

Artificial Intelligence in the Physical Internet

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Abstract: The primary objective of this study is to investigate the influence of Artificial Intelligence (AI) on the evolution of the Physical Internet (PI), a transformative vision for logistics systems, through a thorough analysis of pertinent literature. This research aims to bridge the gap in scientific knowledge regarding AI's integration into the PI by identifying AI methods to enhance both theory and implementation. Specifically, the study focuses on three aspects: (1) the most prevalent AI methods in PI, (2) the potential theme-specific AI enhancements of PI, and (3) the potential AI methods for employment in PI. The study proposes a novel AI-in-PI framework which will help academicians and practitioners in identifying current research patterns of AI in PI. Furthermore, the study identifies literature gaps requiring further investigation and offers valuable insights into the intersection of AI and PI.

Keywords: Physical Internet, Artificial Intelligence, Hyperconnected Logistics, Optimization, Autonomous Vehicles, City/Urban Logistics, PI-Adoption.

Physical Internet (PI) Roadmap Fitness: Select the most relevant area(s) for your paper according to the PI roadmaps adopted in Europe and Japan: ☒ PI Nodes (Customer Interfaces, Logistic Hubs, Deployment Centers, Factories), ☒ Transportation Equipment, ☒ PI Networks, ☐ System of Logistics Networks, ☐ Vertical Supply Consolidation, ☐ Horizontal Supply Chain Alignment, ☐ Logistics/Commercial Data Platform, ☒ Access and Adoption, ☐ Governance.

Targeted Delivery Mode-s: ☒ Paper, ☐ Poster, ☐ Flash Video, ☒ In-Person presentation

1 Introduction

The Physical Internet (PI) is one of the burgeoning transformative paradigms poised to revolutionize global logistics networks by facilitating seamless interconnection. Serving as a tangible counterpart to the digital realm, PI advocates for the interconnectedness and openness of diverse logistics and supply networks, promising to deliver substantial benefits and opportunities. Since Herbert Simon's famous assertion in 1965 that "Machines will be capable of doing any work a man can do," the trajectory of Artificial Intelligence (AI) has been nothing short of remarkable. Originating with the inception of expert systems and fuzzy logic, the journey of AI gained momentum after 2010 with the advent of big data, analytics, and the proliferation of Graphical/Tensor Processing Units (GPUs/TPUs) and deep learning techniques. These advancements have collectively propelled AI into what we now recognize as modern AI.

Previous reviews (see Chen et al., 2021; Pan et al., 2021; Cortes-Murcia et al., 2022; Samadhiya et al., 2023) show a lack of AI focus in PI literature. This study aims to provide comprehensive coverage and incorporate the latest breakthroughs in AI. The research questions (RQs) stated in this paper are as follows:

RQ1: What are the most prevalent AI methods?

RQ2: What are the potential PI-Theme-specific AI enhancements?

RQ3: What are the potential AI methods for PI?

The subsequent sections of this article are organized as follows: the second section outlines the methodology for the review. Followed by bibliometric analysis (Section 3) and content analysis (Section 4). Section 5 provides the AI in PI conceptual framework with answers to the RQs and providing recommendations for future guidelines. Finally, Section 6 concludes with theoretical and managerial implications. To conserve space, the full list of references is available on the GitHub link:

<https://github.com/SS-Chadha/AI-in-PI/blob/new-branch/Literature%20collected%20final.txt>

2 Review Methodology

The research questions are addressed using the Systematic Literature Review (SLR) technique. Thomé et al. (2016) offer guidance on conducting and reporting SLRs. They present a rigorous approach with detailed step-by-step instructions, emphasizing an operations management perspective. This review adapts the Thomé et al.'s guidelines, including five steps: (i) planning and formulating the problem; (ii) searching the literature; (iii) data gathering and quality evaluation; (iv) data analysis, synthesis and interpretation; (v) presenting results and updating the review. Additionally, the PRISMA framework, which stands out as the gold standard for meta-synthesis and meta-analysis across various industries, including the supply chain domain (Naseem & Yang, 2021), is utilized for both data presentation and review revision.

Section 1 covered the first step in Thomé et al. (2016), i.e., planning and formulating the problem. This section describes the next two steps. Databases used for our review are Engineering Village (Elsevier), Scopus (Elsevier), ScienceDirect (Elsevier), Taylor & Francis Online, and Google Scholar. The following keywords and Boolean operators are employed for extracting the relevant scholarly articles (from 2010 to 2024) for our study:

(“physical internet”) AND (“artificial intelligence” OR “machine learning” OR “deep learning” OR “unsupervised learning” OR “supervised learning” OR “reinforcement learning”)

Due to the large volume of articles retrieved from Google Scholar, an additional keyword, “hyperconnected” is incorporated to refine the search, given that the initial number of articles approached 3,000. This decision aligns with Montreuil's characterization of the Physical Internet as “hyperconnected,” emphasizing the interconnectedness of its components across multiple layers and locations (Montreuil, 2015, Oger et al., 2018).

Figure 1 depicts the PRISMA flow map that includes the number of documents retrieved from each of the databases and the screening criteria. A total of 557 documents are recorded. After duplicate removal and keeping only English documents, 414 records are further screened on abstracts, keywords, and topic. This renders 123 records for full article assessment. Ten records are excluded after full article assessment, leaving 113 articles for bibliometric and in-depth content analysis. The last search was conducted on March 28, 2024.

3 Bibliometric exploration

Utilizing VOSviewer, a robust bibliometric analysis tool, we identify relationships among authors, terms, documents, and cited references. Known for its advanced features such as co-authorship, co-occurrence, bibliographic coupling, and co-citation networks, VOSviewer facilitates comprehensive analyses (Jan van Eck & Waltman, 2010). In this study, 113 records (including books, conferences, dissertations/thesis, and journal articles) are reviewed.

Bibliometric analysis comprises of five prime metrics: (1) Year, (2) Authors, (3) Keywords, (4) Types of journals, (5) Citations.

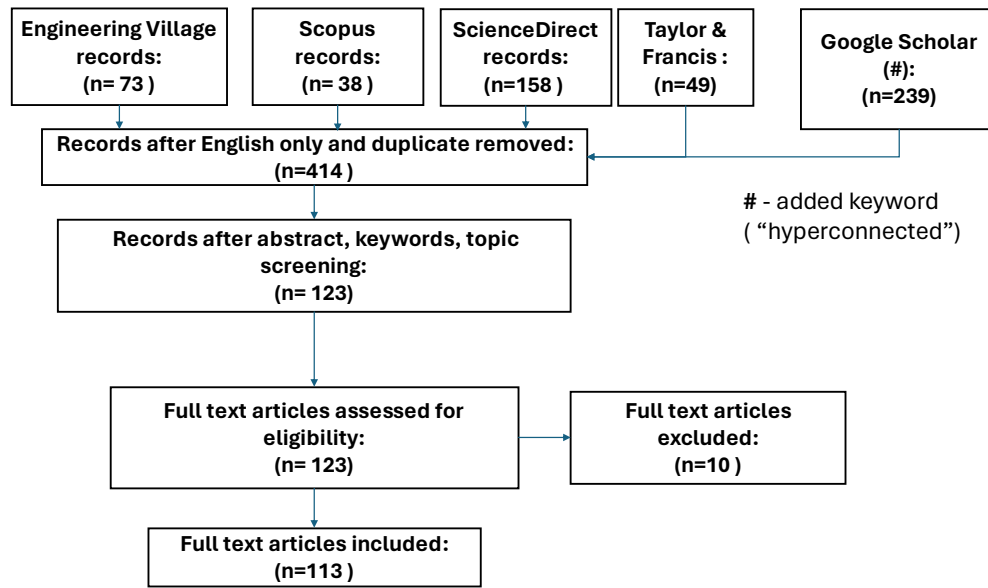


Figure 1 PRISMA flow map

3.1. Timeline trend

The number of publications and citations at various times are used in this study to show the research trend from 2010 to 2024. Accordingly, the first article mentioning some form of AI in PI is Meller et al. (2012), wherein, “a heuristic method, employing three rules to restrict the search, was proposed to determine the optimal modular container size for each product.” The results reveal a substantial increase in the pace of publications in recent years, as seen in Figure 2. Following the publication of the paper on container standardization and selection in 2012, there was a relatively sparse amount of research conducted in that domain until 2017. Since 2017, there has been a noticeable increase in research interest in employing AI in PI research, evident from the linear trend line depicted in blue dotted line.

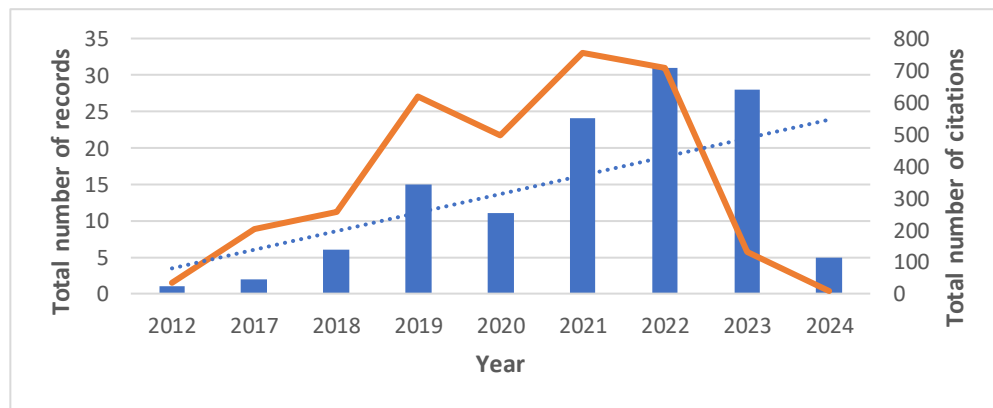


Figure 2 Number of publications and citations per year

3.2. Authors' influence

The top 10 most cited authors are depicted in Figure 3. With 381 citations, Klumpp, Matthias is the most referenced author. With 269 citations, Tran-Dang, H. is rated second, followed by Bruno, Giorgio; Giusti, Riccardo; Manerba, Daniele; Tadei, Roberto with 192 citations each. Klumpp, M authored three journal articles relevant to the scope of this SLR. The most highly cited among them is a solo-authored paper, which introduces a comprehensive multidimensional conceptual framework. This framework aims to distinguish between high and low-performing human-artificial collaboration systems in logistics, aiding in investment

decision-making (Klumpp, 2018). The other two papers are co-authored with Hesenius, M; Meyer, O; Ruiner, C; Gruhn, V, and Zijm, H respectively. Tran-Dang, H closely follows with three articles, all co-authored with Kim, D. Additionally, two of these articles feature co-authors Krommenacker, N and Charpentier, P. These articles focus on the IOT and digitization era for PI.

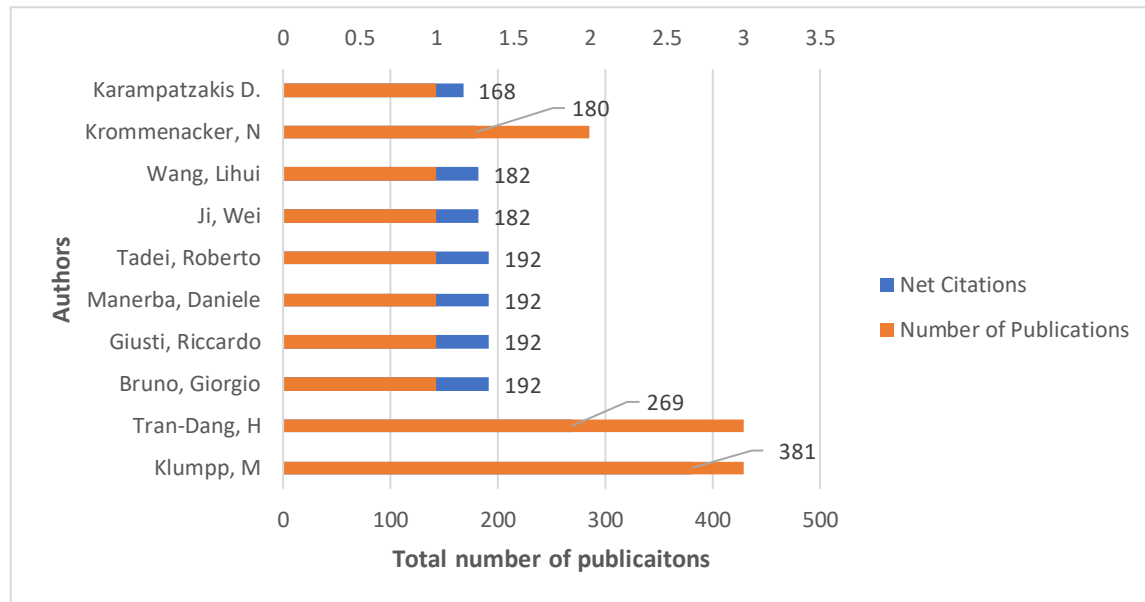


Figure 3

3.3. Keyword analysis

Keywords are nouns or phrases that represent the core content of a piece of literature. The existence of two terms in the same scientific article is referred to as co-occurrence. This study involves a total of 379 keywords. The co-occurrence threshold of keywords was set at 3. As a result, 36 items were inserted into visualization to demonstrate keywords co-occurrence (see Figure 4).

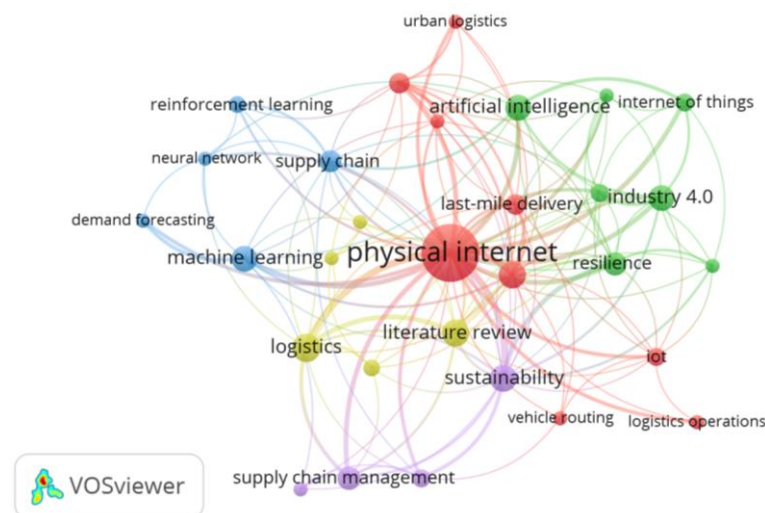


Figure 4

The data is segmented into five distinct clusters, each highlighting specific themes:

- Logistics Operations (red): Encompassing keywords such as “city logistics,” “last-mile delivery,” “optimization,” and “vehicle routing,” this cluster emphasizes the operational facets of logistics.

- Cyber-Physical Systems (green): Including terms such as “artificial intelligence” and “internet of things,” this cluster underscores the fusion of digital and physical systems within logistics, epitomizing concepts such as “industry 4.0” and “digital twin.”
- Data Analytics (blue): Featuring keywords such as “machine learning” and “demand forecasting,” this cluster accentuates the role of data analytics and machine learning techniques in enhancing logistical processes.
- Research trends and Methodology (yellow): Comprising terms such as “literature review” and “bibliometric analysis,” this cluster delves into the meta-level examination of logistics research methodologies and trends (“digitalization” and “omnichannel logistics”).
- Sustainability and Management (purple): Enriched with terms such as “sustainability” and “supply chain management,” this cluster centers on sustainable practices and management strategies within logistics operations.

The keyword trends for AI in PI showcase a strong focus on emerging technologies such as IoT, cyber-physical systems, digital twin, and industry 4.0. Optimization and simulation techniques are also prominent, suggesting efforts to enhance efficiency. Sustainability and resilience keywords reflect a growing concern for sustainable practices, while terms such as machine learning indicate a shift towards data-driven approaches.

3.4. Publication themes and metrics

The publications cover a diverse range of focus areas including operations research, logistics, transportation, environmental sciences, sustainable development, and manufacturing (see Table 1). This diversity caters to different disciplines and interests within the broader field of production and logistics. Gathered records include academic journals (85), conferences (18), books (6), theses (3), and dissertations (5). While both CiteScore and Impact Factor are measures of a journal's influence, they may vary due to differences in calculation methods. For instance, Computers in Industry has a relatively high CiteScore (21) compared to its Impact Factor (10), suggesting it might have received a significant number of citations recently. Journals such as International Journal of Production Economics, Journal of Manufacturing Systems, Journal of Cleaner Production, and Computers in Industry have relatively **high impact factors and CiteScores**, indicating their significance and influence in their respective fields. Journals like International Journal of Production Economics, International Journal of Logistics Research and Applications, and Transportation Research Part E: Logistics and Transportation Review have **high citation counts**, suggesting they are frequently referenced in academic literature. Journals such as IEEE Internet of Things Journal and The International Journal of Advanced Manufacturing Technology focus on niche areas such as IoT and advanced manufacturing respectively.

4 Content analysis

Literature reviews (LRs): The LR records are condensed into three thematic clusters relevant to AI and the PI, highlighting their application and impact on logistics and supply chain management (L&SCM). The first cluster focuses on the PI and digital transformation in logistics, exploring innovative frameworks, deployment strategies, and their role in enhancing resilience and sustainability (L’Hermitte et al., 2018; Tran-Dang & Kim, 2019; Tran-Dang et al., 2020; Pan et al., 2021; Fahim et al., 2021; Safwen et al., 2021; Chargui et al. 2022). The second cluster centers on the integration of AI and advanced technologies in logistics, including applications of machine learning, blockchain, drones, and the Internet of Things, showcasing the evolution towards smarter, data-driven logistics solutions (Giusti et al., 2019; Bekrar et al., 2021; Soebandrija et al., 2018; Kantasa-Ard et al., 2019; Nikitas et al., 2020; Taniguchi et al., 2020; Barykin et al, 2023; Agnusdei et al., 2022). The third cluster addresses digital twins, omnichannel strategies, and warehouse management, emphasizing the role of

digital tools in optimizing supply chain operations, enhancing warehouse efficiency, and supporting sustainable urban logistics (Sampaio et al., 2019; Duong et al., 2022; Yu et al., 2022; Ferrari et al., 2022; Hübner et al., 2022; Bélanger et al., 2023;). These clusters illustrate the convergence of AI and the PI in transforming contemporary logistics practices and paving the way for future advancements.

Table 1 Summary of academic sources (top eleven based on publication counts)

Source	Impact factor	CiteScore	Count	Focus	Type	Citations
International Journal of Production Economics	12	19	7	Operations Research & Management Science	Journal	286
IFAC-PapersOnLine		1.8	7	Electrical and Electronic Engineering, Computational Mechanics, Control and Systems Engineering	Journal	80
International Physical Internet Conference			6	Interconnected freight transport, logistics and supply networks	Conference	7
International Journal of Production Research	9.2	18	5	Manufacturing, Industrial Engineering, Operations Research and Management Science	Journal	107
Dissertation			5		Dissertation	1
Transportation Research Procedia		3.2	4	Social science area of transportation research	Journal	114
International Journal of Logistics Research and Applications	6.6	10	3	Logistics And Supply Chain Management	Journal	280
Transportation Research Part E: Logistics and Transportation Review	10.6	15	3	Logistics and Transportation	Journal	272
Sustainability	3.9	5.8	3	Sustainability	Journal	117
Computers & Industrial Engineering	7.9	12	3	Computer Science, Interdisciplinary Applications	Journal	71

Conceptual frameworks: Within frameworks, two primary clusters emerge. The first cluster focuses on the PI and hyperconnected logistics systems, exploring frameworks and strategies for integrating the PI into city logistics, passenger air transport, last-mile delivery, and critical-product distribution (Kubek & Więcek, 2019; Suryavanshi, 2022; Kayikci et al., 2023). This cluster highlights the potential for enhanced performance, sustainability, and autonomous operations in logistics networks (Suryavanshi, 2020; Shaikh et al., 2023). The second cluster centers on the application of AI and automation in logistics and supply chain management, addressing human reactions, collaboration requirements, and the design of smart product-service systems. It includes conceptual frameworks for automation, innovative mobility concepts for smart cities, and the use of generative AI to optimize supply chain operations (Klumpp et al., 2018; Pan et al., 2019; Guo et al., 2021; Jackson et al., 2024).

PI problems and AI solutions: In the realm of PI logistics, addressing diverse challenges demands a spectrum of AI solutions. Leveraging Proximal Policy Optimization (PPO), joint replenishment problems can be efficiently managed through adaptive policy learning. Long Short-Term Memory Recurrent Neural Networks (LSTM RNNs) may prove indispensable for precise demand forecasting, ensuring optimized inventory management. Reinforcement Learning (RL) emerges as a versatile tool for dynamic tasks such as platoon organization, container and delivery trading, and self-organization, offering adaptable decision-making in real-time scenarios. Machine Learning (ML) techniques excel in joint order fulfillment and replenishment, harnessing historical data for predictive analytics. Meanwhile, the intricate

dynamics of location service areas find resolution through a combination of Deep Learning (DL) models, metaheuristics, and active learning, enabling spatial optimization with efficiency and accuracy. For tackling the classic Vehicle Routing Problem (VRP), a plethora of AI approaches including AI algorithms, metaheuristics, and self-organizing systems offer diverse avenues for optimization.

5 Discussion

The outcomes derived from employing SLR are consolidated in this section through the development of a conceptual framework (akin to Cortes-Murcia et al., 2022). This framework serves to address RQ1-RQ3 by visually illustrating how AI technologies address PI problems. It does so by depicting PI components along the rows and AI solutions along the columns, providing a graphical representation of their alignment (see Figure 5).

Physical Internet domain		Artificial Intelligence									
		Machine Learning				NLP	Computer Vision	Expert Systems	Robotics	Cognitive Computing	Generative AI (Boltzmann Machines, GANs)
		Supervised Learning	Unsupervised Learning	Deep Learning	Reinforcement Learning						
Logistics & Supply Chain Management	City Logistics / Urban Freight Logistics/ Last Mile Delivery	T [Locating service area] Locker	B [Performance improvement]								
				C [Demand forecasting; Joint replenishment; platoon organization; Container trading]							
			T [Locating service area]	T [Locating service area]	C [Delivery trading; Self Organization] T [Task Assignment]						
				V [VRP*; Truck Loading]	*Drone/Bike/Robot						
	Maritime Ports		*Parcel Delivery								
	Indoor Positioning Systems (IPS) and Indoor Location-Based Services (ILBS)			T [Monitoring; Inbound container forecasting]							

PI Theme addressed := B: Business Models; C: Cooperation Models; M: Modular Container; T: Transit Centers; V: Vehicle usage utilization
 [] := PI problem
 ■ Hyperconnected City Logistics / Urban Freight Logistics/ Last Mile Delivery
 ■ Manufacturing /Material Handling Systems

Figure 5 AI in PI conceptual framework

RQ1: What are the most prevalent AI methods?

In the context of the PI, the applications of AI methods are diverse. RL stands out as a prevalent technique, offering adaptive decision-making capabilities for tasks such as platoon organization (Puskas et al., 2020), container and delivery trading (Guo et al., 2021), and self-organization within PI networks. Alongside RL, metaheuristic algorithms play a significant role in optimizing various aspects of PI operations, from vehicle routing to location service area optimization and performance improvement (Meliani et al., 2019; Che et al., 2022). DL methods, with their ability to process vast amounts of data and extract intricate patterns, contribute to tasks such as monitoring (Liu et al., 2022), forecasting (Helmi et al., 2022), and optimizing truck loading (Bai et al., 2020) processes within PI systems. Additionally, ML techniques find utility in joint order fulfillment and replenishment (Leung et al., 2022), as well as active learning approaches within PI networks.

RQ2: What are some PI-Theme-specific AI enhancements?

Across different themes, provided by Treiblmaier et al. (2020), modular containers, vehicle usage utilization, transit centers, data exchange, cooperation models, legal framework, and business models, a range of challenges are identified. Within the context of modular containers, AI-driven solutions are instrumental in addressing challenges such as container packing and bin-packing, potentially revolutionizing container optimization processes. In terms of vehicle usage utilization, AI technologies such as deep learning algorithms and more traditional metaheuristics such as Tabu Search and simulated annealing/self-organization/solver algorithms (which can easily be converted into a RL setting; see Powell, 2011 & 2022),

contribute to optimizing heterogeneous fleet vehicle routing, truck loading, and co-modality, enhancing resource efficiency, and reducing transportation costs. Transit centers, pivotal nodes in the PI network, benefit from AI advancements in location service area optimization, monitoring, and joint order fulfillment and replenishment, facilitated by techniques such as deep learning, machine learning, and metaheuristics. Cooperation models are enhanced by AI techniques such as reinforcement learning, which optimize processes such as platoon organization, container trading, and delivery trading, promoting smoother interactions and resource allocation among stakeholders. Furthermore, AI applications in legal frameworks and business models offer potential for innovative solutions, such as AI-driven route optimization and delivery scheduling, demand forecasting, and adoption modeling, ultimately enabling more agile and adaptive PI systems. The applications of AI in areas such as data exchange, legal frameworks and business models (Ji et al., 2023) indicate the need for further exploration and development in these domains.

RQ3: What are the potential AI methods for PI?

AI technologies such as NLP, Computer Vision, Expert Systems, Robotics, Cognitive Computing, and Generative AI hold significant potential for enhancing PI systems across various dimensions. NLP can facilitate seamless communication and information exchange within PI networks, enabling efficient coordination and decision-making. Computer Vision can aid in the automation of tasks such as object recognition and tracking, enhancing the efficiency of processes such as inventory management and package handling. Expert Systems can provide intelligent decision support, offering recommendations and insights based on complex data analysis and domain expertise. Robotics technologies can enable automation and autonomy in tasks ranging from warehouse operations to last-mile delivery, optimizing resource utilization and reducing operational costs. Cognitive Computing can enhance PI systems' adaptability and responsiveness by leveraging advanced reasoning and learning capabilities to interpret and respond to dynamic environmental conditions. Generative AI techniques such as Boltzmann Machines and Generative Adversarial Networks (GANs) can generate synthetic data for simulation and optimization purposes, facilitating scenario testing and decision-making in PI planning and operations.

AI can significantly enhance the implementation of the PI roadmap developed by the SENSE project (Ballot et al., 2020). By transforming Logistics Nodes into PI Nodes, AI can automate sorting and storage, optimize modular load unit use, and enable real-time tracking and digital service access. In logistics networks, AI-driven predictive analytics can optimize routes and schedules, while IoT sensors monitor goods in transit, ensuring timely and reliable deliveries. AI can integrate individual logistics networks by analyzing data to consolidate shipments and maximize transport asset use. For access and adoption, AI can provide simulation models and virtual assistants to support stakeholders in transitioning to PI concepts. In governance, AI can automate rule enforcement and enhance transparency through blockchain technology, ensuring a secure and compliant logistics environment.

6 Conclusion

The SLR presented here offers an assessment of recent studies (2010-2024), accompanied by an analytical discourse, synthesis framework, and suggestions for future research directions, highlighting the numerous contributions that AI brings to PI.

The potential benefits of AI for adopting the PI are substantial and multifaceted. AI can process and analyze vast amounts of data from numerous IoT devices, enabling seamless integration and real-time tracking across the supply chain(s), thereby enhancing transparency and efficiency. Predictive analytics employing AI and machine learning models can significantly improve demand forecasting, leading to optimized inventory management, reduced waste, and increased customer satisfaction. By automating routine tasks and providing advanced decision

support amid complex logistics operations, AI markedly can boost the efficiency and resilience of the PI.

In conclusion, the exploration of the conceptual framework surrounding PI problems and AI solutions offers profound insights into the evolving landscape of logistics and supply chain management. Through this literature review, we have delved into the complexities of organizational challenges within the context of the PI, highlighting the diverse array of issues organizations face in modern logistics. Concurrently, the integration of AI solutions presents promising avenues for addressing these challenges with greater efficiency and effectiveness. By understanding the interplay between theory and practical applications in organizational settings, we uncover opportunities for innovation and optimization within the logistics and supply chain domain. As organizations continue to navigate this dynamic environment, the synergy between conceptual understanding and technological innovation will undoubtedly play a pivotal role in driving organizational success and resilience in the face of evolving challenges.

Future research must improve decision-making methods within the PI context. AI can enhance decision-making by leveraging real-time data, integrating diverse data sources, AI-enabled tools, and simulation models. Real-time information from IoT sensors and GPS tracking allows immediate operational adjustments, optimizing efficiency and responsiveness. AI's ability to integrate data across the logistics network provides a comprehensive supply chain view, revealing patterns and insights that lead to more informed decisions. AI algorithms can predict demand fluctuations, optimize routing, and anticipate disruptions, enhancing resilience and flexibility. AI-driven tools and simulation models help stakeholders evaluate strategies, ensuring efficient, adaptable logistics operations essential for the successful implementation of the Physical Internet.

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