of Things (IoT)	IoT provides the informational infrastructure required for real-time visibility, monitoring, tracking, and intelligent decision-making.
Secondary Enabling Technologies	Digital Twins	Digital twins support simulation, synchronisation, and adaptive decision-making by creating virtual representations of logistics systems.
	Artificial Intelligence	AI enhances predictive capabilities and supports optimisation, forecasting, and intelligent resource allocation.
	Blockchain	Blockchain improves traceability, transparency, and trust across distributed logistics ecosystems.
	Cloud and Fog Computing	Cloud–fog architectures facilitate data processing, interoperability, and information exchange among distributed logistics actors.
Supporting Infrastructure Technologies	Cyber–Physical systems (CPSs)	Provide connectivity between physical logistics assets and digital decision-making systems.
	Edge Computing	Supports low-latency processing and real-time operational responsiveness.
	Security and Privacy Technologies	Contribute to the protection of logistics data and communication infrastructures.
	Advanced Communication Networks (5G/6G)	Enable high-speed, low-latency communication required for connected logistics environments.

This classification confirms that the PI and IoT are the main drivers of logistics transformation, while other technologies are merely enabling layers.

4.4. Methodological Trends in the Literature

The methodological analysis represented in Table 5 shows that the current state of PI-IoT research is significantly unbalanced.

Table 5. Methodological characteristics and distribution of the reviewed studies.

Methodological Approach	Number of Studies	Percentage (%)	Main Objective	Typical Techniques Used	Representative Studies	Strengths	Limitations
Conceptual/ Framework/ Review Studies	15	34.9%	Develop frameworks and theoretical models	Conceptual modelling, architecture design, and literature synthesis	[15,16,20,39,40]	Provide strategic vision and theoretical foundations	Limited empirical validation
Simulation-Based Studies	5	11.6%	Evaluate logistics scenarios under controlled conditions	Discrete-event simulation, agent-based simulation, and digital twins	[29,31,32,41,42]	Allow testing of complex logistics systems	Results depend on modelling assumptions
Optimization Studies	10	23.3%	Improve logistics performance through decision models	MILP, multi-objective optimisation, heuristics, and metaheuristics	[28,30,35,43,44]	Quantify potential performance gains	Limited consideration of implementation constraints
Empirical/Case Studies	8	18.6%	Validate concepts in real logistics environments	Case studies, pilot implementations, and industrial applications	[17,18,33,34,36]	Provide practical evidence and industrial relevance	Often context-specific and difficult to generalise
Technical/ Infrastructure Studies	5	11.6%	Combine conceptual, simulation, and empirical approaches	Mixed-method designs, digital twins with case validation	[45–49]	Bridge theory and practice	Relatively scarce in the literature
Total	43	100%					

The methodological distribution reveals a clear predominance of conceptual, optimisation, and simulation-oriented research, which together account for approximately 69.8% of the reviewed corpus. Theories that can be supported and the benefits of PI-IoT-enabled systems are illustrated in these studies. Nonetheless, the empirical evidence available is comparatively limited at 18.6% of studies.

This disparity indicates that the field is still centred on conceptual exploration and assessment of technical feasibility rather than large-scale industrial implementation. While studies on optimisation and simulation often find improvements in logistics performance. However, their findings often depend on a number of simplified assumptions regarding interoperability, stakeholder collaboration, and data availability. Consequently, caution should be exercised while interpreting the existing body of knowledge due to the preponderance of conceptual and simulation-based evidence, leading to limited reliability and generalizability of reported performance improvements in actual logistics systems.

A major research gap in the field literature is reflected in the limited proportion of empirical studies taken. Future research should pursue industrial case studies, pilot implementations, and longitudinal assessments that can verify the performance improvements claimed by conceptual and optimisation-based contributions.

4.5. Quantitative Evidence Synthesis

To enhance transparency and traceability, the quantitative evidence presented in the reviewed studies was synthesised according to the three performance dimensions considered in this review as presented in Table 6.

Many core studies demonstrated how organisations saw logistics performance improvements post implementation of PI-IoT. Nevertheless, the extent of these improvements differs greatly amongst a range of logistics contexts, technologies, and evaluations. As a result, quantitative values that appear in the literature should be taken as evidence within context and not as benchmarks.

The review also shows that few studies evaluate environmental, operational, and economic performance simultaneously. Most of the literature targets one or two di-

mensions which indicates a great opportunity for future research on integrated triple-performance assessment.

Table 6. Quantitative evidence reported in core studies.

Study	Cost	Time	CO ₂
[30]	✓	✓	✓
[33]	✓	✓	✓
[34]	✓	✓	✓
[32]	✓	–	✓
[31]	✓	✓	–
[35]	✓	✓	–
[18]	✓	✓	✓

4.6. Contradictions and Tensions in the Literature

Even though it is widely agreed that the PI and IoT have transformative potential, there are several contradictions observed in the studies.

Contradiction 1: Interoperability versus Fragmentation

Many logistic networks remain unconnected and have incompatible technological infrastructure despite the reliance of PI on interoperability and standardisation [19,21,40].

Contradiction 2: Optimisation versus Scalability

Various optimisation models demonstrate good results under specific conditions. However, it remains to be seen whether these solutions are scalable in large and highly dynamic logistics environments [30,35].

Contradiction 3: Collaboration versus Competitive Behaviour

PI facilitates the sharing of resource and logistics operations. Despite their potential applications, organisations are often reticent about sharing data, infrastructure, or logistics resources due to competitive concerns and governance issues [29,38].

Contradiction 4: Simulation Success versus Limited Industrial Validation

Simulation and optimisation studies report high performance benefits. For the most part, only a few studies have provided large-scale evidence, raising doubts on the actual feasibility of some proposed solutions [15,41,42].

Technological potential and operational reality were obvious in tensions. Future research should therefore focus on other factors affecting successful implementation development of organization, behaviour, and governance apart from technological innovation in future research.

Contradiction 5: Security versus Collaboration

Despite PI facilitating open and collaborative logistics networks, organizations are unwilling to share operational data due to cyber security risks, privacy issues, and trust. The literature reveals that safe information sharing is a precondition for interoperability and collaborative sharing of resources. However, only a handful of studies address security governance jointly with logistics optimization.

4.7. Practical Implications

The findings from the contradiction analysis suggest that the implementation of PI-IoT ecosystems is dependent on not just the technological capacities but also the organizational capacities involved. To overcome interoperability barriers, it is advisable to implement standardised communication protocols and open data exchange architectures for better

integration with varied logistics systems [7]. Through modular system architecture, cloud platforms, and phased implementation strategies, organizations can progressively scale their digital capabilities and mitigate associated challenges [8,16]. Moreover, effective collaboration requires mechanisms for shared governance, data sharing agreements based on trust, and multilateral attribution [23,50]. The deployment of such organizational practices, together with technological innovation, creates the right conditions for realizing the full benefits coming from PI-IoT-enabled logistics transformation.

4.8. Contextual Differences Across Logistics Environments

The logistics domain also impacts the effectiveness of PI-IoT integration. Studies that were reviewed in this category attempted to enhance last mile efficiency and mainly focuses on real time visibility, dynamic routing, and traffic responsive coordination [4,6,7]. In multimodal transport systems, the most prevalent mechanisms for coordinating freight flows across multiple modes of transport are interoperability and resource pooling [4,7]. In contrast, the agri-food supply chains predominantly apply IoT-enabled traceability, environmental monitoring, and predictive decision-making for assuring product quality, food safety, and supply chain transparency [8,16]. In manufacturing and industrial logistics environments, a lot of emphasis is put on intelligent automation and predictive maintenance for better efficiency [25,26]. The same PI-IoT technologies may be used across different sectors but reveals the way in which the mechanisms are activated, and the performance improvements gained are very context-dependent, which reiterates the significance of the Context dimension of the CIMO logic. These contextual variations further validate the relevance of adopting the CIMO framework, as they demonstrate that identical technological interventions do not necessarily activate the same mechanisms or generate equivalent outcomes across different logistics environments.

5. Research Gaps and Future Research Directions

From the systematic review, it is observed that the methods and applications of PI and IoT technology in logistics have progressed adequately. Most of the design concepts in engineering analysis make assumptions and idealisation. Five priority research directions emerge from this review: (1) strengthening empirical validation through industrial case studies, pilot implementations, and longitudinal research; (2) integrating emerging technologies such as generative artificial intelligence, advanced digital twins, and autonomous logistics systems to enhance PI-IoT capabilities; (3) developing secure, interoperable, and scalable technological infrastructures that support collaborative logistics ecosystems; (4) advancing mechanism-based performance assessment by improving the understanding of how PI-IoT interventions generate operational, economic, and environmental outcomes across different logistics contexts; and (5) extending PI-IoT research toward human-centric, organisational, and governance perspectives by emphasizing Industry 5.0 principles, organisational resilience, trust, secure data-sharing, and effective human–technology collaboration.

5.1. Gap 1: Limited Empirical Validation

Evidence

Analysis of the methodology indicates a strong predominance of conceptual, simulation, and optimisation studies. Although these methods have provided some useful insight into benefits of PI-IoT-enabled logistics systems, there is still little empirical evidence to support them. There are only a few studies that reported the actual implementation and industrial case studies. Most performance enhancements consequently are derived from

simulation environments, optimisation models, or conceptual architectures and not major operational ones [17,33,34].

Implications

The lack of empirical evidence raises doubts about the ultimate feasibility and scalability of many proposed solutions. Assumptions around interoperability, data availability, stakeholder collaboration, and technological maturity may not be reflecting the real complexity of logistics environments. So, it is uncertain if such performance gains transfer.

Future Research

Future studies should be centred on pilot projects in industry, longitudinal case studies assessments, and large-scale implementation experiments. Performance benefits predicted from simulation and optimisation models would be validated through cross sectoral and logistics scenario comparisons. In addition, the gap between theory and practice can also be reconciled by increased collaboration between researchers and industry practitioners.

5.2. Gap 2: Limited Triple-Performance Integration

Evidence

Despite the frequent appearance of benefits on the environmental, operational, and economic performance in the literature review, few review papers evaluate the three dimensions in conjunction. Most publications tend to focus on one or two performance objectives. In practice it is more common to measure either operational performance or costs with environmental impacts mainly considered as secondary outcomes. There are only a few studies that investigate the interaction and trade-offs between environmental, operational, and economic objectives [30,32].

Implications

Because of the lack of integrated performance assessment, decision-makers cannot assess the overall effectiveness of PI-IoT-enabled logistics systems. Impacts on other objectives may occur unintentionally when optimising just one performance dimension. Strategies that are meant to minimise lead times may in turn lead to increased transportation costs or environmental impacts. Similarly, strategies for sustainability may require further investments.

Future Research

Further research may need to develop integrated evaluation frameworks which can simultaneously evaluate the environmental, operational, and economic performance. Using digital twins, multi-objective optimisation approaches, and advanced simulation models to assess trade-offs and synergies among performance dimensions. Standardised performance indicators would further improve comparability across studies.

5.3. Gap 3: Insufficient Integration Between Physical Internet and Internet of Things

Evidence

Although increasingly recognised as complementary, PI and IoT technologies continue to be separately studied in many studies. Multiple studies are either primarily focused on PI architectures, routing models, or resource sharing mechanisms. Others focus on IoT-based visibility, tracking, and monitoring systems. So far, there have been few PI-IoT implementations that are fully integrated [14].

Implications

The split of structural and informational perspectives conceals the mechanism through which logistics performance improvements are executed. Principles of the PI operate

based on real-time information and coordination capabilities, whereas IoT technologies require interoperable logistics structures capable of exploiting information. Examining these technologies independently may therefore overlook important synergistic effects.

Future Research

Future studies should adopt integrated socio-technical perspectives that consider both physical logistics structures as well as digital information systems. Research should clarify the ways through which PI and IoT activate collective standards, resource pooling, interoperability, adaptive coordination, and predictive decision making. CIMO-based empirical studies can provide valuable insights about these casual relations.

5.4. Gap 4: Scalability and Interoperability Challenges

Evidence

Improvements in performance under controlled conditions have been noted in many reviewed studies. However, several solutions are assessed in a limited operational context, specific sector, or a simple logistic environment. The issues related to interoperability, data sharing, standardisation, and coordination of stakeholders remain unaddressed for large scale deployment. The literature also shows various complaints about fragmented information systems and technological architectures that are incompatible [29,31].

Implications

If adequate scalability and interoperability are not available, the advantages demonstrated by localised implementations may not be transferable to the greater logistics ecosystem. Fragmentation makes collaborative logistics models less effective and limits organisations capabilities to maximise the potential of PI-IoT integration.

Future Research

Future research should be evaluated for scalability which can support heterogeneous logistics networks involving multiple stakeholders. More attention should be paid to interoperability standards, data governance frameworks, semantic integration mechanisms, and cross-organisational coordination models. Digital twins, cloud-fog architectures, and ontology-based interoperability solutions represent promising avenues for further exploration.

5.5. Gap 5: Human and Organizational Factors

Evidence

Most of the reviewed literature focuses on technological capabilities and optimisation mechanisms, while they receive a relatively lower emphasis on humans, behavioural, and organisational aspects. The considerations of stakeholder trust, data-sharing willingness, governance structures, organisational readiness, workforce skills, and resistance to change are often subordinated to the backseat in implementation matters [51,52].

Numerous studies underscore that the collaboration of PI-IoT ecosystems should involve cybersecurity and data privacy as prerequisites. While the examined literature often advocates interoperability and real-time visibility, relatively few studies directly clarify how secure communication, authentication mechanisms, and trusted data-sharing frameworks can contribute to collaboration between multiple logistics users. This creates an important gap between technological capabilities and practical implementation [53].

Beyond technological integration, the evolution from Logistics 4.0 toward Industry 5.0 highlights the need to place human operators at the centre of intelligent logistics systems. Although PI-IoT technologies automate information sharing and decision support, their successful deployment ultimately depends on human trust, organizational readiness,

workforce competencies, and effective human–technology collaboration. The reviewed literature provides only limited discussion of these socio-technical dimensions, suggesting that future PI-IoT ecosystems should balance technological innovation with human-centric design, resilience, and sustainable value creation [51,54].

Implications

A successful deployment is determined by more than technological feasibility. If organisations will not share information, collaborate with competitors, or adapt existing operations, even the most effective solutions may fail. Consequently, implementation barriers are often organisational and behavioural factors rather than technological limitations.

Organizations may avoid sharing operational data without the right cybersecurity and trust mechanisms which could limit interoperability, joint resource pooling, and real-time coordination. Therefore, it is not enough for the PI-IoT to be technologically feasible for it to be deployed. Secure governance and trusted digital infrastructures are equally important.

Furthermore, organizations should complement technological investments with change management strategies, workforce training, and stakeholder engagement initiatives to enhance organizational readiness and facilitate technology adoption. These socio-technical capabilities are essential for building resilient, trustworthy, and human-centric logistics ecosystems consistent with the principles of Industry 5.0 [23,54].

Future Research

Future studies should focus on the socio-technical aspects of PI-IoT adoption, including governance models, collaboration mechanisms, trust-building strategies, and change management processes. The use of behavioural analytics, a human-centric logistics approaches, and Internet of Behaviours (IoB) applications can provide relevant insights into the human factors that would support a logistics transformation. These challenges can be addressed particularly well with mixed-method and interdisciplinary research designs.

Future research should also prioritise the development and validation of socio-technical implementation frameworks that integrate governance mechanisms, trust-building strategies, standardised data-sharing architectures, and human-centred organizational practices. In addition, future studies should investigate how Industry 5.0 principles, including human-centricity, resilience, sustainability, and human–technology collaboration, can complement PI-IoT-enabled logistics systems and facilitate their large-scale adoption. Particular emphasis should be placed on longitudinal studies, industrial pilot implementations, and mixed-method research designs capable of assessing organizational readiness, workforce adaptation, and stakeholder collaboration under real operational conditions [23,54].

5.6. Synthesis of Future Research Directions

The outlined research gaps collectively show a gradual shift to application-oriented research rather than experiment-oriented research. In the future more focus will be required on empirical validation, integrated performance assessment, deeper PI-IoT convergence, scalable interoperability frameworks, and human-centred implementation.

From a CIMO perspective, future studies should not only examine whether PI and IoT enhance logistics performance but also investigate under which contexts, through which mechanisms, and under what organisational conditions enhancement occurs. Shifting from technology-centred analysis toward mechanism-based understanding is considered as a critical step toward the developing sustainable, resilient, and intelligent logistics systems capable of tackling the challenges of Logistics 4.0.

Beyond the research gaps identified in this review, future studies should also explore the convergence of PI-IoT with emerging digital technologies such as generative artificial

intelligence (GenAI), advanced digital twins, and autonomous logistics systems. Generative AI could enhance decision support, scenario generation, and collaborative planning, while advanced digital twins may enable more accurate real-time simulation and predictive optimization of logistics networks. Likewise, autonomous logistics systems—including autonomous vehicles, mobile robots, and intelligent warehouses—could further improve the adaptability, resilience, and operational efficiency of PI-IoT-enabled supply chains. Investigating the integration of these technologies represents a promising avenue for advancing next-generation Logistics 5.0 ecosystems.

Future research should also place greater emphasis on empirical validation through robust research designs. While simulation and conceptual studies have generated valuable theoretical insights, there is a need for longitudinal studies, industrial pilot implementations, multi-case studies, and quasi-experimental research to evaluate the long-term operational, economic, and environmental impacts of PI-IoT integration under real-world conditions. Such empirical approaches would strengthen the external validity of existing findings and accelerate the transition from conceptual development to practical implementation.

6. Conclusions

A systematic literature review of 43 publications from 2020 to 2025 was carried out to investigate how the integration of the Physical Internet and the Internet of Things enhances logistics and supply chain performance improvement. This review's use of a Context–Intervention–Mechanism–Outcome (CIMO) framework allowed for the development of a mechanism-based understanding of the manner in which PI-IoT-enabled logistics systems produce environmental, operational, and economic benefits going beyond mere descriptive analysis of technologies and applications.

The assessment shows that combining the PI and IoT can offer a promising route to making logistics smarter, more sustainable, and more resilient. The studies show improved performance leads of mechanisms like pooling of resources, enhancement of interoperability, increased visibility and feedback, adaptive coordination, and predictive decision-making. In addition, their findings reveal that the PI-IoT integration could yield benefits along the three key dimensions of logistics performance. Environmental benefits arise mainly from transporting goods in bulk to avoid empty trips, and efficient resource use. There are operational benefits in terms of speed, visibility, and service reliability, whereas economic benefits come from better asset utilisation, lower transport costs, and expediency of decision-making.

This review highlights that performance improvements are dependent on context. Outcomes from similar technological interventions may differ depending on organisational readiness, network complexity, conditions of interoperability, and stakeholder collaboration. Because of this, the mechanisms activated within the operational context must be validated to explain logistics transformation rather than technology deployment. Hence, this research adds to an emergent body of literature in Logistics 4.0 by providing a structured synthesis of recent work at the intersection of the Physical Internet and Internet of Things. This research study adopts an analytical perspective based on the CIMO framework, unlike past reviews which are primarily catalogue of technologies and applications.

According to the authors, the primary contribution of this study is to examine the transformation of logistics enabled by PI-IOT through a systematic CIMO lens. The framework helps understand the causal pathways through which logistics performance improvements accrue by explicitly linking the contexts, interventions, mechanisms, and outcomes. Unlike previous technology-centred reviews, this mechanism-based synthesis explains how technological interventions generate performance improvements under specific contex-

tual conditions, thereby providing a stronger theoretical foundation for understanding PI-IoT-enabled logistics transformation. This article finds similarities in how innovations are actually implemented, and, importantly, the results are not created by the technology (like AI or blockchain) but by other mechanisms like sharing resources, interoperability, visibility, adaptive coordination, and collaborative decision-making. Consequently, there is an increased understanding of the nuances of digital logistics transformation. Further, it offers an explanation for why similar deployments lead to diverse results. This review further elaborates the relationship between PI and IoT, as both are complementary components of the socio-technical logistics system. Collaborative logistics networks rely on PI for their structuring basis and on IoT for their coordination in optimum time.

The results also offer practical implications for logistics managers, supply chain practitioners, and policy makers to fast-track digital logistics transformation. Interoperability should be given priority as a strategic capability by organisations. It matters because the effectiveness of PI-IoT-enabled logistics systems depends on exchanging and coordinating activities across organisational boundaries. It is thus important to invest in standard data-sharing frameworks. Real-time visibility should be seen as an essential driver of operational performance, given that IoT technologies give critical information about inventory, asset locations, transport conditions, and operational disruptions, enabling a much more flexible and informed response. Networking is moreover essential within logistics ecosystems as highlighted by this review. Resource pooling, joint infrastructures, and collaboration in public transport consistently are seen as key measures to improve efficiency and sustainability. As a result, organisations should consider governance structures and partnerships that can share information and jointly use resources. The increasing importance of digital twins also offers considerable potential for enhancing logistics planning and operational control through scenario analysis, predictive monitoring, and adaptive coordination between physical and digital environments. These mechanisms provide practical guidance for designing collaborative logistics networks, improving resource utilization, reducing environmental impacts, and supporting resilient and sustainable supply chain operations. From a managerial perspective, organisations should prioritise interoperable digital infrastructures, secure data-sharing mechanisms, workforce capability development, and collaborative governance models before scaling PI-IoT initiatives. From a policy perspective, governments and regulatory bodies should promote interoperability standards, cybersecurity frameworks, and digital infrastructure investments that facilitate secure collaboration among logistics stakeholders while accelerating sustainable supply chain transformation.

When making sense of the outcomes of this review, a number of limitations should be accepted. Only papers that are indexed in Scopus were analysed. In the Scopus database, logistics, supply chain, and Industry 4.0 studies are more than enough. However, other databases have relevant studies that are not covered. This review only targeted publications released between 2020 and 2025. While this time frame indicates the most recent PI-IoT contributions, earlier works may consist more additional insights relevant to the logistics transformation. Moreover, the studies reviewed show considerable heterogeneity in their methodology, such as the conceptual framework, optimisation models, simulation studies and case studies.

While this abundance offers a full picture of the field, it renders formal quantitative meta-analysis impossible and direct comparison unfeasible. Ultimately, the performance outcomes recorded in the literature are highly context dependent and should therefore be regarded as indicative rather than generalisable.

The review highlights several future research opportunities. It remains a high priority to conduct empirical validation. There are many articles that discuss industrial scale (conceptual and optimisation based) activities. Going forward, further research is needed on

piloting studies, longitudinal case studies, and cross-sector implementation evaluations driven by the benefits forecasted in the foregoing models. Another significant direction is the further embedding of digital twins within PI-IoT-based logistics systems. The merging of sensing, digital representation, and adaptive decision-making has significant potential to enhance logistics visibility, resilience, and sustainability. Further studies must test real industrial deployments in realistic operating conditions and how implementation is affected by organisational structures, governance mechanisms, interoperability requirements, and stakeholder behaviour, and so on. More attention should also be paid to the other hand, as today's logistics systems are working with dynamic uncertainty environments reflecting changes in demand supply disturbances through the delivery process and changing networks. Thus, future studies ought to devise adaptive and resilient optimisation techniques that can assist real-time decision-making in complex logistics ecosystems.

Overall, this review demonstrates that PI-IoT integration extends beyond technological convergence to become a strategic enabler of intelligent, collaborative, and sustainable logistics ecosystems. By adopting a mechanism-based CIMO perspective, this study provides a stronger foundation for future research and practical implementation while supporting the transition toward resilient, human-centric, and data-driven logistics systems envisioned by both Logistics 4.0 and Industry 5.0.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/logistics10080168/s1>, Table S1: PRISMA 2020 Checklist. Reference [55] is cited in the Supplementary Materials.

Author Contributions: Conceptualization, S.T.; methodology, S.T.; validation, M.A., A.K.S., F.M., and M.D.N.; writing—original draft preparation, S.T.; writing—review and editing, S.T. and F.M.; supervision, M.A., A.K.S., M.D.N., and F.M. All authors have read and agreed to the published version of this manuscript.

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Abbreviations

The following abbreviations are used in this manuscript:

CIMO	Context, Intervention, Mechanism, Outcome
IoB	Internet of Behaviours
IoT	Internet of Things
PI	Physical Internet
PRISMA	Preferred Reporting Items for Systematic reviews and Meta-Analyses
RFID	Radio Frequency Identification

Appendix A

Table A1. Corpus table.

No	Author(s) (Year)	Enhanced Criteria/Description	CO ₂	Time	Cost	Mapping	Key Technologies	Critical Analysis & Contradictions
1	[56]	Consumer-centric circular supply chain for SCG recycling with behavioural gap analysis	✓	X	X	PI + Circular Economy	IoT, Blockchain	Highlights critical behaviour–action gap. Strong socio-technical perspective but lacks operational or quantitative validation of logistics performance.
2	[34]	Smart agri-food logistics architecture enabling real-time traceability and anomaly detection	✓	✓	✓	PI + Smart Logistics	IoT, Blockchain, EPCIS	One of the few empirically validated systems. However, scalability beyond pilot implementation and integration with legacy systems remain unclear.
3	[45]	Real-time CPoIoT kernel ensuring deterministic execution and safety in logistics systems	X	X	✓	CPoIoT Infrastructure	Rust, Real-time OS	Focuses on system-level performance rather than logistics KPIs. The link between kernel efficiency and supply chain optimization outcomes remains insufficiently demonstrated.
4	[57]	Virtualised network training environment for IoT-enabled logistics systems	X	X	✓	Educational Infrastructure	Cloud, Virtual Labs	Addresses skills gap but not directly logistics performance. Indirect contribution to PI adoption through workforce readiness.
5	[19]	Ontology-based PI traceability system for real-time visibility and coordination	✓	✓	✓	PI + SCM	IoT, Cloud, Fog Computing	Strong interoperability contribution, but assumes full data integration, real-world fragmentation remains a major unresolved barrier.
6	[20]	Conceptual framework linking PI and circular economy via technological and collaborative drivers	✓	X	X	PI + CE Framework	IoT, Blockchain, Big Data	Purely conceptual. Identifies key attributes but lacks causal validation and measurable performance impact.
7	[51]	Internet of Behaviours (IoB) integrating human behaviour data into IoT ecosystems	X	X	X	IoB + PI Extension	AI, IoT, Big Data	Introduces behavioural dimension but raises privacy and ethical contradictions, limiting real-world deployment in logistics.
8	[29]	Urban freight analytics using AI, digital twins, and collaborative logistics models	✓	✓	✓	PI + City Logistics	AI, IoT, Digital Twins	Strong systems approach, but data sharing assumption between stakeholders is unrealistic in competitive environments.
9	[58]	Energy-efficient resource allocation in CPoIoT using optimization models	✓	X	✓	CPoIoT Optimization	5G/6G, IoT, MINLP	Strong mathematical formulation but detached from logistics context (focus on energy, not flows or routing).
10	[59]	Smart logistics node classification for digital and automated transport integration	✓	✓	✓	PI Infrastructure	IoT, CAT systems	Identifies gap between digitalization and automation. Lacks implementation roadmap and cost-benefit quantification.

Table A1. Cont.

No	Author(s) (Year)	Enhanced Criteria/Description	CO ₂	Time	Cost	Mapping	Key Technologies	Critical Analysis & Contradictions
11	[21]	PI-based ontology for traceability and interoperability across supply chains	✓	✓	✓	PI + IoT	Cloud, Fog, Ontologies	Similar to [19] strong semantic layer but limited scalability validation in heterogeneous ecosystems.
12	[52]	HCCI tool for designing smart IoT products considering user interaction	X	X	X	IoT Design Layer	HCI, IoT	Focuses on product design, not logistics. Useful for human-centric PI, but indirect contribution.
13	[46]	Transaction management framework for edge–cloud IoT systems	X	✓	X	IoT Infrastructure	Edge/Cloud Computing	Strong on system performance but lacks integration with logistics decision-making or supply chain optimization.
14	[60]	Blockchain-based secure data association and ownership management in IoT	X	X	✓	IoT + Blockchain	Smart Contracts	Addresses trust and data ownership but introduces complexity and computational overhead, limiting scalability.
15	[36]	Hyperconnected autonomous supply system for critical products using PI principles	✓	✓	✓	PI + Autonomous Logistics	Multi-agent systems, IoT, Robotics	Strong real-case validation (COVID). However, scalability and generalization beyond crisis context remain unclear.
16	[15]	Literature review on PI resilience and future research directions	X	X	X	PI Framework	IoT, Digital Twins	Identifies a major gap: resilience is underexplored in PI. Purely conceptual with no operational metrics.
17	[37]	Big data streaming framework for IoT-based forecasting in PI environments	X	✓	X	IoT + Data Layer	Big Data, Spark, ML	Strong data pipeline but disconnect between forecasting and logistics decision-making.
18	[47]	Edge computing framework for real-time CPS-IoT control optimization	X	✓	X	CPS-IoT Infrastructure	Edge AI, CEP	Significant latency reduction, but no direct logistics performance evaluation (cost/CO ₂).
19	[61]	Privacy-preserving collaborative edge computing for Social IoT	X	X	X	IoT Security Layer	DL, Edge Computing	Addresses privacy challenges but introduces computational overhead and complexity.
20	[17]	CPI-enabled architecture for aviation MRO intralogistics optimization	✓	✓	✓	CPI + Industrial Logistics	Digital Twin, IoT, Robotics	Strong industrial application, but case-specific (aviation) → limited generalizability.
21	[33]	Physical Internet container for multimodal wood logistics optimization	✓	✓	✓	PI + Transport Optimization	Smart Containers, Sensors	Practical contribution with measurable gains, but limited to specific sector (wood logistics).
22	[39]	Smart service platform for road-based Physical Internet implementation	✓	X	X	PI Architecture	IoT, SOA	Conceptual architecture; implementation feasibility and economic viability unclear.
23	[62]	Federated learning-based secure computation offloading in CPS-IoST systems	X	✓	X	CPS-IoT	Federated Learning, Edge Computing	Improves latency and privacy but ignores logistics-level optimization objectives.
24	[30]	Multi-objective optimization of PI-enabled production-distribution system	✓	✓	✓	PI Optimisation	MINLP, NSGA-III, IoT	Highly relevant: rare work integrating CO ₂ , cost, and time. Still lacks real-world deployment validation.

Table A1. Cont.

No	Author(s) (Year)	Enhanced Criteria/Description	CO ₂	Time	Cost	Mapping	Key Technologies	Critical Analysis & Contradictions
25	[48]	Blockchain-assisted resource allocation for secure CPS-IoT systems	X	✓	X	CPS-IoT	Blockchain, DRL	Improves security + latency but adds computational burden and scalability issues.
26	[18]	IoT-based localization system for fresh food logistics tracking	✓	✓	✓	Smart Logistics	Sensors, Magnetic Communication	Strong for quality monitoring, but limited to tracking, not full logistics optimization.
27	[43]	PI-enabled multi-model optimization for meals-on-wheels delivery	X	✓	✓	PI + Routing Optimization	MILP, Clustering	Real-case validated. However, CO ₂ dimension missing despite sustainability claim.
28	[31]	Digital twin-based synchronization framework for PI hubs	✓	✓	X	PI + Digital Twins	IoT, ML, Simulation	Strong operational improvement, but cost dimension not explicitly optimised.
29	[49]	Lightweight authentication protocol for IoT systems security	X	X	X	IoT Security	Cryptography, PUF	Purely technical; no direct contribution to logistics or PI performance.
30	[12]	Systematic review on IoT-enabled sustainable supply chains in Industry 4.0	✓	X	X	IoT + SSCM	IoT, Industry 4.0	Comprehensive overview but no quantitative validation or optimization models.
31	[63]	IoT cybersecurity dataset and intrusion detection for network protection	X	X	X	IoT Security	ML, IDS, SDN	Strong technical contribution, but irrelevant to logistics performance or PI optimization.
32	[64]	Blockchain-enabled traceability in olive oil supply chain	✓	X	✓	PI + Food SCM	IoT, Industry 4.0	Enhances transparency but economic gains are theoretical and not empirically validated.
33	[44]	Cloud–fog architecture for PI-enabled supply chain optimization	X	✓	✓	PI + Optimization	IoT, Fog Computing, A*	Includes routing optimisation, but CO ₂ dimension is missing despite sustainability claims.
34	[40]	Industry Commons ecosystem for cross-domain data sharing in PI systems	X	X	X	PI Ecosystem	Ontologies, AI, Data Sharing	Highlights major barrier: lack of interoperability and trust, but remains conceptual.
35	[42]	Digital twin-based packing optimization for PI containers	X	✓	✓	PI + Optimisation	Digital Twin, Sensors	Strong operational contribution, but limited to packing problem (not full SC optimization).
36	[35]	Stochastic optimization model for resilient PI-enabled production distribution systems	X	✓	✓	PI Optimisation	Stochastic Programming, Heuristics	Strong model + resilience, but no CO ₂ /environmental objective included.
37	[16]	Conceptual analysis of PI under digital transformation technologies	X	X	X	PI Framework	IoT, AI, Big Data, 5G	Identifies key enablers but lacks measurable performance evaluation.
38	[65]	AI-driven smart mobility and transport systems in smart cities	✓	✓	X	Smart City + PI	AI, ITS, IoT	Broad conceptual scope; PI only marginally integrated.
39	[38]	Reinforcement learning for smart container bidding in PI logistics	X	✓	✓	PI + AI Optimization	Multi-agent RL	Innovative decentralised approach, but assumes cooperation despite competitive actors.

Table A1. *Cont.*

No	Author(s) (Year)	Enhanced Criteria/Description	CO ₂	Time	Cost	Mapping	Key Technologies	Critical Analysis & Contradictions
40	[41]	RFID-based logistics simulation model for scalable PI systems	X	X	X	PI Simulation	RFID, IoT	Demonstrates feasibility, but simplified model limits real-world applicability.
41	[66]	Intelligent transport unit (ITU) for secure and monitored logistics	X	X	X	PI Infrastructure	IoT, Sensors, C-ITS	Improves safety, but no measurable impact on cost/time/CO ₂ .
42	[32]	Agent-based simulation integrating carbon trading in PI logistics	✓	X	✓	PI + Sustainability	Multi-agent systems	Rare integration of carbon markets, but simulation-based only (no real data validation).
43	[28]	Optimization of collaborative LTL logistics under PI paradigm	X	✓	✓	PI Optimisation	Network Flow, Heuristics	Strong cost/time optimization, but environmental impact not considered.

A* pathfinding algorithm and the real-time processing capabilities enabled by IoT and fog computing.

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