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Towards cyber-physical internet: A systematic review, fundamental model and future perspectives☆

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A B S T R A C T

Physical Internet (PI) has emerged as an open global logistics system in which physical, digital and operative interconnectivity are combined by units, interfaces and protocols. The PI initiatives have revolutionized the logistics industry, which significantly promotes logistics sustainability, digitalization and the interconnection of logistic services. Since the inception of PI in 2010, there has been significant and increasing interest from both academia and practitioners, leading to remarkable advancements in related research and development. Conducting a comprehensive review of the most up-to-date works related to the PI can help researchers recognize emerging research directions to systematically and effectively advance the research toward the next stages of PI. Thus, this paper consists of a systematic literature review (SLR) of the field. This review shows that digitalization is the key enabling force of PI, and how digitalized cyber space affects PI is still unclear. This motivates us to analyse the necessities and rationales for accessing the Cyber-Physical Internet (CPI). Then, the fundamental CPI model is designed with a five-layer architecture, which acts as the OSI model in the computer network, to define the underlying working mechanisms of each layer for maintaining an open, cooperative and scalable CPI. Finally, future research directions are summarized to illustrate the major research and development roadmap to innovative CPI to make this next-generation logistics as simple as sending email.

1. Introduction

Physical Internet (PI), hailed as a solution for addressing the unsustainability of global logistics (Montreuil et al., 2012b), is an open logistics system where the networks and services are highly interconnected. Notably, PI can be considered a metaphor for the digital internet (DI) within the physical realm. Concepts such as encapsulation, interfaces, and protocols from DI are similarly reflected in PI

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(Montreuil, 2011), making PI distinctive from the traditional logistics systems. Like the internet, which interconnects computer networks worldwide, PI enables the interconnection of logistics networks in the physical world. In computer networks, transmission units ensure that data can be transferred efficiently and reliably from one node to another. The standardized and modularized containers play roles similar to transmission units within the PI networks. The goods are encapsulated in the containers, and in the PI network, the container is the object of all operations. PI transforms the operational models of traditional logistics, and optimizes the logistics operations enabled by digital technologies, improving the overall performance of the logistics system (Montreuil, 2011).

PI has been studied for more than a decade by academia and industry and is still evolving, with an increasing number of countries and regions attaching importance to its development. The PI research centers are located mainly in Europe, especially in countries such as France, Belgium, Germany, and the Netherlands. In addition, many research institutes and universities in Canada, the U.S., Australia and China are conducting relevant research. These research centers drive the innovation of PI at the theoretical, technical and applied levels. Several European-wide projects have been piloted, as well as some international projects led by Canada, the US and Australia states aimed at applying the concept of PI worldwide. Moreover, China, Japan, Korea and other Asian countries are conducting relevant practices to improve the efficiency and sustainability of logistics and supply chains. The EU and Japan have successively developed roadmaps to enable PI, and other countries and regions are also actively involved in the exploration of PI.

According to the PI foundations, technological innovation is a key driver of its evolution. A wide range of cutting-edge technologies have been integrated into PI, including the Internet of Things (IoT), digital twin (DT), artificial intelligence, cloud computing, blockchain, and 5G/6G technology. These technologies should be able to generate digitalization of PI, but they are usually applied in isolation, to address partial issues within the PI framework (Dutta et al., 2023). In addition, PI's goal is to make logistics systems work like the internet. The implementation of PI containers has contributed to creating an interoperable and hyperconnected PI infrastructure in the physical world, which is similar to the function of data packet on the internet. However, there is still no clarity on what and how the digitalization wave can bring to the cyber space in PI as internet operates.

The cyber space offers an underlying environment for digital interaction, while the interaction between the cyber and physical spaces can be bridged by Cyber-Physical System (CPS). CPS facilitates real-time data exchange and dynamic interactions between these two spaces, which enhances the fusion of control and decision-making. This aligns with CPI, where the logistics process in the real world is mapped to the cyber space in real time and rapidly responds to the commands issued from the cyber space. Preliminary studies have introduced CPS into PI, while CPS is only used to manage and coordinate routing protocols to achieve consistency in decision-making across different logistics networks (Pan et al., 2022b). Most studies have concentrated on building digital twins for equipment or logistics hubs to achieve synchronization and autonomous control. However, there has been limited exploration of large-scale instances, resulting in unclear boundaries regarding the integration of CPS with PI.

To fill the research gaps stated above, this study begins with a systematic literature review (SLR) of existing studies on PI. This review aims to reveal key concerns within current PI research, assess the application of digital technologies in this domain, and summarize the existing bottlenecks in the development of PI. Building upon these insights, the study then presents a vision of CPI, proposing that the limitations inherent in PI can be effectively addressed through CPI. To lay a theoretical foundation for CPI, a five-layer model is designed as the OSI model in the internet. The CPI model defines key functions and protocols separated and coupled by layers. Finally, a roadmap for the implementation of CPI is outlined, providing promising research directions for future investigations

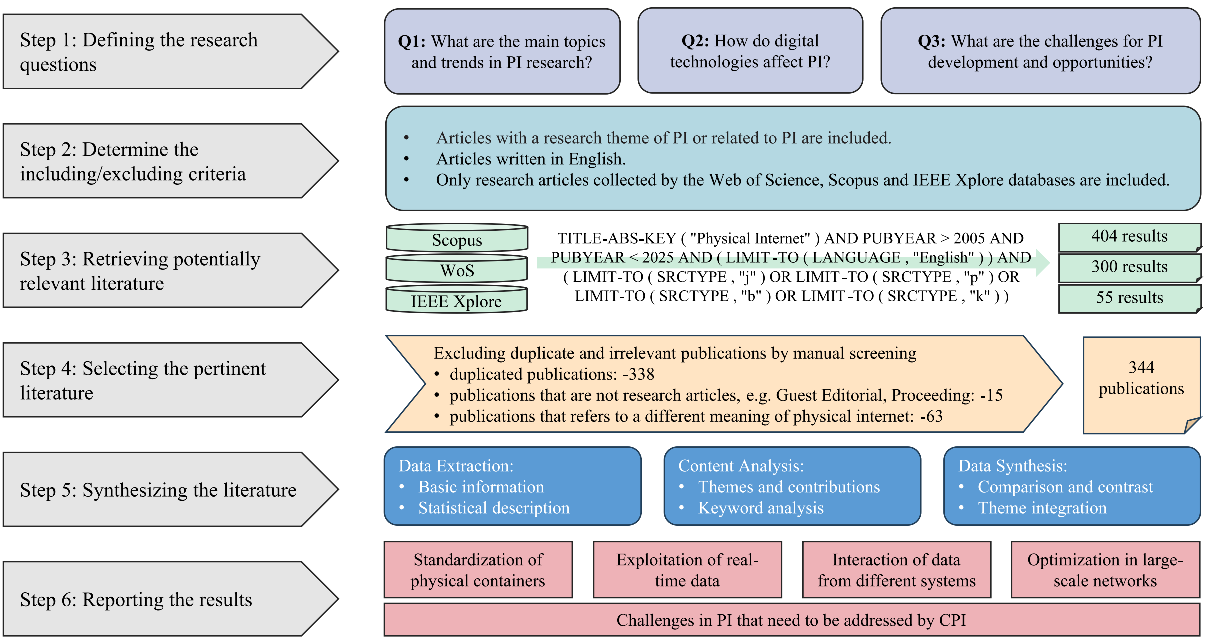

Fig. 1. Systematic literature review (SLR) methodology.

into CPI.

The remainder of this paper is structured as follows. Section 2 introduces the systematic literature review (SLR) methodology and conducts a bibliometric analysis. Section 3 presents a systematic review of PI studies and identifies the remaining gaps. Section 4 proposes a five-layer model as a foundational approach to enable CPI. Section 5 outlines the CPI roadmap, detailing the steps for CPI implementation. Finally, Section 6 summarizes the contributions and limitations of this study.

2. Review methodology and bibliometric analysis

This section defines a review methodology for exploring the boundaries that determine how cyber capabilities can address the limitations of the current PI. The specific settings for conducting SLR are given in Section 2.1. Then, a bibliometric analysis is generated in Section 2.2 as the preliminary SLR results.

2.1. SLR settings

SLR is a well-established review methodology that has been widely applied (Durach et al., 2017). Fig. 1 provides a general overview showing how we used the six steps of the SLR to conduct our work.

The first step of the SLR methodology is to define the research question to enable a literature review. As the aim is to explore the critical dimensions of PI research, the following questions guide our inquiry: (1) What are the main topics and emerging research trends in PI? Understanding these trends is vital for identifying the current state of research, and informs future investigations that can address the knowledge gaps. (2) How do digital technologies influence the development and effectiveness of PI? Analyzing the impact of technologies is essential for recognizing how technological advancements can enhance the efficiency and sustainability of PI systems. (3) What challenges does PI face in its development, and what opportunities can be leveraged for future growth? Identifying both challenges and opportunities is crucial for stakeholders to devise strategies that can facilitate the successful implementation and evolution of PI. By addressing these questions, this review contributes to a deeper understanding of PI, highlights directions for future research, and provides insights that can drive innovation in this field.

To provide a comprehensive overview of the research interests and related topics in PI research, we refrained from establishing a narrowly defined research scope during the data collection phase. However, to ensure the academic quality of the review, we set criteria regarding publication type and writing language. We ultimately select the Web of Science, Scopus and IEEE Xplore databases as sources of literature. Web of Science and Scopus are major academic databases that cover a wide range of disciplines and are widely used for research purposes (Lafkihi et al., 2019; Liu et al., 2022b; Pan et al., 2021). IEEE Xplore is a specialized database focused on

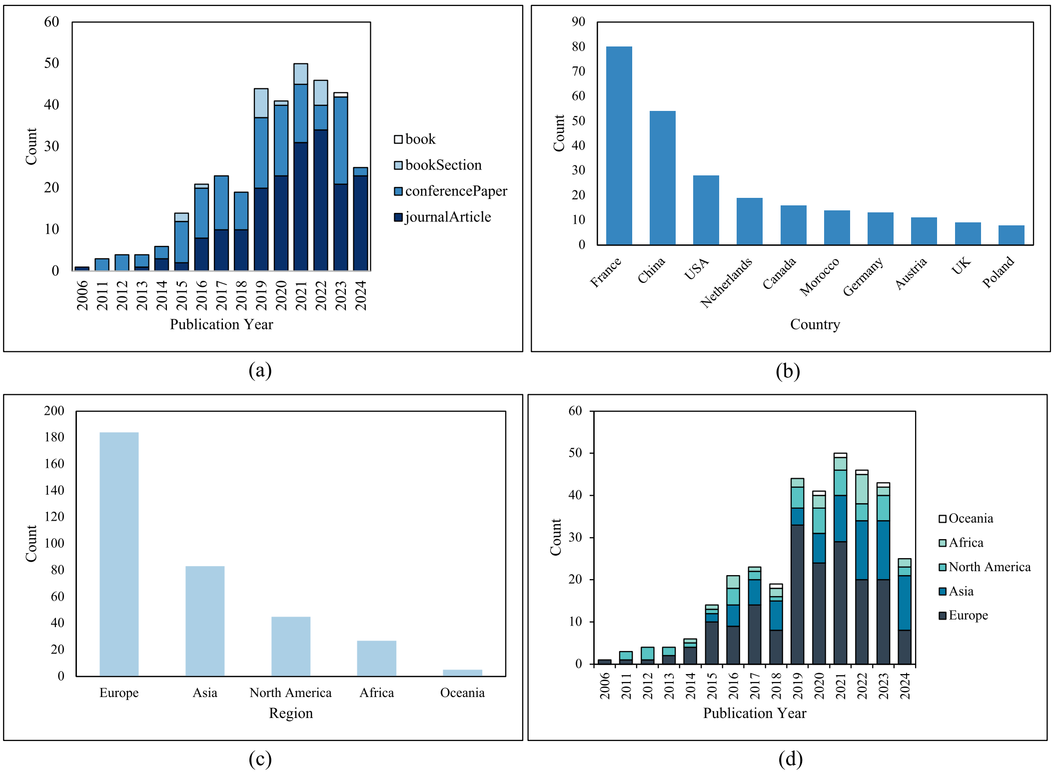

Fig. 2. Statistical results of PI-related publications.

engineering, computer science, and technology literature, including a considerable number of PI-related articles. When the potentially relevant literature was retrieved, “physical internet” was used directly as the search term. Publications whose search terms appeared in the title, keywords and abstract were filtered. To our knowledge, the concept of PI first appeared in a magazine in 2006 (Münch et al., 2024). Therefore, we set the publication date in the search criteria to filter out articles published after 2006 and excluded reports, press releases, and other types of publications. As of June 2024, 404 data items have been retrieved from Scopus databases, 300 from Web of Science databases, and 55 from IEEE Xplore.

The fourth step of SLR involves manually screening titles, abstracts, and content to exclude duplicates and publications unrelated to the topic. In this phase, we first consolidated the data collected from the three databases and deleted duplicate articles. During the screening process of the remaining data, we identified several conference proceedings and guest editorials that did not meet the inclusion criteria, which we subsequently removed. Additionally, we recognized certain articles that were mistakenly included; these articles contained the term “physical internet” but referred to concepts distinct from our intended definition. The articles that were confused were related primarily to the digital divide/physical internet access, physical infrastructure/networks of the internet, and physical IoT devices/CPS networks. After these three rounds of exclusion, a total of 344 items remained.

The last two steps of the SLR will be explained in later sections. In the following subsections, we conduct bibliometric analyses of selected publications to gather fundamental information on PI research. First, we analyze the statistical characteristics of the number of publications, focusing on temporal and geographical dimensions, to gain insights into the overall trends and scope of the research field. Next, we employ the bibliometric visualization software CiteSpace to perform a keyword analysis. We identify and analyze keywords from the literature to understand research hotspots and emerging trends. In the next section, we identify the consistencies and discrepancies of different studies and integrate the theme to create a comprehensive understanding of PI. On the basis of this synthesis, we also identify gaps in the current research and potential directions for future studies.

2.2. Bibliometric analysis

As shown in Fig. 2 (a), the total number of publications related to PI clearly tends to increase. Since 2011, PI has been in an exploratory phase, with a notable increase in related publications by 2015, particularly in conference papers. Several milestone events in the development of PI may help explain these fluctuations. In 2014, the European Union launched the Horizon 2020 program to promote research and innovation in this area. Additionally, the inaugural International Physical Internet Conference (IPIC) was held, garnering global attention. Despite a decline in publication numbers in 2018, there was a significant surge in 2019, which was driven primarily by research activities in Europe, as indicated in Fig. 2 (d). Over the subsequent five years, the number of publications remained consistently high, fluctuating approximately 45 annually. Although the statistics extend only until June 2024, it is anticipated that publication levels will continue at this rate in 2024. This stability reflects the maturity stage at which the PI has reached. Moving forward, only new innovations can propel the continued evolution of PI.

Fig. 2 (b) displays the ten countries with the highest number of publications to date. France, China, and the U.S. lead in terms of publication numbers. However, the majority of the top ten countries are located in Europe, highlighting a strong research ecosystem and collaborative relationships in the region. The collaborative nature of research in Europe may facilitate knowledge sharing and innovation, which are crucial for PI. Fig. 2 (c) further supports this observation, showing that European publications far outnumber those from other regions. In contrast, the low publication counts from other areas suggest significant barriers to the development of PI,

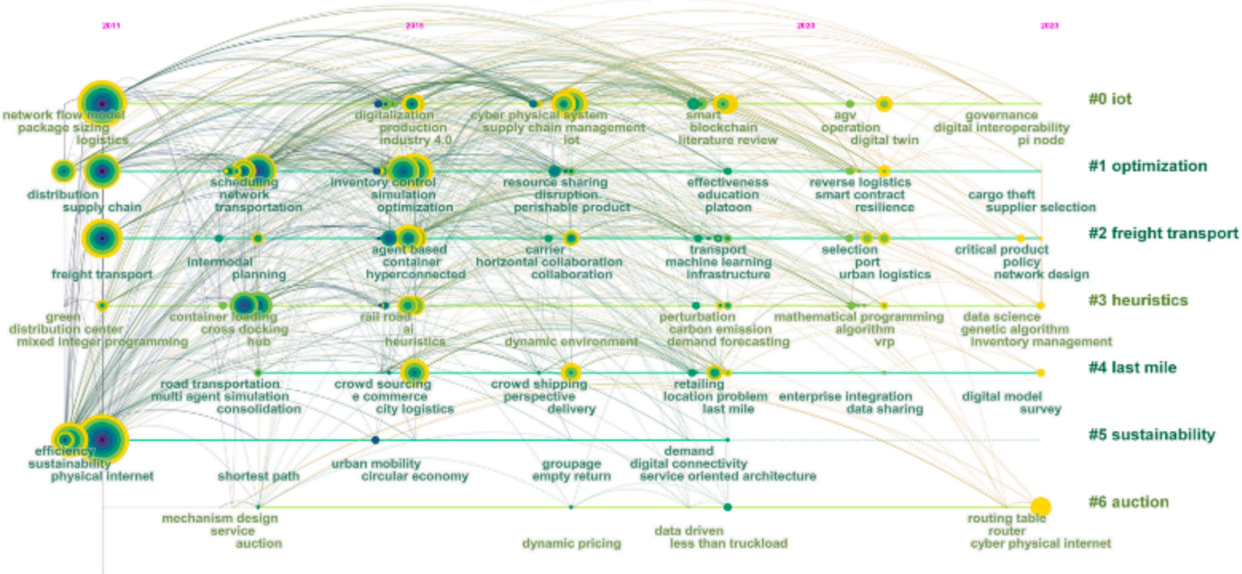

Fig. 3. Keyword clustering timeline.

possibly due to cultural, policy and economic differences. This trend poses a challenge to the global vision for PI. Fig. 2 (d) clearly illustrates the shifting attitudes toward PI across different regions. The foundation of PI research originated from collaborations in North America and Europe. With the introduction of supportive policies in Europe, the region has emerged as the primary battleground for PI development. However, since 2016, interest in PI has grown significantly in Asia, surpassing North America and potentially even exceeding Europe in the future. This indicates a promising development trend for PI in Asia.

In Fig. 3, the timeline is presented as a series of horizontal lines, with each line representing a cluster of keywords positioned at their first occurrence. Within each cluster, the keyword most strongly associated with others serves as the cluster label, with a larger label serial number indicating a greater cluster capacity. The circles represent keywords, whereas the concentric rings reflect the temporal distribution of their occurrences. Larger circles indicate higher frequencies of keyword appearances; this figure displays only a subset of the most frequently occurring keywords.

From the perspective of clustering, half of the keywords in Cluster #0 are related to digital technology. This not only highlights the frequent references to digital technology in PI research but also underscores the close relationship between the IoT and other digital technologies, reinforcing the notion that the IoT acts as a bridge between the physical and digital worlds. Cluster #1 features keywords that reflect common optimization scenarios in PI research, encompassing transportation optimization and inventory management within supply chains. Cluster #2 includes keywords related to the development of freight-related infrastructure and the emergence of new transportation modes driven by interconnected transport networks. Cluster #3 addresses common operations research problems in PI, typically involving mathematical modeling followed by solutions derived from improved heuristic algorithms. Keywords in Cluster #4 predominantly pertain to urban logistics optimization, indicating that the last mile of urban logistics is a significant research topic within PI. Cluster #5 prominently features three representative keywords—efficiency, sustainability, and PI—identified as the earliest and most frequently mentioned terms in PI research, closely related to keywords in other clusters. These three terms are intrinsically related because PI emerged as a solution to improve logistics efficiency and sustainability. Cluster #6 contains fewer keywords with a broader temporal span of co-occurrence. The timing and frequency of CPI appearances suggest that CPI represents a new revolution, with auctions playing a crucial role in the routing mechanism design of CPI.

From a temporal perspective, some keywords that were once focal points in PI research have seen a decline in mention in recent years. This phenomenon can be attributed to two primary factors. First, prior research may have reached a comprehensive level, maintaining existing designs—such as cross-docking operations and packing processes—until new innovations emerge to drive further development. Second, the refinement of research has led to the evolution of concepts, exemplified by the gradual replacement of “intermodal” with “synchromodal.” For infrastructure, operational mechanisms, or technology applications, there is a continuous trend toward greater sophistication and efficiency.

3. Key findings

In addition to the preliminary bibliometric analysis above, this section conducts a deeper analysis of the literature based on the remaining SLR steps. The PI-related literature is divided into three key stages, as noted in Sections 3.1-3.3, respectively, in accordance with the PI roadmap from Europe (ALICE, 2020). Finally, the current gaps are extracted and summarized from the CPS perspective, which are the key motivations for moving towards CPI in Section 4.

3.1. PI initiatives

The concept of PI first emerged from a survey of The Economist on June 17, 2006 ("The Physical Internet", 2006). The survey focused on express carriers and logistic service providers. The physical internet, as the title of this survey, refers to the logistics network that operates as efficiently as the internet. This metaphor soon triggered a rethinking of logistics as well as a paradigm shift within the field (Dong and Franklin, 2021; Sarraj et al., 2014b; Colin et al., 2016). The first PI project took place in France in 2009, with the final report “Openfret” published in April 2010. This project completes the initial exploration of the conceptualization and implementation of a PI network, highlighting the potential of PI (Ballot et al., 2011). On the basis of Openfret, another project, MODULUSHCA, was launched to develop a standardized modular container along with communication protocols. It is an initial exploration of the PI at the European scale (Landschützer et al., 2015). Thereafter, the European Union funded a series of projects, known as the Horizon 2020 Programme. As a funding project, the SENSE project aims to put the academic vision into practice to accelerate the transition to zero-emissions logistics (Ciprés & de la Cruz, 2019). Europe has therefore taken the lead by releasing two versions of the PI roadmap to lead the development of the PI. In the latest version of the roadmap, they plan for trials until 2030 and deployment in the following decade in five directions, including logistics nodes, logistics networks, logistics network systems, operations, and management. In addition to European countries, the Japanese government also released a PI roadmap in 2022 on the basis of the contemporary situation of Japanese society.

The emergence of PI transformed the conventional logistics of physical objects. It suggests universal interconnectivity in terms of physical, operational and digital properties through encapsulation, interfaces and protocols and evolves motivated by innovations in technology, business and infrastructure (Ballot and Pan, 2021; Montreuil et al., 2012b). In the PI’s vision, the global supply network is anticipated to evolve toward enhanced coordination and collaboration among its participants (Simmer et al., 2017; Zijm & Klumpp, 2016). To facilitate this evolution, the internet-based protocol framework has been developed to systematically define the functions of the PI system and establish network standards (Kant and Pal, 2017; Kubek and Więcek, 2019; Montreuil et al., 2012a; Yu and Zhong, 2023). The supporting service platform has been developed as a step forward in technical realization (Windolph et al., 2023). These initiatives aim to promote interoperability across diverse logistics networks, thereby enhancing the overall efficiency and effectiveness of the supply chain ecosystem.

Because of the interconnected logistics networks, PI fosters the integration of multiple transport modes (Pawlewski, 2015). The concept of multimodal transport is evolving in the context of PI toward intermodal transport (Crainic, 2013; Furtado & Frayret, 2015; Pencheva et al., 2022; Vida et al., 2023) and synchromodal transport (Ambra et al., 2019; Labarthe et al., 2024; Lemmens et al., 2019; Sakti et al., 2023; Yee et al., 2021). PI also fosters the integration of logistics resources and services, facilitating some new logistics models, such as shared freight (El Ouadi et al., 2021; Thompson et al., 2020) and crowd shipping (Kunze, 2016). These models offer innovation and flexibility in good transportation, enable better performance of logistics activities and positively impact the economy, environment, and society (Ballot, 2019; Chargui et al., 2018; Fazili et al., 2017; Furtado et al., 2013; Mangina et al., 2020b; Suzuki & Kraiwuttianant, 2024). However, this shift necessitates that stakeholders relinquish their dedicated supply networks, which may deter participation. Therefore, establishing an incentive mechanism to encourage stakeholder engagement, along with a robust profit allocation framework to retain them, is crucial. Otherwise, stakeholders may be unwilling to assume the risks associated with such a transformation (Plasch et al., 2021; Sternberg and Norrman, 2017; van Duin et al., 2023; Adamczak et al., 2017; Sharif Azadeh et al., 2021). This sharing and collaborative business model aligns with the inherent requirements of various contemporary frameworks, such as Industry 4.0 (Akkerman et al., 2022; Cohen et al., 2019; Magas & Kiritsis, 2022; Maslarić et al., 2016), the circular economy (Cichocki et al., 2023; Phuong Tran & Ha, 2024; Rajahonka et al., 2019; Zijm et al., 2019), Society 5.0 (Gumzej & Rosi, 2023), the humanitarian supply chain (Grest et al., 2019; Grest et al., 2021; Grest et al., 2020; Zhang et al., 2023b), and lean thinking (Cornejo et al., 2020). Moreover, PI has also given rise to new concepts, such as hyperconnected city logistics, which exhibit connectivity in more dimensions (Campos et al., 2021; Crainic & Montreuil, 2016; Sohrabi et al., 2016; Taniguchi et al., 2023). Nevertheless, much of the existing research remains theoretical, and there is a pressing need to explore suitable integrated business models through practical application (Niu et al., 2022; Osmólski et al., 2019; Pan, 2019; Phillipson, 2023).

Self-organization and automation are two prominent features that set PI apart from conventional logistics, which relies on advancements in data development and understanding (Mangina et al., 2020; Soebandrija et al., 2018). Digital technologies play a crucial role in the transition to PI, with the IoT facilitating the connection and communication of elements within PI networks (El Jaouhari et al., 2022; Franklin, 2019; Hopkins & Hawking, 2018; Tran-Dang et al., 2022). Additionally, DTs/CPSs enable self-organization and autonomous operations within PI systems (Brunetti et al., 2024; Hirata et al., 2024; Nguyen et al., 2022; Nitsche et al., 2021; Pujo & Ounnar, 2018). Blockchain technology enhances the transparency, traceability, and security of logistics operations (Alkhudary et al., 2022; Bekrar et al., 2021; Chargui et al., 2024; Pan et al., 2021), whereas AI technologies support transport and distribution decision-making processes (Blunck & Bendul, 2016; Cortes-Murcia et al., 2022; Gumzej, 2023; Klumpp et al., 2019; Nikitas et al., 2020; Nitsche & Kusturica, 2022; Osama et al., 2023; Shaikh et al., 2023; van Heeswijk et al., 2019). However, exploration of the application of this technology is still in its early stages (Tran-Dang & Kim, 2021). A significant challenge lies in the integration of these technologies, while each is effective when applied individually, their combined implementation remains complex (Dutta et al., 2023; Zsifkovits et al., 2020). Furthermore, ongoing training for the personnel involved is essential to keep pace with these advancements (Klumpp & Ruiner, 2019; Klumpp & Zijm, 2019; Zijm & Klumpp, 2017). Although the adoption of digital technologies has addressed various issues within the PI network, a systematic and comprehensive technological framework, along with integrated solutions for PI, is still lacking. The integrated application of digital technologies enables PI to make real-time decisions and execute tasks through internal mechanisms that are self-adjusting and optimizing without external control. Such digitalization has the potential to significantly enhance logistics performance (Shen et al., 2022). To this end, future research will continue to focus on utilizing digital technologies to interconnect the physical, digital and operational layers, as well as to explore the interactions between the layers (Ban et al., 2020; Fergani et al., 2019; Jharni et al., 2020; Lopez-Molina et al., 2018; Matusiewicz, 2020, 2024b; Moshood & Sorooshian, 2021; Münch et al., 2024; Nouiri et al., 2023; Pettit et al., 2022; Samadhiya et al., 2023; Treiblmaier et al., 2020).

The PI Initiative represents a significant advancement in the logistics and supply chain landscape, leveraging technology, collaborative policies, and educational frameworks to optimize resource allocation and enhance operational efficiency (Coşkun et al., 2019; Deepu and Ravi, 2021; Fahim et al., 2024; Liu et al., 2022c; Wang et al., 2022; Iskanderov and Pautov, 2021; Viktor et al., 2023). The initiative aims to create a seamless and interconnected network that benefits all participants involved (Thompson, 2021). Significant progress has been made in recent years in both academia and industry. As we move forward, the PI Initiative will continue to adapt and evolve, promoting sustainable practices and ensuring that the logistics ecosystem is well equipped to address future challenges.

3.2. PI implementation

Research on the implementation of the PI encompasses three primary directions: physical components, network construction, and operational mechanisms. Physical components refer to those fundamental elements within a PI system, such as PI containers and PI nodes. The design of PI containers and PI nodes can significantly influence the operational efficiency of the entire system (Ounnar & Pujo, 2016). In this context, digital technologies play a crucial role by enhancing the digital capabilities of these components, enabling real-time data exchange, improving resource management, and increasing the overall responsiveness of the network. Advanced infrastructure promotes more sustainable transport methods and operational processes, improving overall efficiency and reducing wasted resources.

3.2.1. Physical component

The container is the first to undergo a transformation, as there are increasing demands for both physical and intelligent characteristics from transport units. Specifically, these containers not only protect the cargo but also transmit information to support decision-making processes (Graf & Harald, 2015; Rahimi et al., 2016). To facilitate the interoperability of PI networks, the physical attributes of PI containers must prioritize modularity and standardization. PI containers are designed to accommodate multiple types of cargo, which can increase the vehicle's load factor and reduce the risk of theft (Gastón Cedillo-Campos et al., 2024). Therefore, it is crucial to consider compatibility in container design. Compatible containers can be reassembled for transport with various types of cargo, thereby reducing empty loads (Sternberg & Denizel, 2021). However, achieving standardization in container dimensions poses practical challenges. The size of containers directly impacts truck utilization and cargo shipping volume (Meller et al., 2012; Meller & Ellis, 2011). To address this, (Lin et al., 2014) proposed a method for selecting appropriate-sized containers to avoid wasted space, while (Ji et al., 2021) takes shippers' preferences into account. Modular PI containers are composed and disassembled as needed. Therefore, a dynamic identification method was developed to flexibly respond to the composition and decomposition of containers (Aksentijevic et al., 2022). The intelligence of the PI container is the basis for the efficient and sustainable operation of the PI network. Sensors embedded within containers form WSNs for data collection and communication during transport, enabling environmental monitoring and accurate localization of PI containers (Dang Hoa & Kim, 2018; Hayek et al., 2023; Pal & Kant, 2022; Tran-Dang et al., 2017). These data can be utilized to create a digital twin of a composite container, which aids in organizing and managing container operations (Charpentier et al., 2021). Furthermore, integrating other technologies, such as cloud computing, edge computing, and artificial intelligence, allows for more complex applications, including cargo monitoring and routing throughout PI networks (Gumzej, 2021; Gumzej et al., 2020; Krommenacker et al., 2016; Sallez et al., 2016; Taudes & Reiner, 2022; Tran-Dang & Kim, 2018). PI containers are expected to autonomously bid on transport services by learning bidding policies (van Heeswijk, 2020). Through the use of intelligent containers, effective shipment control within the transportation network can be achieved, thereby providing in-transit services to procurement customers (Arnas et al., 2013).

Since PI containers may be reassembled at the logistics hub for a new routing plan, these hubs must be technologically advanced compared with current facilities to facilitate the required operations (De Bruyn et al., 2017). On the one hand, the design of developed facility layouts simplifies container loading operations and reduces operating time, enabling the flexible transfer of containers. On the other hand, logistics hub devices have been upgraded to enhance automation in operations. For example, container transshipment robots improve the efficiency of container transshipment in intermodal road–rail freight transport (Illés et al., 2020). There are three cross-docking hubs with different functional features (Chargui et al., 2022): a road-based cross-docking hub where PI containers are transshipped from inbound trucks to outbound trucks, a road-rail hub that transfers PI containers from inbound trains to outbound trucks, and a road-based transit center that enables the transfer of trailers from one inbound truck to another outbound truck. Common logistics operations within a cross-docking hub include truck scheduling, container grouping, container routing and truck loading. These operations are interactive and often involve uncertainties (Walha et al., 2014). Truck scheduling and container grouping present considerable challenges because of their inherent uncertainties. Research in this area has varied focuses and optimization objectives, e. g., minimizing energy consumption during container transshipment, reducing routing time and cost, and minimizing truck delays, some of which involve multiobjective decision-making (Chargui et al., 2019, 2020, 2021a; Essghaier et al., 2023; Chargui et al., 2019a; Chargui et al., 2019c; Chargui et al., 2021b). Since truck scheduling is a classic operations research problem, many studies address it by developing mathematical models. The same approach is applied to the truck loading problem (Deplano et al., 2021; Grover & Montreuil, 2021). The stability of the container routing process is crucial, as it can significantly impact the time window for truck scheduling. In dynamic environments, a hybrid control structure that integrates multiple routing strategies is often employed (Pach et al., 2014; Saliez et al., 2015; Vo et al., 2018). Alternatively, multiagent modeling using heuristics presents a viable solution. In this framework, agents can autonomously perceive their surroundings, make independent decisions, and execute tasks. These agents can interact and collaborate, making this approach particularly suitable for real-time decision-making in dynamic environments (Walha et al., 2015, 2016; Chaabane and Trentesaux, 2019; Walha et al., 2016a). Moreover, since maritime transport is one of the dominant modes of long-distance cross-border transportation and a part of intermodal transportation, ports are also expected to make a smooth transition to PI (Caldeirinha et al., 2022; Fahim et al., 2021a–c, 2022).

Other types of PI logistics nodes, such as warehouses, should also adapt to align with the shifting logistics paradigm (Edouard et al., 2021; Quak et al., 2020). Online order fulfillment warehouses need to achieve fast fulfillment to meet increasing demands. Optimizing flow control and warehousing decisions is essential to cope with explosive storage and a considerable number of orders (Onal et al., 2018; Zhang et al., 2020). Given the complex and variable internal environment of PI hubs, developing indoor location technology solutions is necessary to provide accurate spatiotemporal information (Hayward et al., 2022; Zhao et al., 2020, 2024b). Additionally, the sharing, coordination, and synchronization of logistics resources within the PI hub must be established (Kong et al., 2017). Leung et al., 2022 proposed the use of a digital twin for the PI warehouse to enhance inbound synchronization, incorporating a machine learning model to optimize joint order fulfillment and replenishment operations within the hub. The model introduced by Rebuglio et al., 2023 can help analyze incoming information to improve the effectiveness of the digital twin. Furthermore, machine learning can be employed to forecast inbound containers (Helmi et al., 2022b), which is crucial because it directly affects planning, scheduling, and resource allocation within the PI hub. In urban logistics networks, smart lockers serve as specialized PI hubs that provide storage space for parcels (Faugère & Montreuil, 2020). Their design must accommodate parcels of various sizes while ensuring a high utilization rate.

3.2.2. Network structure

Computer networks serve as key inspirations for the design of the network structure of PI networks. The successful development of the internet illustrates the effectiveness of decentralized approaches in addressing challenges within large-scale networks. Consequently, an open hub network has been proposed for PI to facilitate decentralized logistics and supply operations, providing an alternative to traditional logistics organizations (Ballot et al., 2012). An open hub network is characterized by hubs that are openly accessible to all stakeholders, with service capacity shared among users. This structure enhances the resilience of the PI network, enabling it to autonomously recover from disruptions and interruptions (Aron & Sgarbossa, 2023; Colin et al., 2015; Kulkarni et al., 2022; X. Liu et al., 2023; Yang et al., 2017a). Early studies on supply network design explored the potential benefits of open supply webs. Compared with private and shared supply networks, open hub networks significantly improve performance and business outcomes in terms of flow costs, investments, delivery times, and the number of available and utilized hubs (Sohrabi & Montreuil, 2011). Furthermore, a greater degree of hyperconnected structure correlates with improved performance of the logistics system (Kaboudvand et al., 2021). To implement such a network structure, (Meyer et al., 2019) proposed a blockchain-based decentralized solution for integration into the distributed network structure. However, the blockchain configuration suggested in this study has limitations concerning node scalability, which may hinder its broad implementation.

The number and location of PI nodes are critical factors for the performance of the PI network. Many studies have addressed the hub or facility location problem within the PI network. However, only a few studies have employed data mining techniques, such as clustering, to determine optimal locations (Helmi et al., 2022a). Most research in this area has focused on formulating mathematical models to address various scenarios related to the problem. For example, (Jharni et al., 2023) proposed establishing access points within PI networks. These access points serve to connect existing logistics infrastructures with new PI hubs, facilitating the gradual deployment of PI networks. Both access points and new PI hubs are strategically located on the basis of the flow of goods passing through these points. Additionally, (Fergani et al., 2022) described a hybrid network comprising dedicated sites and open hubs. Notably, some PI hubs are designed to be mobile, enhancing flexibility in accessing the PI network. In last-mile scenarios, these mobile hubs function as access points between consolidation centers and demand zones, enabling flexible domination of tight urban spaces (Faugère et al., 2020). Research by Herrmann & Kunze, 2019, Ghaderi et al., 2022 and Zhang et al., 2023a has focused on the siting of facilities in city crowd logistics, which serve as parcel transfer points. However, owing to the inherent complexity of city crowd logistics, fully addressing this issue via traditional operations research models is difficult. Both (Naganawa et al., 2024) and (Hu et al., 2019) have developed models to determine optimal PI hub locations and routing decisions, but with different optimization objectives. In this context, the collaborative hub location problem, as explored by (Habibi et al., 2018), highlights the importance of deeper collaboration modes, particularly under conditions of cost uncertainty. A common approach to this type of problem involves constructing a two-stage stochastic programming model, which is often solved via heuristic or metaheuristic algorithms. Nevertheless, as the network size increases, the number of variables increases, and the complexity of the environment increases, making computation more challenging and necessitating algorithmic improvements. To address these issues, some studies have focused on developing effective algorithms for problem solving (Abdelsamad et al., 2021; Chouar et al., 2021).

To analyze the PI network and understand its behavior characteristics, modeling and simulation are frequently used approaches. (Karakostas, 2019) modeled networks on the basis of queuing theory and analyzed performance properties such as throughput, processing time, and traffic size. To investigate how structural functions and resource configurations influence the overall system, (Sun et al., 2018) developed a multiagent simulation for an urban intermodal logistics system that incorporates interactive protocols. However, such studies usually fail to reflect the actual situation and regulations of urban transport due to a lack of data. Similarly, (Nouiri et al., 2021) created a multiagent model for a multiplant, multiproduct PI supply network. This study compared the performance of the PI network with that of classic networks across multiple scenarios and logistics configurations, evaluating the effectiveness of three replenishment policies. In a related study, (Sohrabi et al., 2020) examined the performance of distribution networks in collaborative and hyperconnected contexts and concluded that hyperconnected networks offer a higher level of service. Additionally, (Ben Mohamed et al., 2017) conducted a simulation of pickup and delivery transport within an urban logistics network, addressing several complex features. (Venkatadri et al., 2016) compared a conventional logistics network and a PI network, both of which were managed via a two-way point-to-point dispatch model. This study distinctively models the flow of goods in both logistics networks. In conclusion, the advantages of PI are clear. cargos shipped through PI networks can be consolidated at the PI hubs, resulting in high inventory turnover rates and low inventory costs. Moreover, this system effectively minimizes empty truck trips, contributing positively to sustainable logistics practices (Caballini et al., 2017).

3.2.3. Operational mechanism

Logistics operations must be appropriately adapted to align with different logistics models. On the one hand, the transition to the PI positively impacts certain logistics operations. On the other hand, the implementation of PI necessitates the development of new logistics operations to achieve its objectives. In the context of open and interconnected logistics, various challenges arise in areas such as business collaboration, information sharing, and resource optimization and configuration.

Collaborative transport is not a new topic in logistics. However, the concept of PI elevates it to a new level. The scope of solutions has expanded from the carrier level to the supply chain level and subsequently to the supply network level (Pan et al., 2019a). Resource integration is considered a critical tool for enhancing the competitiveness of supply chains (Adamczak et al., 2019). For example, (Pan et al., 2019b) designed a smart product-service system in PI, accompanied by a corresponding business model. This system integrates vertical collaboration for demand forecasting with horizontal collaboration to facilitate resource sharing among various stakeholders. Nevertheless, implementing such a system presents challenges, as the related theoretical research remains in its infancy. Effective incentive mechanisms are crucial for motivating stakeholders to participate, alongside equitable cost-sharing and gain-sharing schemes that ensure that stakeholders maintain a viable profit margin (Hezarkhani et al., 2021; Vargas et al., 2020). Once these theoretical frameworks are adequately developed, they can be integrated into network optimization models to support decision-making. In this context, the S-BPM (subject-oriented business process management) approach provides valuable insights by modeling communication within the supply chain at the digital level (Neubauer & Krenn, 2017). This approach facilitates both vertical and horizontal integration of process actors, thereby enhancing collaboration among stakeholders. To foster carrier collaboration, (Saoud & Bellabdaoui, 2017) developed a hierarchical and distributed framework model, further contributing to the discourse on collaborative logistics.

The participation of multiple organizations is an inherent characteristic of the PI business model, which encompasses both collaboration and competition. Effective cooperation requires seamless data flow across the network and information sharing among organizations, facilitating real-time decision-making in the PI system (Yao, 2017). To support this requirement, the IoT and cloud computing provide essential infrastructures for real-time data collection, storage, and analysis. The tracking and tracing of PI container flows can be accomplished using signaling data from mobile networks, which have been studied in various scenarios (Frendi et al., 2024; Karampatzakis et al., 2019; Nachet et al., 2024; Roch et al., 2015; Scholler et al., 2022; Tran-Dang et al., 2020; Zhang et al., 2016). All relevant information can be integrated to support the coordination of transport activities (Peters & Limbourg, 2023). This integration enables a global, permanent, and real-time view of freight transport flows. In this context, information sharing must be conducted efficiently and securely, ensuring transparency throughout the process. To achieve this, blockchain technology, along with smart contracts, has been introduced to create an interoperable PI system where all relevant stakeholders can access updated data. This combination allows for the automatic execution of contracts, thereby enhancing operational efficiency. The entire process is marked by safety, time efficiency, and cost effectiveness (Betti et al., 2019; Narzt et al., 2021; Niavis & Zafeiropoulou, 2023; Paliwal et al., 2020; Treiblmaier, 2019). By standardizing supply and logistics services, as well as their underlying protocols, a data pipeline bridging the federation of platforms has been developed (Hofman, 2015), providing another potential solution for interoperability within the PI. However, the large volume and heterogeneity of data in the PI system complicate data processing. Therefore, it is essential to explore the value of data effectively through the use of appropriate technologies and methods. In this context, (Chouar et al., 2022) proposed an improved metaheuristic algorithm that reduces data complexity and compresses processing time through data clustering. This algorithm can be integrated into various decision-making processes in PI, thereby enhancing overall decision-making capabilities.

The features of PI also drive the evolution of resource optimization and coordination. Collaborative logistics brings resources together while providing better incentives for individuals within decentralized organizations (Lafkihi et al., 2019b). This context underscores the need for game theory approaches to support strategic decision-making. For instance, (He et al., 2024) investigated the optimal pricing strategies for carriers and road operators under distributed and horizontal collaborative pricing frameworks. Auction mechanisms are frequently used to solve transport resource allocation problems in collaborative freight transportation planning (Bae et al., 2022). PI containers can be reassigned to carriers at transshipment hubs to improve routing efficiency, with auction mechanisms facilitating the allocation of container bundles to transport services (Lafkihi et al., 2020; Pan et al., 2014). Assignments may also consider historical customer satisfaction and expectations (Rezaei et al., 2023; Tian et al., 2021). Additionally, carriers can select transport requests at transshipment hubs and bid for them at competitive prices (Qiao et al., 2019, 2020; Qiao et al., 2017; Qiao et al., 2019a). In scenarios of high demand, multiple rounds of auctions can be conducted, supported by demand forecasting (Qiao et al., 2019a). It is foreseeable that automated auctions and dynamic resource utilization will become mainstream in the future. Furthermore, (van Heeswijk, 2022) proposed a multiagent reinforcement learning algorithm to represent the strategic bidding behavior of carriers and shippers. Real-time pricing can also be achieved with multidimensional information about the transport service (Tan et al., 2023). The recycling of empty containers posttransportation is another critical concern, as improper allocation can lead to network imbalances. Attention has been given to the reallocation of empty containers by carriers on their return trips (Colin et al., 2015; Nakechbandi and Colin, 2020).

In addition to information sharing and intelligent scheduling, the dynamic routing mechanism is crucial for the faster and more efficient consolidation of containers within the PI network (Lai & Cai, 2020; Satici & Dayarian, 2024). Relay transportation is commonly employed for long-haul shipments, allowing for the consolidation of dispersed idle resources for selective shipping (Li et al., 2022b; Li et al., 2022a). This consolidation is facilitated by intelligent agents that monitor the location and condition of goods and assess routing opportunities (Ambra et al., 2021). The interoperability of PI is demonstrated primarily through interactions among these agents within the network (Hauder et al., 2018). Current research addresses routing problems in PI networks through two main approaches: mathematical modeling with heuristics and agent-based simulations. In the first category, the routing problem for two-echelon delivery has been extensively studied, with transport modes varying by scenario, including vans, autonomous delivery robots, public transport, zero-emission vehicles, and traditional vehicles (Kızıl and Yıldız, 2023; Lin et al., 2022; Liu et al., 2022a, 2024; Shahedi et al., 2023). (Chadha et al., 2022) suggested integrating peddling in shipment consolidation to improve truck utilization and reduce travel distances. Additionally, (Arnau et al., 2022; Crainic et al., 2020; Orenstein & Raviv, 2022) proposed a hyperconnected service network that supports multileg delivery. (Kantasa-Ard et al., 2023) addressed the vehicle routing problem with simultaneous pickup and delivery, and (Ancele et al., 2021) investigated the scenario where containers can be exchanged through cross-docks during pickup and delivery. (Di Febbraro et al., 2018) proposed ride-sharing and crowd-shipping schemes with matching algorithms and routing solutions. Similarly, (Schoen et al., 2019) suggested enabling containers to reach their destinations by hitching rides, effectively sharing transportation capacity. Kantasa-Ard et al., 2021a suggested enabling containers to reach their destinations by hitching rides, effectively sharing transportation capacity. Shi et al., 2020 focused on real-time routing optimization in the joint distribution problem, highlighting the importance of data collection and processing at each link for optimal route selection. However, this interactive planning approach often requires significant computational time for a single session. To mitigate this, Kalicharan et al., 2020 suggested reducing the problem size. However, this is not a feasible solution in practice. While the proposed optimization model may be effective on a small scale, it is challenging to manage a global network because of uncertain key parameters (Jharni et al., 2022). Furthermore, many heuristic algorithms lack validation for effectiveness in global-scale networks. A more feasible approach could involve routing operations akin to the internet, using current routing tables to determine the next hop (Wu et al., 2024).

The second category focuses on moving the container from the origin to the destination. While the design of the PI routing protocol draws significantly from that of DI, it cannot be identical because of the inherent physical characteristics of the PI container. The routing protocol proposed by (Gontara et al., 2018) is close to the BGP protocol used on the internet. However, vehicles carrying containers are used as links, which may lead to their influence on transport being overlooked. The routing protocol designed by (Achamrah et al., 2024) supports dynamic and reactive decision-making and addresses a wide range of network disruption risks. (X. Qu et al., 2024) designed interior and exterior routing protocols that can be applied to large-scale logistics networks. Sarraj et al., 2014a suggested that each node maintains routing tables to handle service updates and incoming flows, and Ng et al., 2024 designed a routing table to track the carbon footprint, enabling carbon reduction-oriented routing, which could also support carbon trading (Sun et al., 2020). Briand et al., 2022 explored an auction-based routing protocol that incorporates payment considerations. However, the actual PI transport network is inherently complex. An effective routing scheme must enable timely responses and dynamic decision-making in unforeseen circumstances. To achieve this goal, the exploration of technologies such as the IoT, cloud-fog computing, intelligent agents, machine learning, blockchain and CPS is essential. These technologies are widely used for real-time monitoring of shipments, traceability throughout the supply chain, prediction of the network state, and autonomous response to changes in the network (Hasan et al., 2021; Mededjel et al., 2022; Li et al., 2023b; Mededjel et al., 2018; Pan et al., 2022b).

The interconnected nature of the PI network facilitates the emergence of distributed inventories, enabling dynamic sourcing strategies. An appropriate inventory model can effectively reduce inventory levels by leveraging its high degree of flexibility. The model developed by (Yang et al., 2017c) can address uncertain demand and supply chain disruptions. With this inventory control model, the supply network becomes more resilient. For the PI supply network under the (Q, R) inventory policy, three different selection criteria of replenishing points were compared in Pan et al., 2015b, Pan et al., 2013 and Yang et al., 2015. Regardless of which replenishment policy is used, the PI supply network performed better than the classic supply network. However, the study does not suggest the best inventory control model for PI but rather an initial exploration. When the optimal policy structure is unknown, deep reinforcement learning is a promising approach for making replenishment decisions. Vanvuchelen et al., 2020 exploited deep reinforcement learning to solve the joint replenishment problem in the PI network and developed policies that approximate the optimal policy structure. However, in large-scale networks, the performance of such algorithms is affected by other factors and may not always outperform. Yan et al., 2023 designed hybrid algorithms for solving multiobjective optimization problems in inventory replenishment. The inventory model proposed by Kim et al., 2023 satisfies customer expectations of fulfillment responsiveness. Derhami et al., 2021 proposed a data-driven model to assess product availability in a retail network. The model can be used for inventory planning for some products that are prone to substitution and multisourced transshipment. Zhao et al., 2024a focused on the supplier selection problem under multisourced supply and incorporated indicators of social sustainability in decision-making on inventory management. Yang et al., 2017b investigated the vendor-managed inventory strategy in PI. A heuristics-based optimization model was proposed to help vendors make inventory decisions, whereas replenishment decisions in PI are highly dynamic. However, this highlights the significance of data collection for inventory management. The inventory control model under PI can be improved by database synchronization (Sutanto & Sarno, 2015). Alternatively, machine learning can be used to predict future demand, including demand volume, demand distribution, and even customer behavioral preferences, and accurate predictions can be used for inventory management decisions (Kantasa-Ard et al., 2020, 2021b; Bidoni and Montreuil, 2021; Kantasaard et al., 2019).

3.3. PI applications

Built on a strong foundation of theoretical research and practical experience, PI provides a systematic theoretical framework to help organizations understand and implement innovation. The solid groundwork allows PI to be adapted and extended to different industries and application scenarios (Chen et al., 2022).

In manufacturing, PI fosters a ubiquitous interconnected environment. RFID tags can be used in containers for product identification and tracking (Lin & Cheng, 2018; Zhong, 2016). The introduction of modular smart containers enhances loading efficiency and minimizes wasted space (Ferreira et al., 2021; Ha et al., 2017). By leveraging big data analytics, IoT, and cloud computing technologies, an intelligent shop floor environment is created. This environment facilitates proactive scheduling, where machines and jobs can make autonomous decisions (Lin et al., 2017; Wang et al., 2016; Zhong et al., 2017). The collected real-time data will be the parameter of the scheduling model to support shop floor scheduling (Zhong & Xu, 2016). Additionally, PI has revolutionized traditional production by proposing mobile modular production systems and establishing PI hubs to balance intralogistics operations (Fergani et al., 2020b; Puskás et al., 2021; Fergani et al., 2020a). The deployment of PI infrastructures alongside technological integration creates a hyperconnected cyber-physical manufacturing environment that enhances visibility, traceability, and temporal and spatial synchronization of operations (Guo et al., 2021b; Chen et al., 2023).

In supply chain management, PI is extensively applied to production-inventory-delivery problems, enhancing the overall efficiency and responsiveness of hyperconnected supply chains. This model is particularly effective in highly customized markets, as it enables joint scheduling on the basis of real-time information flow (Ji et al., 2023a; Xue et al., 2023). Through data analysis and intelligent decision-making, resources can be allocated more efficiently and unnecessary inventory and production waste can be reduced, thereby improving the service level at a lower cost (Ji et al., 2019; Peng et al., 2020). Moreover, the interconnected and shared resources in PI-enabled systems allow for optimized planning and scheduling to cope with various disruptions (Darvish et al., 2016; Ji et al., 2023b; Nouiri et al., 2020; Peng et al., 2021, 2024; Tordecilla et al., 2023). For the supply chain of perishable products, where excessive time in transit can lead to product deterioration, real-time sensing and automatic control can effectively reduce this waste (Pal and Kant, 2019, 2020; Pan et al., 2022a; Schoen et al., 2017). PI also enhances the planning, scheduling and execution of dynamic transactions for perishable products (Kong et al., 2016, 2018). In addition to city logistics, PI has also been applied to military logistics, maritime transport, and passenger air transport to increase network efficiency (Krogsgaard et al., 2018; Matusiewicz et al., 2023; Soedarno et al., 2020; Tran-Dang & Kim, 2019). The hyperconnected supply network significantly impacts the retail sector. High-value products often require physical showcases for customer interaction. The PI-enabled fast replenishment of products optimized the value of showcasing

(Park et al., 2019). In the new retail era, the order fulfillment mode has changed. The application of PI in new retail city logistics addresses challenges related to warehousing, transport, and human resource management (Kim et al., 2021; Li et al., 2023a; Luo et al., 2022; Matusiewicz, 2024a; Zheng et al., 2019). PI containers function as mobile warehouses, allowing loading and unloading in various urban locations, which increases flexibility in transport options for reverse logistics (Chen et al., 2017; Fatnassi et al., 2016; Pan et al., 2015a; Petitdemange et al., 2023). Additionally, the monitoring and traceability of PI containers support informed routing decisions (Luo et al., 2021).

The development of PI is a part of smart city construction (Mahor et al., 2022). In the case of autonomous vehicle delivery, the application of PI containers enables rearranging the PI containers through centralized control; therefore, the customer can unload/load the containers without human intervention (Tetouani et al., 2019). PI also fosters platooning technology. By reducing the distance between vehicles through autonomous driving technology, this mode of transport reduces traffic congestion and increases transport efficiency (Puskás, 2021; Puskás et al., 2020; Puskás & Bohács, 2019). In addition, PI is applied in building construction. PI-enabled building information modeling systems can improve the compliance of planning and operations through real-time tracking and tracing of construction materials or prefabricated components (K. Chen et al., 2018; Ismail, 2023; Yin et al., 2024; Zhong et al., 2015). Moreover, the auction-based resource allocation mechanism associated with PI is particularly beneficial for parking management, enabling the efficient allocation of parking spaces in urban environments (Tan et al., 2021).

4. Research gaps

PI initiatives focus on the early exploration of concept formations. They involve theoretical foundations, development environments, technical frameworks, and application prospects. These initiatives provide insights into related concepts and their integration with other technologies. In contrast, PI implementations examine specific methods, techniques, and mechanisms to achieve the desired outcomes. They bridge theory and practice by proposing solutions for various challenges. PI applications, on the other hand, utilize these components, models, or solutions to address specific problems in particular scenarios. They emphasize the practical integration of PI concepts within various industry contexts. The shift from initiatives to implementations to applications reflects a transition from theory to real-world problem-solving. Existing research on PI has been quite comprehensive, however, there are still issues that prevent PI from being implemented on a large scale. Through the concept of CPI, we aim to build upon the existing research in PI while addressing these challenges.

First, efforts to design PI containers have been made by Europe but are focused mainly on the fast-moving consumer goods industry, which has relatively few products. In practice, it is difficult to standardize physical PI containers in the real world, because they involve a variety of sizes and shapes for freight, are suitable for heterogeneous logistics infrastructure in different regions, and conform to standards, policies, and regulations in different countries. However, it appears that the digital instances of PI containers make overcoming the above obstacles easier, especially motivated by the data packet, which is also a kind of uniform data container that can be transmitted over different networks with distinctions.

Second, many studies have adopted digital technologies to enable the traceability and visibility of objects, with support from the

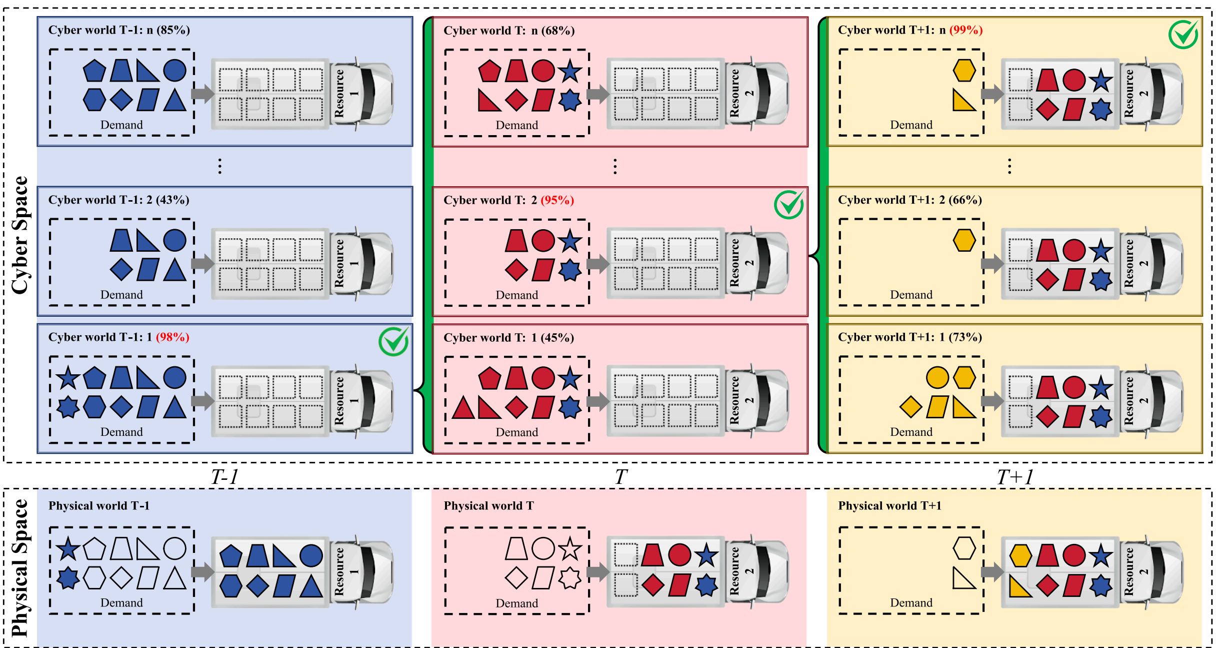

Fig. 4. CPI vision.

large volume of real-time data. However, these data are limited in describing the physical properties of objects in transit. Thus, leveraging the scope of data toward a broader cyber space makes it possible to restore a vivid digital world of physical networks, where simulation, optimization and learning can be performed, to affect and guide the physical processes.

Third, previous studies have proven the advantages of the resource sharing brought about by the PI. Effective resource sharing is established via sufficient information sharing among stakeholders. However, PI stakeholders may be reluctant to share sensitive data, such as market needs, prices, and capacities. Thus, it would be worth exploring the fundamentals of data structures, protocols and technologies to promote information exchange among PI stakeholders.

Fourth, operations research is adopted as a key methodology to address the optimization problems in PI. The expanding PI network significantly increases most problem sizes, which leads to lower solving efficiency. Moreover, ubiquitous uncertainties and disturbances decrease the effectiveness and availability of applying optimization results in PI practice. The observation of the internet prompts us to consider why it is stable, robust and efficient for message transmission and how it can affect the PI.

5. Toward CPI

Through the cyber space, the problems arising with a PI network scale-up can be solved beyond the limitations of reality. Hence CPI is proposed as a promising next generation PI, which takes full advantage of the possibilities and capabilities afforded by the cyber space. The cyber space thoroughly explores all the possible scenarios prior to the event occurring in each time slice by using computational resources. Generally, the scenarios that unfold in the physical world are those with the highest probability of occurring under cyber space prediction. Once an event occurs in the physical world, the cyber space promptly calculates all possible scenarios for the next time slice on the basis of the scenario that occurs in the current time slice, ensuring that everything is under control.

In Fig. 4, the blue, pink, and yellow blocks refer to time slices T-1, T, and T + 1, respectively. The various shapes represent different demands, which may be a difference in the quantity of goods, the type of goods, or the destination of the transport. The color of the shapes according to the time slice the demands are generated. The cyber space forecasts the delivery demand for each time slice and shows the n-scenarios with the highest probability of occurring in the prediction. In time slice T-1, scenario 1, which is predicted by the cyber space, has ten generated demands. Eight are transported by Resource 1, and two remain to wait for the next transport resource. The cyber space then predicts the demand that will be generated in time slice T. In time slice T, predicted scenario 2 becomes a reality. Four new demands are generated, and Resource 2 is ready for transport. However, the total of six demands does not fill the carriages, so Resource 2 does not depart. In time slice T + 1, two new demands are generated, which is consistent with scenario n predicted in the cyber space. Thus, regardless of what exactly occurs in the physical space, the cyber space can always generate the most effective solution through its strong computing ability with real-time data from the physical world.

5.1. CPI five-layer model

In a logistics system where the cyber and physical realms are closely integrated in a decentralized manner, the architecture of each node is crucial. By combining components at both the cyber and physical levels, this architecture influences the system's robustness,

Table 1
Definition of key CPI components.

CPI components	Definition
Physical Entity/Cyber Entity	In CPI, all physical objects have corresponding physical entities and cyber entities. The physical entity refers to the actual physical component. The cyber entity is a digital representation of the physical entity within the CPI system.
CPI-Protocol Shipment Units (CPI-PSU)	The CPI-PSU is the sole object of operation in the CPI transport process, and all goods transferred over the CPI network are encapsulated within CPI-PSUs. In the entire CPI, there are only a limited number of CPI-PSU specifications. Each CPI-PSU has a unique identifier, known as the CPI-PSU ID. The entire CPI system focuses on optimizing transport around this limited number of CPI-PSU specifications.
CPI-Channel	The CPI-channel is used for transporting CPI-PSUs within the CPI. There are also a limited number of types and specifications for CPI-channels in the CPI system.
CPI-Protocol	The CPI-protocol is a set of protocols for establishing standards for cyber-physical elements and standardizing control strategies in CPI.
Physical Internet Protocol (PIP)	Protocol address in CPI under the CPI-protocol, primarily used for routing work in CPI-PSU and network segmentation in the CPI.
CPI-Media Access Control (CPI-MAC)	Used to identify unique physical addresses in the real world; each PIP address has a corresponding CPI-MAC address.
CPI-Routing Table	A data structure at the CPI network layer, containing information such as destination addresses, next-hop addresses, hop counts, etc., used to determine how to transfer CPI-PSU from the source to the destination.
CPI-Request	This is a request initiated by the CPI roles to trigger goods transport within the CPI network. The request usually includes source and destination addresses, source and destination port numbers, goods information, and some additional data.
CPI-Transmission Control Protocol Header (CPI-TCP Header)	Data structure added by the CPI transport layer to the CPI-PSU, including sequence numbers and port numbers.
CPI-PIP Header	Data structure added by the CPI network layer to the CPI-PSU, including starting PIP addresses and hop counts.
CPI-Link Header	Data structure added by the CPI link layer to the CPI-PSU, including next-hop CPI-MAC information and local CPI-MAC information.
CPI-Segment/CPI-Packet/CPI-Frame	A CPI-PSU carrying a CPI-TCP header/A CPI-PSU carrying a CPI-PIP header/A CPI-PSU carrying a CPI-Link header.

standardization, and ease of implementation. Inspired by the principles of the traditional five-layer internet model, this study proposes a unified underlying architecture for CPI, including the application, transport, network, link, and infrastructure layers. Each layer is designed on the basis of standard CPI components in the physical and cyber worlds, serves a specific function, provides standardized interfaces for adjacent layers, and can be updated and iterated independently. CPI components are the fundamental elements that constitute the CPI five-layer model. These components are abstracted from both digital and physical concepts. The definitions of each CPI component essential for building the CPI five-layer model are summarized in Table 1.

The CPI five-layer model, shown in Fig. 5, adopts a layered architecture to segment the responsibilities of CPI vertically from top to bottom. The responsibilities of each layer are described below:

Application Layer: For sending operations, it parses CPI requests and then locates the appropriate CPI-PSU data bodies on the basis of the criteria specified in the CPI request, managing and matching CPI-PSUs at the digital level. For receiving operations, goods are delivered from the transport layer.

Transport Layer: For reliability, leveraging the digital twin characteristics of CPI entities establishes a connection between CPI entities through digital simulation before initiating a CPI request, ensuring route reachability. It also allocates or designates port numbers for both ends of the connection.

Network Layer: Information is exchanged and transmitted between neighbors on the basis of network layer protocols with network topology information updated in real time and routing tables created. For sending and receiving operations, routing decisions for CPI-PSUs are made on the basis of the routing table. If the next-hop address is nonlocal, the CPI-PSU is passed to the link layer; otherwise, it is forwarded to the transport layer.

Link Layer: Sending operations query the corresponding CPI-MAC address through the next hop's PIP address. It also generates a checksum for data received from upper layers and encapsulates this along with the physical attributes of the goods. For receiving operations, it verifies the CPI-MAC address, determines whether it is a local address and takes subsequent actions, while also verifying the checksum in conjunction with both data and physical attributes.

Infrastructure Layer: Sending operations are responsible for loading all CPI-PSUs from the pending send area into the CPI channel, optimizing for resource utilization and other specified metrics (akin to a bin-packing problem). For receiving operations, it is in charge of unloading CPI-PSUs from the CPI channel.

Different combinations of layers constitute various types of CPI roles. These distinct CPI roles shoulder different functions, segmenting the functionalities of CPI horizontally. The roles of the CPI are defined below:

CPI-Host: The primary CPI services object. It can send all valid CPI requests, and CPI transfers goods from the sender's CPI host to the receiver's CPI host on the basis of the requirements specified in the request. A CPI host is generally composed of a complete five-layer structure.

CPI-Router: Any device in CPI that possesses the capability of CPI-PSU forwarding decisions and forwarding can become a CPI-router. "Forwarding" refers to the ability to accept and send CPI-PSUs, and "decisions" refer to determining the direction of the next stop for the CPI-PSU on the basis of its destination. Examples include distribution centers and transshipment centers. A CPI-router is generally composed of a network layer, a link layer, and an infrastructure layer.

CPI-Switch: Any device in CPI with the capability to forward PSUs can become a CPI switch. Unlike CPI-routers, CPI-switches do not make decisions about the next hop for CPI-PSUs on the basis of their destination; instead, they mechanically forward them

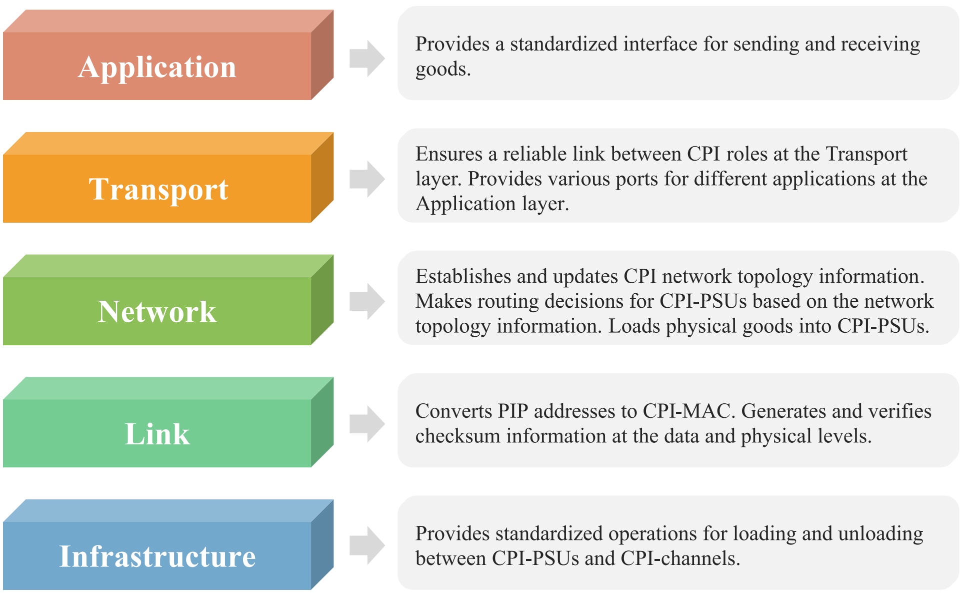

Fig. 5. CPI five-layer model.

according to the next CPI-MAC information in the CPI-PSU's link header. A CPI switch is generally composed of a link layer and an infrastructure layer.

5.2. Operational mechanism

Fig. 6 presents a simplified process for sending and receiving a CPI request between two adjacent CPI hosts. Each layer possesses two service capabilities: sending services and receiving services. The sending service is responsible for transferring the CPI-PSU from the upper layer to the lower layer, whereas the receiving service is responsible for moving the CPI-PSU from the lower layer to the upper layer. In Fig. 6, the sending host initiates a CPI request to deliver 72 items to the receiving host. The request includes information about the goods being transported, the starting/ending PIP address, and the starting/ending port number. When a CPI request is issued, the CPI officially begins to provide services.

First, the application layer constructs the cyber entities of the goods on the basis of the information provided by the request. It then plans one or more CPI-PSUs to encapsulate these cyber entities. The identified CPI-PSUs and the cyber entities are subsequently passed down to the transport layer. The transport layer first checks whether a connection between the starting and ending port numbers specified in the request has already been established. A connection here refers to a virtual pathway derived from the rapid simulation of the transport process through various types of cyber entities in the CPI. If such a connection does not exist, it will attempt to establish one. Once the connection is in place, the starting and ending port numbers are packaged into the TCP header and written into the cyber entities of the CPI-PSU. Upon completion, similar to the application layer, the CPI-PSU and the cyber entities of the goods are then passed down to the network layer.

After receiving the information from the above layers, the network layer queries the routing table using the destination's PIP addresses to determine the next-hop PIP address. It then generates or updates a PIP header containing both the starting and ending PIP addresses and embeds it into the CPI-PSU's cyber entity. Concurrently, the physical entity of the goods is loaded into the CPI-PSU at this layer. After this step, both the CPI-PSU and the goods' cyber entity are passed down to the link layer.

The link layer then locates the next-hop CPI-MAC address and the CPI channel for use on the basis of the next-hop PIP address. The link layer also generates a checksum, utilizing all the known information about the current CPI-PSU and goods. This checksum ensures the integrity and security of both the cyber and physical entities during the transfer process. All the abovementioned information is used to generate or update the link header.

The link layer passes the fully encapsulated CPI-PSU to the infrastructure layer's sending buffer. The CPI-channel at the infrastructure layer continuously extracts CPI-PSUs from the sending buffer, loads them into the channel, and then transmits the CPI-PSUs to the next CPI role according to the requirements specified in the headers.

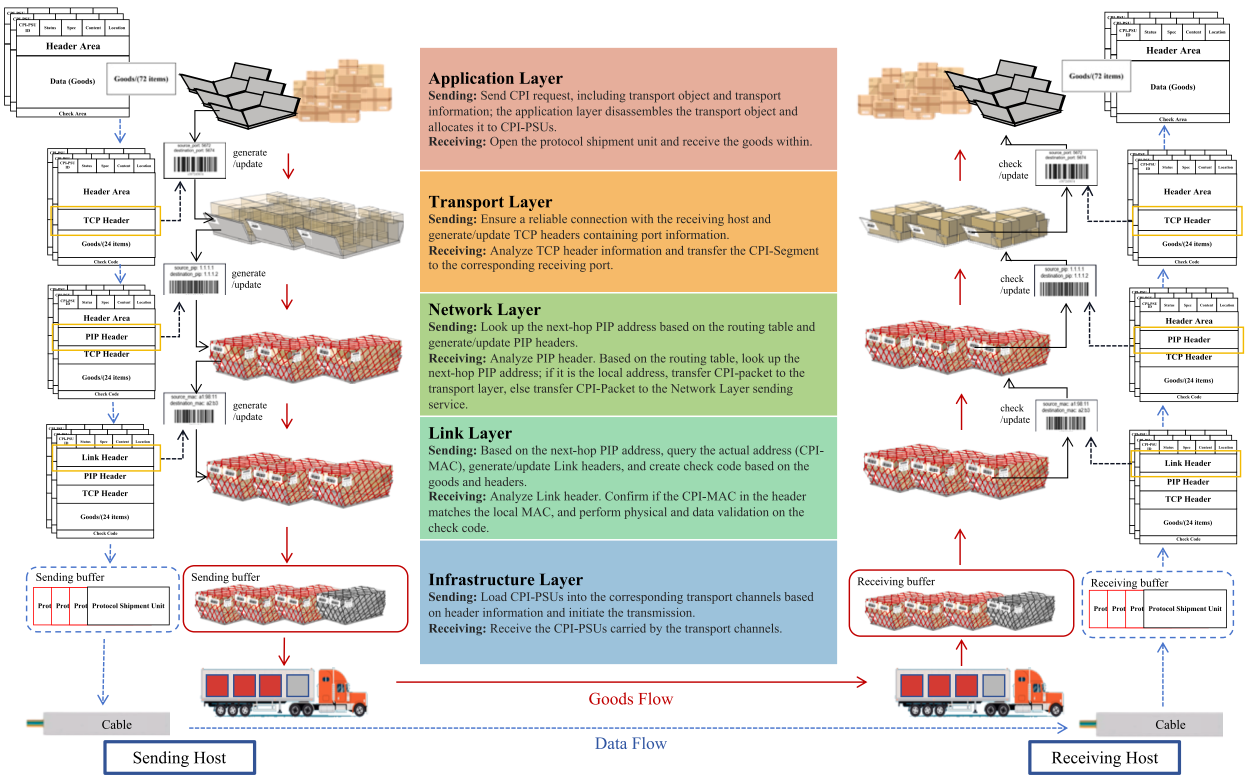

Fig. 6. Process of sending and receiving a CPI request between two adjacent CPI hosts.

As shown in Fig. 6, the CPI-PSU directly arrives at the receiving host after traversing the five-layer architecture of the sending host. Initially, the Infrastructure layer at the receiving end unloads the CPI-PSU from the corresponding CPI-channel and places it into the receiving buffer. The link layer subsequently examines the CPI-PSU in the receiving buffer from the infrastructure layer, parsing the contents of the link header. It ensures the integrity of both the cyber entity and the physical entity. It also checks the MAC information in the header, comparing it against the local MAC and the neighboring MAC. If the MAC matches the local MAC, the CPI-PSU is passed upward to the network layer; if it matches the neighbor's MAC, it is sent to the sending services at the same layer.

Upon reaching the network layer, the receiving services of this layer scrutinize the PIP header information of the CPI-PSU. They also query the routing table on the basis of the destination PIP address to determine the next hop. If the address of the next hop is a local address, the CPI-PSU is moved upward to the transport layer; otherwise, it is handed over to the sending services at the same layer. Following this process, the transport layer receives the CPI-PSU passed from the network layer. The receiving services in this layer check the TCP header and identify which upper-level application should receive this CPI-PSU on the basis of the receiving port number in the header. The CPI-PSU is then transferred to the corresponding application at the application layer. Finally, the application layer receives the goods and releases the occupied CPI-PSU.

Fig. 7 illustrates how different CPI roles execute more complex CPI requests by utilizing either all or parts of the functionalities provided by the CPI five-layer model. In the requests depicted in the figure, the CPI-PSU passes and routes among various CPI roles. Each CPI role independently operates and makes decisions on the received CPI-PSU, ensuring that the cargo ultimately reaches its destination.

The CPI five-layer model presents both opportunities and challenges. By allowing each CPI role to run the underlying system of the five-layer model independently, the entire logistics network avoids the need for centralized decision-making and data service centers. Data can be transferred quickly and smoothly between adjacent on-working CPI roles, reducing the likelihood of large-scale failures in the logistics network. The standardized data design and decentralized operational mode simplify the process of registering and joining logistics resources and facilitating resource sharing. However, the CPI five-layer model also faces challenges. First, the network traffic load increases with the large volume of data transferred between CPI roles. Additionally, all the roles are required to run services for at least two layers of the CPI five-layer model, which increases the hardware and computational requirements for CPI roles within CPI. Finally, the implementation of this five-layer model still necessitates consideration for setting standards for PIP and CPI-MAC, designing routing and PIP protocols, and coordinating hardware design and data transmission methods. In short, the concept of CPI has potential advantages, but considerable work remains for its implementation.

6. Future research directions of CPI

CPI is a next-generation system interconnecting multitier, multileg, multihub, and multimodal complex cross-border logistics systems that are better built, operated and managed to create global logistics synergy in search of new postpandemic norms. The CPI innovatively introduces a "cyber layer" on top of the PI, in which the flow of objects in the physical domain can be sensed, configured, supervised, and optimized through the flow of information in the cyber space. Therefore, the state and status of objects in the physical logistics system can be collected, communicated and synchronized with the cyber space on a real-time basis. With the information collected in real time, cyber-physical visibility and spatiotemporal traceability can be established to achieve resilience in the logistics network system. Fig. 8 shows the CPI roadmap, which was developed for the creation of cyber space. It involves three main research directions: CPI digitalization, CPI network configuration and services, and collaboration mechanisms in CPI. Notably, some research content within these directions interacts with each other and therefore needs to be developed together.

6.1. *Digitalization technologies*

In the context of Industry 4.0, digitalization technologies have been recognized as key enablers of industrial production transformations (Rüßmann et al., 2015). These technologies facilitate the development of smart shopfloor/factories, which represent a fully digitalized model of products and manufacturing processes, and enable a high level of automation and integration within the manufacturing sector (Lasi et al., 2014). PI was once claimed to be the logistics' response to Industry 4.0, as it also embraced

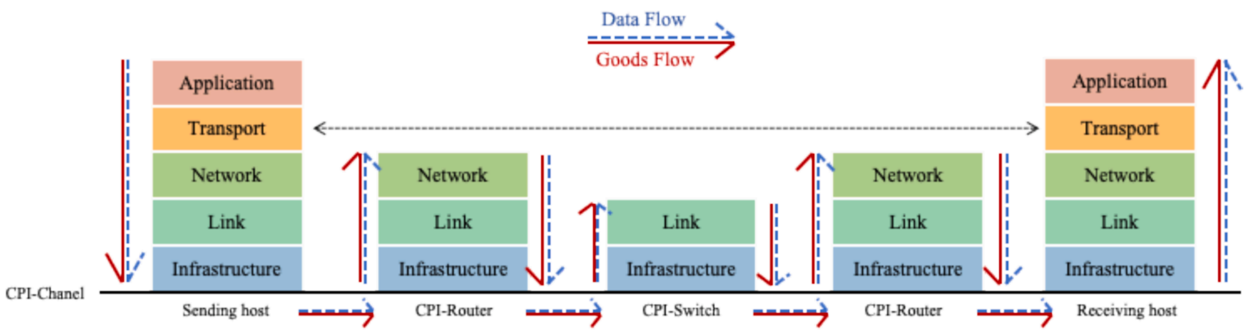

Fig. 7. Process of sending and receiving a CPI request between two adjacent CPI hosts.

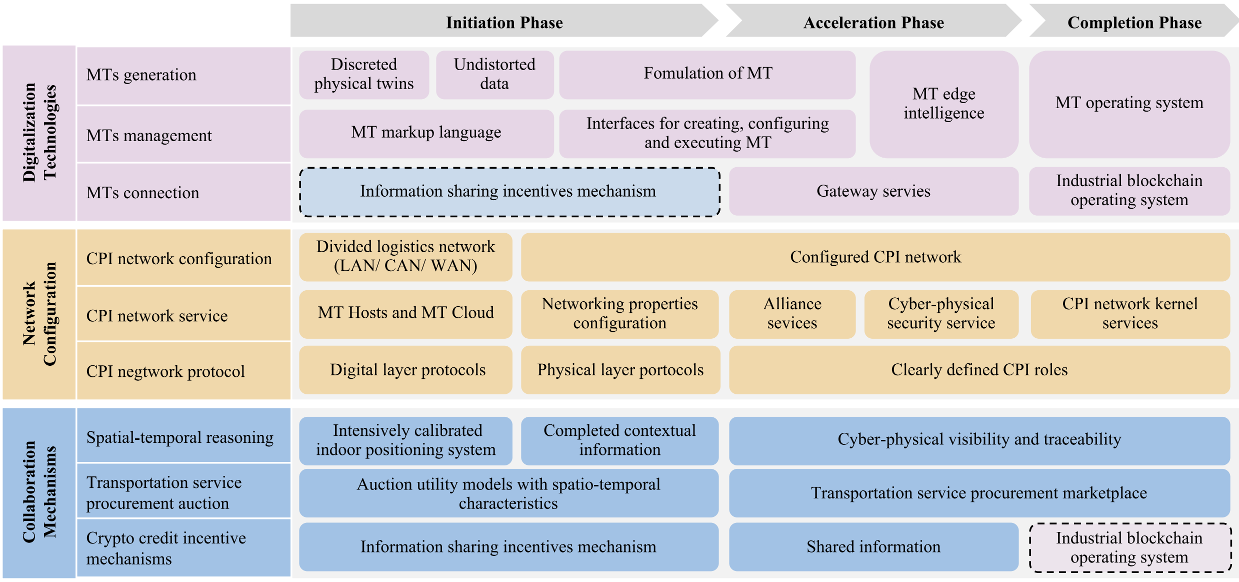

Fig. 8. CPI roadmap.

technological change, and transformed the logistical paradigm of the current time (Maslarić et al., 2016). However, even though Industry 4.0 has enriched a series of enabling technologies for digitalization, it requires more of an artist approach rather than systems engineering to answer open questions like "what should be digitized and how they should be digitized?" in the manufacturing industry. It seems that CPI more easily embraces digitalization technologies, because the overall aim is always tracking and tracing PI. This is why, when discussing automation and digitalization strategies with industrial collaborators, they are generally willing to invest in

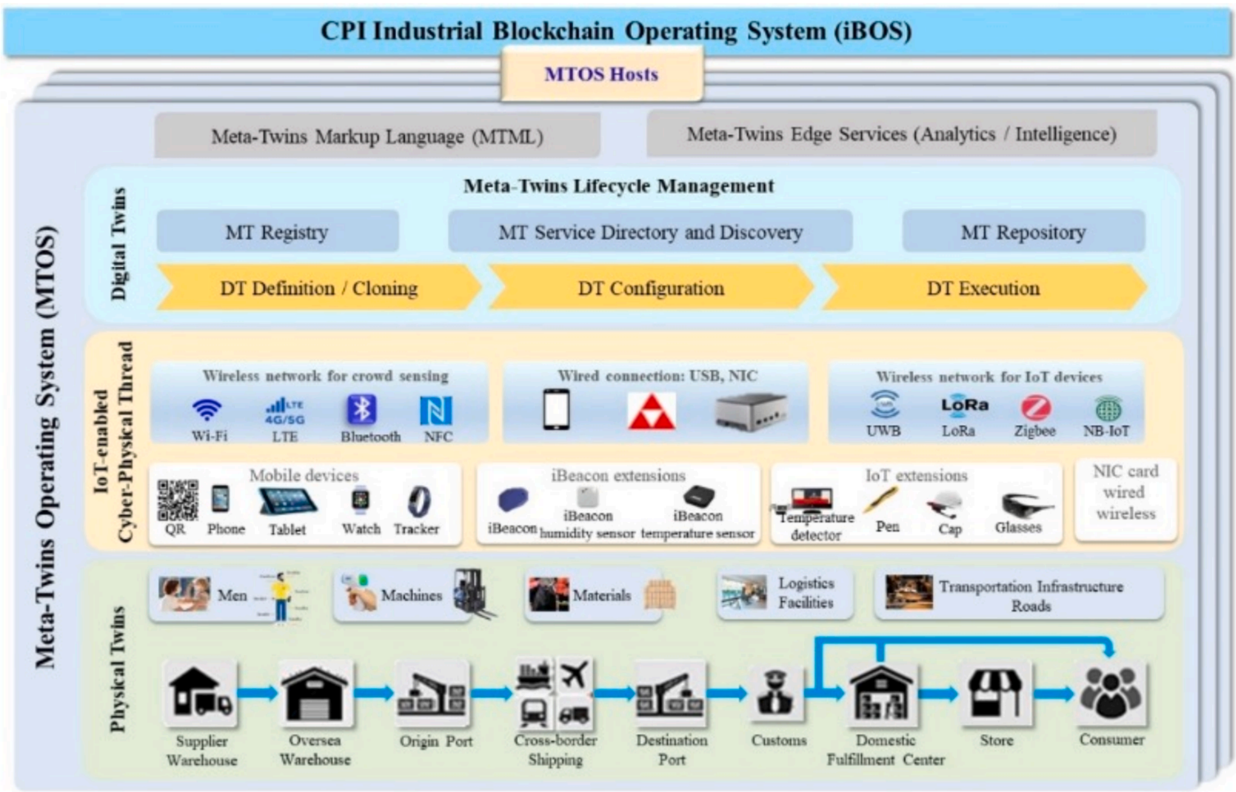

Fig. 9. IoT-enabled Meta-Twins digitization framework and technology.

automating and digitalizing logistics operations. However, most e-commerce logistics operators typically rent their warehouses and facilities with a lease of 2–5 years. They face the challenge of accepting either a warehouse rental rise or the high cost of relocating automated logistics facilities. Digitization seems to be more cost-effective in Hong Kong, however, it is an art requiring specific skills (Herold et al., 2021). Unlike automation, which can be "bought", "turnkey" digitization solutions do not yet exist, although concepts such as the IoT, digital twins, CPS, AI, and data analytics have been widely discussed and researched.

To develop such a cyber layer to sense, supervise, and connect all the physical items in logistics systems, the fundamental work entails proposing a systematic digitization framework by adopting smart IoT devices or gateways (Qu et al., 2016). With the real-time collected data, digital twins for physical objects are created, and further combined to form *meta*-twins (MTs) governed by smart contracts in the blockchain platform. This digitization framework involves three key steps. First, the physical logistics system is decomposed into discrete physical twins to create digital twins via a finite element method. A major concern here is how to determine the physical twin granularity, which significantly influences the effectiveness and cost of data collection. Second, the most suitable IoT devices for physical twins are selected. There are various types of available devices, such as smartphones, tablets, personal wearable devices, iBeacons, and some specialized IoT devices. A challenge encountered here is to choose an economical and user-friendly device for each physical twin to guarantee that undistorted data are collected. Third, digital and physical twins are connected to formulate MTs. MTs are the basic processing objects in the CPI network. An important concern here is how to minimize the technical difficulties in setting up plug-and-play (PnP), scalable, and reconfigurable MTs.

Fig. 9 shows an overview of the systematic digitization framework for building CPI infrastructure. The MTs are managed through their hosts, and the MT hosts are operated with the Meta-Twins Operating System (MTOS). Meta-Twins Markup Language (MTML) is important for achieving MT PnP scalability and interchangeability in CPI networks. Indeed, substantial efforts have been made in devising such languages for Industry 4.0 manufacturing automation (e.g., AutomationML—Automation Markup Language, and OPC UA—Open Platform Communications Unified Architecture) and construction automation (e.g., bcXML—Building Construction Extensible Markup Language and bcXML—Building Construction Extensible Markup Language). We note that no such major efforts have been reported in logistics because of the challenge of global logistics complexity. The MT lifecycle manager provides user interfaces for creating, configuring and executing MTs (including upgrading and addressing obsolesence) (Li et al., 2019b). The registry is used to create and define MTs. The Directory hosts services for MTs to configure and "download" for use during their execution process. Discovery searches for MT services. The repository records events and associated MT data. Finally, MT services are edge intelligence, with, for example, workflow logic to process MT raw data to useful information and forward it to the CPI blockchain and sophisticated analytics for high-level processing to determine its boundary conditions (visibility and traceability). Such local spatial–temporal analytics enable MTs to "look around" from the current spatial–temporal window first and then collaborate with each other for planning, scheduling and execution in future spatial–temporal windows. Through the repository, MTs can make full use of past data to support different machine learning algorithms.

The organization and management of MTs in CPI are inspired by the manufacturing paradigms. Industry 4.0 has shifted traditional centralized productions, into loosely coupled and decentralized production collaborations, starting from cloud manufacturing (Tao et al., 2011), to open manufacturing (Z. Li et al., 2018), to social manufacturing (Xiong et al., 2018), etc. Blockchains have been

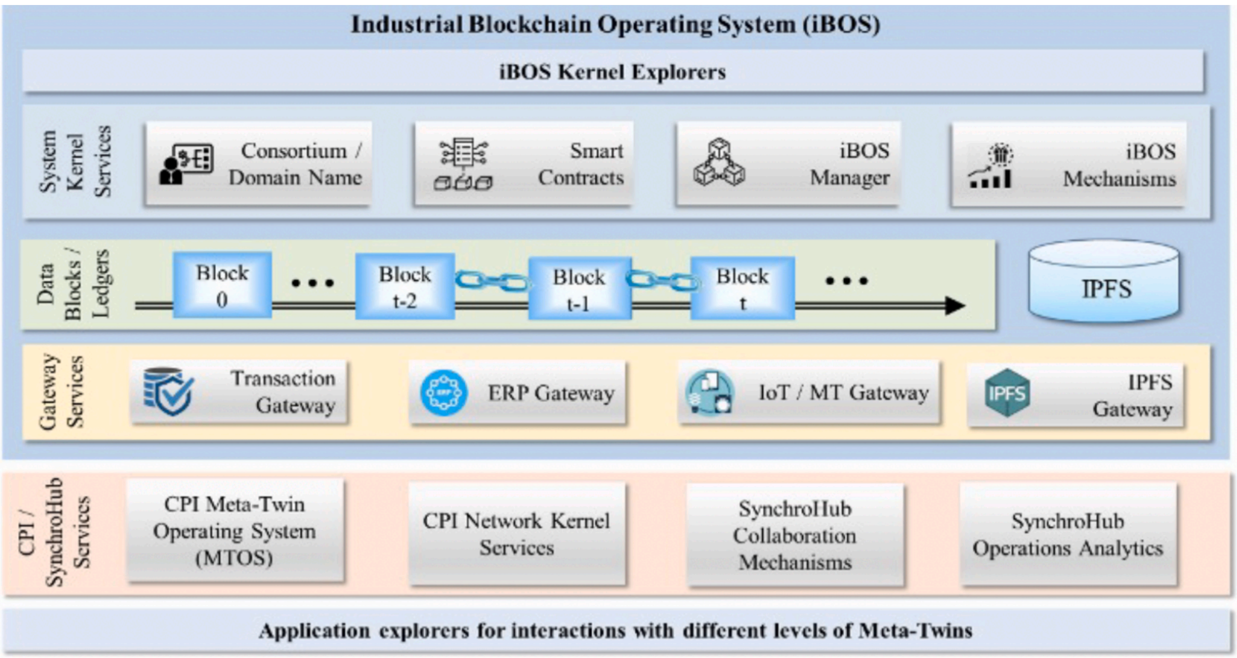

Fig. 10. Industrial blockchain operating system (iBOS).

integrated as the underlying mechanism for these paradigms to coordinate information sharing among multiple collaborative parties, with the alternative benefits of enhancing cybersecurity industrial applications (Li et al., 2021, 2023c,d; Fernández-Caramés and Fraga-Lamas, 2019). From the management perspective, information sharing among MTs can also lead to potential cybersecurity challenges. MTs' connections rely on mutual communication and information sharing. The key question that needs to be addressed is, what MT information should be shared for intended purposes, and what method or platform should be used for information sharing? To guarantee the authenticity of the shared information among the MTs, an industrial blockchain operating system (iBOS) can be developed, as shown in Fig. 10 (Li et al., 2019a; Rachana Harish et al., 2021). The middle layer in Fig. 10 includes ledgers or data blocks, and IPFSs (InterPlanetary File Systems) for storing shared data and large-sized data, respectively. The upper layer in Fig. 10 includes kernel components covering data security, consensus protocols, incentive mechanisms, and inherent blockchain functions. This layer simplifies the blockchain operations and specialized terminology for the developers and users. iBOS is a flexible platform for developing compatible and PnP gateways for other applications, as indicated in the lower layer. Some examples are the ERP gateway for the interface of proprietary enterprise information systems (EISs) and the IoT (MTs) gateway for processing MT information, to and from, the ledger layer. iBOS explorers are user interfaces implemented through mobile or desktop apps.

By generating MTs, and facilitating data exchange among them, the universal interconnectivity of the CPI components can be achieved at the physical layer, digital layer, and operational layer. All the environmental changes in the logistics process can be sensed instantly and effectively. Data from different sources or periods can be efficiently integrated to provide more comprehensive services and decision support. This highly networked and intelligent scenario also enables the 1:N relations in logistics, which means the logistics operators should be capable of collaborating with more than 1 robot because only complex scenarios need humans to be engaged, and most of the CPI operations will be highly instructed by the CPI protocols. For instance, the E-commerce logistics picker will be assisted by multiple robotic arms and logistics robots for the collaborative picking of different kinds of goods.

Digitalization serves as a foundational pillar for the realization of CPI, and represents a crucial direction for future research. In this context, MTs and iBOS are proposed as fundamental components to the CPI's digitalization. MTs act as operating objects within CPI, and their formulation and interconnection are vital to the digitalization process. Moreover, from the perspective of aligning with Industry 4.0 developments, HRC emerges as a promising research branch within CPI. The deployment of CPI facilitates the application of HRC in the logistics sector, breaking new ground in this field, while the implementation of HRC also contributes to the advancement of CPI toward greater automation and intelligence.

6.2. *Network configurations and services*

With the emergence and adoption of the domain name system (DNS), TCP/IP, and the World Wide Web (WWW), the internet gained momentum in the 1980 s. Packets are basic units of data for the internet. Two basic network configurations have prevailed. They are LAN (Local Area Network) and WAN (Wide Area Network). The network components include bridges, DNSs, gateways, hubs, internet protocol (IP) addresses, ports, routers, subnets, and switches. All these work in the cyber space. In contrast, logistics networks operate in the physical domain. In previous EU PI projects, worthwhile discussions and efforts have been made to "imitate" these internet components (Ballot et al., 2021; Sarraj et al., 2014b). However, such imitation is very challenging. By creating a cyber space on top of the PI, CPI thus takes full advantage of internet concepts and components with the internet addressing the flow of information, whereas PI handles the flow of materials.

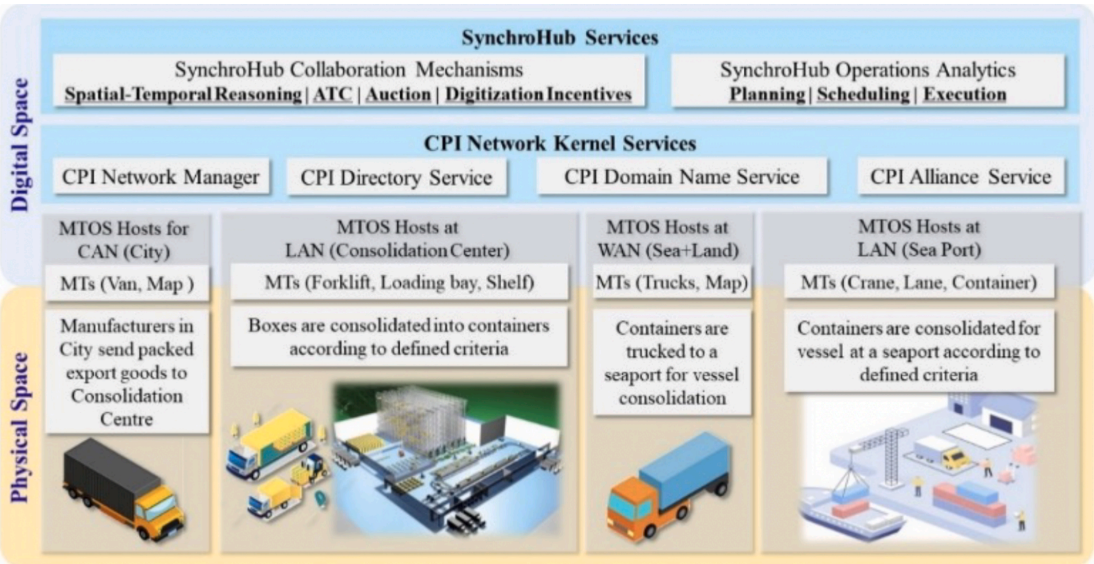

Fig. 11. CPI network configuration and services.

Fig. 11 proposed three CPI network configurations that capture the core networking features of global logistics. Local Area Network (LAN) consists of local logistics facilities coordinated by leading operators but followed by participating stakeholders. Typical examples include ports and terminals, logistics parks and distribution/consolidation centers, and production facilities. Within a LAN, MTs for humans (labor), machines (reusable hardware resources and infrastructure), materials and orders are created purposefully for the intended internal operations. For example, airports use unique trolleys for moving passenger baggage and air cargos, and the paths/roads are markedly different from those in city transportation networks. In a LAN, an indoor positioning system (IPS) is needed for indoor logistics operations. Nevertheless, IPS requires intensive calibration, which is labor intensive and difficult within indoor environments whose spaces are often irregular. There is a strong desire to overcome this challenge to develop a generic IPS for different applications.

Wide Area Network (WAN) connects LANs for long-haul cross-border logistics. Twenty-foot and forty-foot containers are considered basic units used by both shippers and carriers in CPI WAN networks. The container load and route planning should be coordinated and synchronized. Containerization should maximize interchangeability among different modes of transportation. However, air cargo containers are different, and interchangeability is achieved at the pallet level. Catchment Area Network (CAN) connects LANs for logistics within catchment areas (often called the hinterland). Another typical CAN configuration is based on “hub-spoke”, where the LAN hub serves the “spokes” of shippers and carriers within the hinterland or catchment area. A single mode, usually land transport, is used in a CAN. However, one complication is that the geographical catchment areas of multiple LANs of different transportation modes may overlap within their CPI CAN network configurations.

In addition to properly configuring the CPI network, determining what CPI network components and services should be provided to establish cyber-physical traceability and trackability is an important task. The first component is the CPI MT hosts (host computers) that operate the MTOS for managing MTs. Other CPI network services can also be deployed at MT hosts to share computing resources. The second component related to MT hosts is the Meta-Twins Cloud, which can be compared to iCloud for a variety of Apple devices in terms of purpose, functionalities, and usage. The third component is the CPI network configuration manager, which provides facilities for creating, configuring, and monitoring LANs, CANs and WANs. This manager addresses the networking properties of MTs and MT hosts. This process is essentially the same as configuring computer network properties such as setting IP addresses. If PTs already have network interface cards, their network properties are represented by their DTs. If PTs do not have their own network cards, then they share and inherit the network properties of their MT hosts. The fourth component includes the CPI DNS paired with the directory service. MTs and MT hosts in CPI networks strongly resemble IP devices and hosts. We propose adopting internet DNS for CPI networks, and the necessary extensions will be investigated. This will manage corporate and individual users with varying access authorities within domains. This also applies to the CPI directory service, which provides unique mappings between domain names and CPI network addresses, similar to IP addresses. An Alliance Name Service (ANS) as the fifth CPI component is also proposed. ANS can be compared to chat friend groups widely used in instant messaging platforms (e.g., WhatsApp and WeChat groups). ANS is important because the industry often forms and uses alliances to share logistics services and resources with special mutual agreements. Finally, CPI networks have a cyber-physical security service to identify CPI security vulnerabilities.

Once the CPI network for global logistics is configured and the network services are defined, the next step is to determine how the transmission unit is transferred to the CPI network to direct the actual shipment of containers in the physical logistics network. This problem could be solved by taking a programmatic approach. First, we propose starting with the TCP and PIP for the digital layer of the CPI flow of information. This is because MTs and MT hosts are normal internet devices and computers, and they are completely compliant with the four-layered TCP/IP model. Second, whether and how TCP/IP protocols can be imitated to establish protocols for the physical layer of CPI networks should be explored. Moreover, CPI network protocols need to be investigated in a broader stand by considering how materials are stored, moved, loaded/unloaded, and picked/sorted/packed rather than just material containment. Third, typical MTs used in global logistics systems are categorized according to their roles and features to create CPI MTs (for picking/sorting/packing, storage, cross-docking and consolidation, conveyors, automated guided vehicles (AGVs), trucks/vans, boats, etc.) compared with internet components such as ports, routers, subnets, hubs, and switches. They are identified through their unique MAC addresses and traced/tracked by their PIP addresses. Fourth, the command Ping has been around since the 1980 s and is still widely used for testing network connections and latency with IP devices by transmitting test data packets. Similar commands should be developed for CPI to reflect the haulage time between different logistics nodes in real time. Finally, mobile access points (MAPs) can be compared with wireless access points (WAPs). We investigate how Wi-Fi can be “imitated” for CPI networking. If an MT is mobile like a smartphone, a dynamic IP address is assigned by MAP hosts. Innovating seamless indoor and outdoor MAPs by integrating indoor positioning systems (IPSs) and global positioning systems (GPSs) is also an interesting topic.

6.3. Collaboration mechanisms

The power of CPI is demonstrated through CPI visibility and traceability, which are technologically innovative, financially expensive and socially sensitive. The major concerns are threefold: spatial–temporal reasoning for cyber-physical visibility and traceability with real-time data, transportation service procurement auction models for CPI network synchronization, and crypto-currency incentive mechanisms for CPI information sharing and collaboration.

Global logistics involve indoor and outdoor operations. GPS (global positioning system) and BPS (Beidou positioning system) can be readily used for outdoor wide-ranging positioning, typically for CPI WANs. For indoor logistics operations, an indoor positioning system (IPS) is needed. First, the IPS requires intensive calibration, which is labor-intensive and difficult within indoor environments whose spaces are often irregular. Additionally, visibility/traceability is not limited to spatial–temporal data but also includes the ambient data associated with logistics operations, for example, for vaccines and fresh food products. Finally, the data were collected in the context of logistics operations. Contextual information should also be used for spatial–temporal reasoning for visibility/ traceability.

CPI provides a marketplace for transportation service procurement (TSP), where shippers and carriers are buyers and sellers, respectively, and forwarders are brokers. The auto-execution mechanism of smart contracts enables a decentralized CPI network to automate TSP trading, facilitating the timely self-organization of the transportation resources (Leng et al., 2019). Furthermore, the application of blockchain technology ensures that each auction is recorded, allowing for traceability and verification by third parties. Previous research has explored auction models for TSP problems (Guo et al., 2021a; Xu et al., 2018). Auctions produce instant pricing decisions. However, due to the inherent complexity and uncertainty (not knowing each other), only a limited number of decision variables can be considered. This task explores auctions in the context of IoT-enabled CPI network visibility and traceability. We consider typical consolidation points (orders, pallet loads, containers, truckloads). Spatial-temporal decision variables and parameters are considered in auction utility models.

Visibility and traceability require real-time data, and their collection is not free. Indeed, enormous efforts are required to set up an Industry 4.0 environment for global logistics systems. Information sharing has long been recognized as a winning proposition in supply chains. The EPC Global Network was among the largest efforts to develop RFID-based platforms to enable information sharing. However, the EPC Global Network did not deliver what it promised. One critical issue is how technology investments and benefits should be shared among upstream, midstream and downstream players along supply chains. The benefit levels differ from those of supply chain echelons—the earlier the data are collected and shared in the supply chain, the more downstream parties can benefit. It is necessary to propose an incentive mechanism to motivate parties to “donate” (share) data in CPI networks with blockchain crypto tokens.

7. Conclusion

By restructuring logistics organizations, upgrading infrastructure, and optimizing operational processes, PI has changed the traditional logistics mode of operation. These developments enhance logistics efficiency and promote the sustainability of logistics networks. With ongoing technological innovation, the evolution toward digitized, automated, and intelligent logistics systems is an inevitable trend. However, the current PI has obviously not yet reached this goal. It is essential to identify the gaps between the current state and the expectation.

In response, we conducted a systematic literature review of the existing research on PI. After a systematic screening process, 344 relevant publications remained. By analyzing these publications, we identified and summarized the current limitations of PI. To fill these gaps, we propose the concept of CPI. CPI aims to establish a cyber space on top of PI for seamless data flow and interaction. On the basis of the tightly integrated cyber space and physical space, a vivid logistics network can be created and restored in the cyber space where logistics infrastructure and operations can be reformed. To realize this vision, we introduced a five-layer model for CPI. This model serves as a foundational framework designed to maintain a separation of responsibilities, allowing protocols, mechanisms, and standards to be loosely coupled to accommodate various logistics scenarios. It provides a scientific guide for the development and implementation of CPI, analogous to the OSI model in computer networking. Furthermore, we present a simplified logistics scenario to illustrate the fundamental operational mechanisms of this model. Finally, we outlined a short-term roadmap for CPI implementation. Several milestones have been established, including digitalization, network configuration and service, and collaborative mechanisms. This roadmap provides a clear path for future efforts.

However, several limitations of this study need to be addressed in the future. First, the literature analyzed in this review was sourced from three databases: Web of Science, Scopus, and IEEE Xplore. Consequently, this may result in the omission of valuable studies not indexed in these databases. Second, we did not establish specific inclusion criteria for research topics to obtain a comprehensive overview of the current state of PI development. However, this also leads to our analysis being somewhat disparate, complicating the integration of themes. Third, the CPI five-layer model proposed in this paper is only a conceptual framework that needs to be implemented and verified further with more real-life scenarios. Fourth, we have tried to specify the research directions as small granularities. However, each granule still contains many unknown technical and practical challenges regarding the development of CPI.

CRediT authorship contribution statement

Hang Wu: Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Conceptualization. **Ming Li:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Chenglin Yu:** Writing – original draft, Investigation, Formal analysis, Conceptualization. **Zhiyuan Ouyang:** Writing – original draft, Investigation. **Kee-hung Lai:** Writing – review & editing, Investigation. **Zhiheng Zhao:** Writing – review & editing, Formal analysis. **Shenle Pan:** Writing – review & editing, Investigation. **Shuaian Wang:** Writing – review & editing. **Ray Y. Zhong:** Writing – review & editing. **Yong-Hong Kuo:** Writing – review & editing. **Fangni Zhang:** Writing – review & editing. **Wenjie Huang:** Writing – review & editing. **Zuo-Jun Max Shen:** Investigation. **Eric Ballot:** Writing – review & editing, Investigation. **George Q. Huang:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to

influence the work reported in this paper.

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