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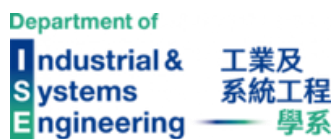


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Addressing the Reachability Problem in the Physical Internet: A PI-Link Protocol Inspired by the Internet

Gero Niemann¹, Rod Franklin¹ and Malte Spanuth¹

1. Kühne Logistics University, Hamburg, Germany

Corresponding author: gero.niemann@klu.org

Abstract: *This paper introduces the PI-link protocol, a standardized communication protocol inspired by Internet architecture, to address the foundational challenge of reachability in the Physical Internet (PI). Drawing on the analogy of the Internet Protocol (IP), the PI-link protocol enables dynamic, resilient interconnection across independent logistics networks. Unlike optimization-focused approaches that assume a pre-established PI, this research develops a scalable protocol facilitating ad-hoc communication and shipment flow, even under disruptions. The protocol's feasibility and effectiveness are validated through a simulation based on real-world logistics data from Vietnam. By emphasizing interoperability, standardized data exchange, and decentralized operation, this work contributes a critical building block for operationalizing the PI and sets the stage for future research in dynamic routing and logistics network integration.*

Keywords: *Physical Internet, Protocols, Protocol Stack, Interconnection, Internet, Agent-based simulation, TCP/IP, Reachability.*

Physical Internet (PI) Roadmap Fitness: *Select the most relevant area(s) for your paper according to the PI roadmaps adopted in Europe and Japan: ☒ PI Networks, ☒ System of Logistics Networks, ☒ Access and Adoption.*

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1 Introduction

Logistics networks are challenged by fragmentation, limited interoperability, and rigidity in the face of disruptions. While current systems can handle predictable, pre-planned flows efficiently, they often collapse under unexpected disturbances, prompting costly and inefficient manual interventions. These ad-hoc workarounds, such as emails and phone calls to find alternative transport options, lack coordination, scalability, and responsiveness. The Physical Internet (PI), introduced by Montreuil (2011), aims to overcome these limitations by fostering a dynamic, interoperable network-of-networks. Through seamless interconnection of logistics systems, the PI promises improvements in efficiency, resilience, and sustainability.

Central to the vision of the PI is the notion of dynamic rerouting, enabled by standardized communication protocols analogous to those that underpin the Digital Internet. This paper focuses on the foundational requirement of reachability, the ability to deliver any physical shipment from any origin to any destination across independent logistics networks. Reachability is a prerequisite to optimality. Before routes can be optimized, the system must first be capable of establishing connections across network boundaries. As such, addressing the reachability problem represents the first step towards a PI (Dong & Franklin, 2021).

The Internet provides a compelling template for addressing this challenge. Its architecture, particularly the Transmission Control Protocol/Internet Protocol (TCP/IP) suite, offers lessons in how standardized protocols can enable resilient, large-scale communication across autonomous systems. The Internet Protocol (IP) achieves reachability by assigning unique addresses, supporting packet fragmentation, and enabling dynamic, decentralized routing through interoperable mechanisms. Drawing from these principles, recent developments in the Cyber-Physical Internet (Wu et al., 2025) advocate the integration of Internet-based models into logistics system design.

Despite considerable research on routing optimization, containerization, and collaborative transport mechanisms within the PI domain, most contributions assume that a functioning PI network already exists. This assumption overlooks the crucial challenge of establishing such a network and the necessary mechanisms and processes for its operation. This is more of an engineering challenge than an operations research (OR) problem. Engineering often deals with physical structures and processes, while OR provides a framework for optimizing those structures and processes using mathematical models.

To develop the PI-link protocol (PILP), we follow the idea of the IP and follow formal communication protocol design methods (Bochmann & Sunshine, 1980). Subsequently, we demonstrate the protocol's feasibility and effectiveness through an agent-based simulation built on real-world logistics data from Vietnam. By focusing on functionality rather than optimization, the paper establishes the protocol as a foundational enabler of the PI, laying the groundwork for future research into higher-layer services such as cost-based routing or carrier assignment.

In sum, this research contributes to the operationalization of the PI by offering a scalable and implementable protocol solution for dynamic interconnection. It addresses the overlooked yet fundamental question of how to ensure that shipments reach their destination across independent networks, thereby making a critical first step toward a truly resilient and adaptive logistics system.

The remainder of this paper is structured as follows. Section 2 reviews existing research on PI protocols, identifying key differences, limitations, and introducing the reachability problem from a literature-based perspective. Section 3 outlines PI-link protocol through a five-step framework. Section 4 presents a case study to test the protocol's functionality and demonstrate its contribution to improving reachability. Finally, Section 5 concludes the paper with a summary of findings, limitations, and directions for future research..

2 Literature review

2.1 PI protocols

Early PI protocol research (e.g., Sarraj et al., 2014) drew on Internet models to highlight benefits like improved fill rates and reduced emissions, though scalability remained a challenge. Gontara et al. (2018) addressed this with a scalable routing protocol inspired by the Internet's Boundary Gateway Protocol (BGP), while Lafkihi et al. (2019) and Briand et al. (2022) introduced incentive-driven cooperation and auction-based assignment to improve efficiency. Other studies proposed dynamic consolidation (Shaikh et al., 2021), hyper-connected parcel networks (Orenstein & Raviv, 2022), and decentralized routing with privacy safeguards (Sun et al., 2024).

Resilience under disruption has been another key focus. Yang et al. (2017b, 2017a) and Nouri et al. (2020, 2021) demonstrated that PI models outperform traditional supply chains by

maintaining service levels and reducing emissions and costs during disruptions. Peng et al. (2021) highlighted the trade-offs between flexibility and lead time in integrated systems. Achamrah et al. (2023) proposed a reactive routing protocol enhancing PI resilience via centralized coordination.

Previous literature on the PI has largely focused on its anticipated benefits and on solving routing optimization problems under constraints like consolidation and transport assignment (Wu et al., 2025). However, as the PI scales, problem complexity increases, and real-world uncertainties reduce the applicability of such solutions. Practical challenges, such as sourcing shipment data or tracking costs across networks, remain unresolved and must be addressed to implement routing mechanisms effectively.

Another limitation is the common assumption that intelligence lies within the PI network itself, requiring nodes to make routing decisions dynamically. This differs from the Internet model, where intelligence is host-based and routers forward packets based on simple rules (Comer, 2013). This Internet-inspired structure (decentralized, resilient, and protocol-driven) suggests a promising template for the PI. Like the Internet, the PI should not micromanage internal node operations or impose centralized control but instead rely on shared standards and protocols for seamless interoperability across self-managed networks.

Protocol frameworks inspired by Internet architectures have been proposed by Montreuil et al. (2012), who introduced a PI protocol stack based on the OSI model. Dong & Franklin (2021) later referenced the five-layer DoD model used in Internet design, categorizing PI tasks accordingly. More recently, Wu et al. (2025) advanced the Cyber-Physical Internet (CPI) concept, which separates cyber and physical domains to enhance logistics via Internet-like principles. Their research agenda emphasizes digital infrastructure, intelligent automation, and interconnectivity. Wu et al., (2024) applied CPI in the Greater Bay Area, using mechanisms aligned with the Internet's link and transport layers. However, scalable core protocols like TCP/IP have not yet been proposed (Wu et al., 2025). Dong & Franklin (2021) suggest reducing complexity by dividing PI operations into two problems: reachability and optimality. They argue that the reachability problem, how to send a shipment from A to B, should be addressed first, operationally managed at the Link and Network layers.

2.2 Reachability problem

Reachability, a concept from graph theory, defines whether a path exists between two nodes in a graph $G = (V, E)$, where V is a set of nodes (vertices) and E a set of edges (Diestel & Diestel, 2000). Graphs can be undirected, where connections are symmetric, or directed, where relationships are one-way. This distinction influences whether a node v can be reached from another node u via a defined path.

The concept has been foundational in computer networks, especially since the early development of ARPAnet (Cerf & Kahn, 1974). To ensure reliable inter-network connectivity, the Internet Engineering Task Force developed TCP/IP, with the IP addressing the reachability problem. IP assigns unique addresses and enables routing using a datagram model, where packets travel independently. It also manages fragmentation for networks with varying transmission capacities to enable connection of disparate networks through standardized addressing, routing, and communication mechanisms, enabling reachability of any node.

What is needed to solve the reachability challenge for the PI is a similar protocol. Besides reachability, a similar protocol could enable a collaborative, dynamic and interconnected network-of-networks that provides redundancy, a key factor for robustness and resilience (Ezaki et al., 2022), by allowing certain components to take over the functions of failed ones

without compromising system performance (Wan et al., 2018). In the practical context of a transport system, this translates into the availability of alternative routes between origins and destinations, allowing rerouting as an operational contingency strategy to ensure reachability even in case of disruptions (Tomlin, 2006).

In logistics, various international agreements function similarly to protocols, standardizing flows and ensuring the smooth transfer of goods across global networks (Dong & Franklin, 2021). These include frameworks such as Incoterms, customs agreements, international modal regulations, and postal agreements, which collectively support efficient cargo movement worldwide. While these factors represent key logistical considerations for addressing reachability, they do not encompass the full scope of challenges. Given that the PI aspires to mirror the principles of the Internet, it is essential to also account for reachability factors from a networking perspective. The structure and functionality of the IP, when adapted to the specific requirements of logistics, have the potential to provide a foundational framework for establishing seamless interconnectivity within the PI. By leveraging insights from IP, a more robust and scalable approach to reachability in logistics can be developed.

3 PI-link protocol definition

In developing our protocol, we build upon the Cyber-Physical Internet (CPI) model introduced by Wu et al. (2025). Specifically, we extend their conceptualization of the Physical Internet Protocol (PIP) and its integration within the CPI architecture. While our research aligns with the overarching vision proposed by Wu et al. (2025), it advances their framework by offering a more detailed and operational protocol for interconnection, analogous to the specification of the IP outlined in RFC 791 by Postel (1981).

Understanding complementary architectural layers is essential (Bochmann & Sunshine, 1980). The TCP/IP suite is based on the five-layer DoD model (Clark, 1988; Comer, 2013), and we analogously reference the upper and lower layers around the PILP. In the PI, a future PI-control protocol, similar to TCP, would manage end-to-end shipment flows (Dong & Franklin, 2021; Hofman et al., 2017; Montreuil et al., 2012). Above this, the cyber-physical system (CPS) layer interfaces with users. Below, the physical layer corresponds to transport means like vehicles and sorters, akin to the Internet's physical infrastructure. See Appendix 1 for a visual comparison.

To define the PILP, we follow the protocol definition framework outlined by Bochmann & Sunshine (1980). Their approach consists of the following five main steps.

Step 1: Defining the purpose of the layer

The purpose of the network layer is the establishment of an interconnected network that enables end-to-end shipment flow in a dynamic manner. This is done by the interconnection of two nodes, one in network A and one in network B. The PILP supports the establishment of such a network of networks. These independent networks, referred to as Autonomous Systems (AS) in the Internet (Leiner et al., 1985), have been adapted to the logistics domain in Gontara et al. (2018).

Step 2: Specifying the service of the layer

The network layer establishes the functional and procedural mechanisms necessary to ensure that shipments can be routed both within and across independent networks while maintaining the specified level of service (Montreuil et al., 2012; Wu et al., 2025). Additionally, it continuously monitors shipments as they move through the PI, detects routing deviations, mitigates potential disruptions, and identifies real-time routing opportunities to optimize

efficiency. To enable the services of this layer, certain functions must exist such as addressing, fragmentation management, cost tracking and prioritization.

Step 3: Identifying the service provided by the lower layer.

Beneath the network layer (where the PILP operates) are the link layer and the physical layer. The link layer incorporates the link interface, which facilitates integration with the operator's internal operational systems (e.g., a transport management system). This interface enables communication between the PI network and node-internal operations, ensuring that local transport processes can align with the standardized requirements of the broader PI architecture.

The physical layer is concerned with the physical movement of the shipment through transportation means. It provides essential digital services to support the protocol such as provision of delivery information and collection of information from business processes or through IoT and RFID devices installed on the physical shipment or transportation means (Brunetti et al., 2024; Montreuil et al., 2012; Pan et al., 2021; Wu et al., 2025).

Step 4: Detailing the internal structure of the layer

The primary role of the network layer in the PI is to ensure forwarding of shipments, which relies on a variety of supporting functions. At the core of these functions is the PILP, serving a foundational role similar to that of the IP within the Internet architecture (Comer, 2013; Kurose & Ross, 2017). On the Internet, the network layer includes auxiliary protocols (e.g., Open Shortest Path First (OSPF), Routing Information Protocol (RIP), etc.), which support the operation of the services of this layer.

Step 5: Describing the protocol

To explain the protocol, we first outline the network layer's service primitives and how they operate across a transport chain. We then specify the protocol's functionality from a technical systems perspective to support its integration into node-level software (e.g., ERP, WMS, TMS), similar to IP in routers. Finally, we present the detailed header specifications.

Network layer service primitives

The functional description of PI-nodes is inherently conceptual, as each node or network operates according to its own internal business processes. As a result, protocol supporting functions such as routing and consolidation may be implemented differently by each node. However, these functions receive information from the PILP service. A service specification typically uses a set of service primitives to abstractly define the operations available at the service interface (Bochmann & Sunshine, 1980). Thus, all nodes are required to adhere to standardized procedures for *wrapping*, *monitoring* and *unwrapping* information carried by, or to be carried by, the PILP. Please find a figure on this process in Appendix 2.

Wrapping is the process of preparing the PILP information package initiating the movement of shipment(s) between nodes. This is done after a load has been constructed (e.g., consolidation of several shipments), the route has been determined (based on local node procedures), and the assignment to a proper transportation means and carrier has been performed by the node.¹ The shipment information package, which forms the primary data carried by the PILP, contains particular information on the items being carried in the load. This information can be encrypted and is never accessed by the PILP, which is only concerned with ensuring that the load reaches the next node and the details of the transport trip itself. When wrapping, the node fills the

¹ These are operations subject to the node/network operator and not the PI link protocol.

wrapper field with all necessary information and sends the physical load out on the link accompanied by the PILP message. A visualization can be found in Appendix 3.

While the load is in transit, its progress is actively *monitored*, and the costs incurred are continuously tracked and recorded (note that this monitoring is performed via either a system timer, active IoT, or some other mechanism feeding information to the PILP). Upon arrival at the next node, the protocol message is unwrapped (the *unwrapping* process), which involves extracting and examining the wrapper's information (not the internal wrapped message unless the node has been authorized by the consignor to do so). This includes load data (see below), the cost objectives set for the load and link, and the actual costs incurred during transit. The node then conducts a critical comparison between the cumulative actual costs and predefined target costs. The predefined target costs are provided by the control layer.

Further processing of the collected information is done on the control layer. However, in case of out-of-bound situations (i.e., too high costs, disruptions, etc.) the node may consider requesting additional advice from the control layer on how to proceed. After the wrapper is fully analyzed it will be cleared, and the shipments within the load are subject to the node's operational procedures preparing the shipment for its next leg in moving towards its destination. Once the shipment has been prepared for its next movement, a new wrapper is instantiated, and the link process starts again.

The process begins with an order, which is assigned a shipment header containing relevant order details. When multiple such shipments are consolidated and wrapped with a link header, they form a load.

Header formats

Link header	Shipment header(s)	Order 1	Origin Lat	Cost (monetary)	Priority (wrapper)	Destination Lat
				Cost (lead time)	Requirement (wrapper)	
				Disruption state		
		Order 2	Origin Lon	Cost (emission)	Fragmentation	Destination Lon
				Dimensions (wrapper)		
				Weight (wrapper)	Fragment	
	Shipment header(s)	Order 1	Order number	Dimensions	Priority	Postal address (ISO 19160)
			Shipper	Weight	Requirement	
		Order 2				

Figure 1: Headers

The protocol's core is the link header, which comprises a PI-link wrapper encapsulating one or more shipment headers, along with their orders. This structure is inspired by the Internet Datagram Header (Postel, 1981)². The wrapper contains link-specific information necessary for the loads' movement across a particular link, while the order details facilitate the shipment's journey across multiple links to its final destination by providing receiver information. The wrapper addresses the requirement for consolidation, by providing a summary of the shipment requirements, and the requirement for interoperability as the wrapper format should be understandable by all stakeholders in the shipment process.

The addressing requirement is fulfilled by including GPS coordinates (latitude and longitude) for the link's origin and destination, forming a precise and standardized routing scheme as suggested by Gontara et al. (2018). Each wrapped order also contains the full postal address,

² Readers are encouraged to refer to Postel (1981) for detailed technical descriptions of the IP for comparison with the following PILP descriptions. To conserve space, we will not explicitly relate subsequent PILP descriptions to the IP analogy.

revealed upon unwrapping for final delivery. Adopting standards like ISO 19160 (S42) supports interoperability, where wrapper addresses define a geographic point and order addresses specify detailed delivery information (e.g., street, floor, recipient). This mirrors how IP addresses locate a network, while MAC addresses identify individual devices within it (Comer, 2013).

Shipments often have varying requirements, while transportation modes and networks possess differing capabilities. Ensuring compatibility between these requirements and capabilities is essential for achieving reachability. To address this, the wrapper requirements field includes all relevant requirements, such as refrigeration and careful handling, ensuring they are met during transit. In addition to requirements, dimensions and weight are critical for planning and consolidation according to limited transport mean capacities.

Fragmentation becomes necessary when a subsequent network or transportation mode cannot accommodate the size of a shipment. To support this process, the load wrapper includes two dedicated fields for managing fragmentation.³ The first is a binary field (true/false) indicating whether fragmentation is permitted. If fragmentation occurs, a second field provides an array with three values: the original shipment number, the fragment's sequence number, and the total number of fragments. This structure enables reconfiguration at subsequent nodes.

The priority field is defined both at the shipment level and for the overall load within the wrapper by an integer value between 1 (lowest) and 3 (highest), indicating the shipment's processing preference. The wrapper's priority reflects the highest priority among the individual shipments within the shipment. This priority can be dynamically adjusted during transit.

Both the order and load levels include fields for dimensions and weight, with the shipment-level values representing the aggregated totals of the associated orders.

To address the cost tracking requirement, the wrapper collects the costs that are occurring on the link. These costs refer to monetary costs, time and emissions (Dong & Franklin, 2021). Disruptions along the link will influence the costs occurring on the link. Therefore, the wrapper also provides a dynamic adjustable field to track the disruption state (e.g., delayed by congestion, rerouted, etc.).

Lastly, the shipment header specifies for each order an order number and shipper field. Those fields are relevant to identify the order and call back to the shipper (or its representative human or logistics agent) in case of disruptions or unplanned situations (Montreuil, 2011)

4 Case study

In this case study, we aim to demonstrate that the proposed protocol effectively facilitates reachability within a logistics network. Additionally, simulation is used to identify and mitigate potential design errors during the development phase (Bochmann & Sunshine, 1980). The foundational assumption underpinning this analysis is that all participating nodes within the network have adopted and implemented the protocol. Under this condition, we illustrate that shipments can reliably reach their intended destinations not only during steady-state operations but also under disrupted scenarios, and that this is achievable with only a marginal increase in associated costs.

The network utilized in this case study is constructed on a GIS-based map, reflecting empirical data provided by a major German logistics service provider (LSP) operating in Vietnam.

³ These fragmented transports should not be mistaken for split deliveries, (e.g., Dror et al., 1994) where an order is delivered to a customer in multiple separate shipments over time. In contrast, fragmented transport splits a shipment into smaller units that take different routes and are reassembled before final delivery.

Vietnam's logistics landscape is predominantly shaped by two major economic hubs: the Hanoi region in the north and the Ho Chi Minh City region in the south. Accordingly, the majority of network nodes are concentrated within these regions. See Appendix 4 for a visual overview.

Inbound flows originating outside of Vietnam are modeled as entering the country either through land border crossings or via the seaports located in Hanoi or Ho Chi Minh City. Outbound flows directed to domestic consignees terminate at their respective receiving nodes, whereas shipments destined for international consignees are assumed to exit the network through the aforementioned seaports.

For the sake of simplicity, all transport within the network is assumed to occur via road freight, specifically using trucks. Each of the two economic centers has two central warehouses (in our model). These warehouses serve as key transshipment points, receiving goods from domestic and international suppliers and coordinating the distribution of shipments to both domestic and international destinations.

4.1 Simulation model

The simulation model uses AnyLogic's multi-agent system with a discrete-event approach to capture interactions between nodes with distinct behaviors (Lee & Kim, 2008; van der Zee, 2006). Custom Java code supports model extensions and external data integration. The network model is constructed using inbound and outbound flow data from the warehouses. Based on the observed flows, the network comprises four distinct types of nodes: *Supplier Nodes* are the starting points of shipments, receiving orders and initiating outbound flows. *Transfer Nodes* act as forwarding hubs, handling consolidation and fragmentation at locations such as consolidation centers and seaports. *Warehouses* receive inbound shipments, store them temporarily, and dispatch new outbound shipments when triggered by orders. They can serve as both origins and destinations, thus making a process break. *Receiver Nodes* mark the end of the shipment journey, accepting final deliveries and completing the transport process.

Each node is characterized by a set of operational attributes that influence routing decisions. These include specialized handling capabilities—such as the ability to accommodate cooling requirements or hazardous materials—and capacity constraints. Under steady-state conditions, node capacity is assumed to be utilized at 80%. Once a node reaches full capacity (100%), it is no longer able to accept additional inbound shipments, although it may continue to dispatch outbound shipments, thereby reducing its utilization level.

Nodes may also experience disruptions that completely suspend their operations. In such cases, neither inbound nor outbound flows can be processed. Furthermore, each node is equipped with a fleet of truck agents responsible for executing deliveries. These trucks operate on a round-trip basis, returning to their respective home nodes without carrying backloads. The operational capabilities of each truck mirror those of its home node, ensuring consistency in service provision throughout the network.

As previously outlined, the proposed protocol does not define optimal routing, consolidation, or carrier assignment strategies; instead, it enables these functions by establishing a standardized foundation. Therefore, in order to demonstrate the protocol's capabilities, we implement these supporting functions using a straightforward yet effective logic. Since these functions are inherently dependent on the characteristics of the flows they manage, we present them in conjunction with the flow types modeled in the simulation. The simulation captures four primary flow types:

- **Supplier to Consolidation Center:** Single-order shipments are routed to the nearest consolidation center using the supplier's truck fleet.

- **Consolidation Center to Warehouse:** Orders with matching requirements are consolidated (up to 2 TEU) and sent to predefined warehouses using available trucks.
- **Seaport to Warehouse:** Shipments arrive in 2 TEU containers and are split into 1 TEU units due to truck capacity limits, then routed to the destination warehouse.
- **Warehouse to Receiver or Seaport:** Outbound orders are consolidated (up to 2 TEU) and delivered to either domestic receivers or seaports for international transport.

Consolidation within all nodes is governed by a timeout mechanism. If orders remain in the node beyond a predefined threshold without reaching the conditions for consolidation, they are dispatched individually as single order loads to avoid excessive delays.

The flows in the simulation are modeled to be universal, rather than tailored to specific products. However, at selected points in the simulation, we introduce product-specific parameters to illustrate the application and effectiveness of the protocol's specifications. For instance, certain flows are designated as requiring temperature-controlled transport. This cooling requirement is encoded in both the order and link headers, thereby constraining the options for consolidation and limiting the selection of eligible nodes to those capable of meeting the specified handling conditions. This demonstrates how protocol-defined attributes can guide and automate routing decisions in response to operational constraints.

To ensure accurate cost tracking based on real-world scenarios, we use truck speed and cost data from Briand et al. (2022).

4.2 Reachability demonstration

We first demonstrate the concept of reachability using a case study example, followed by supporting functions that address real-world logistics constraints. Figure 2 shows a simplified network with four nodes: N5 (supplier), N108 (default consolidation center), and N12 (destination warehouse).

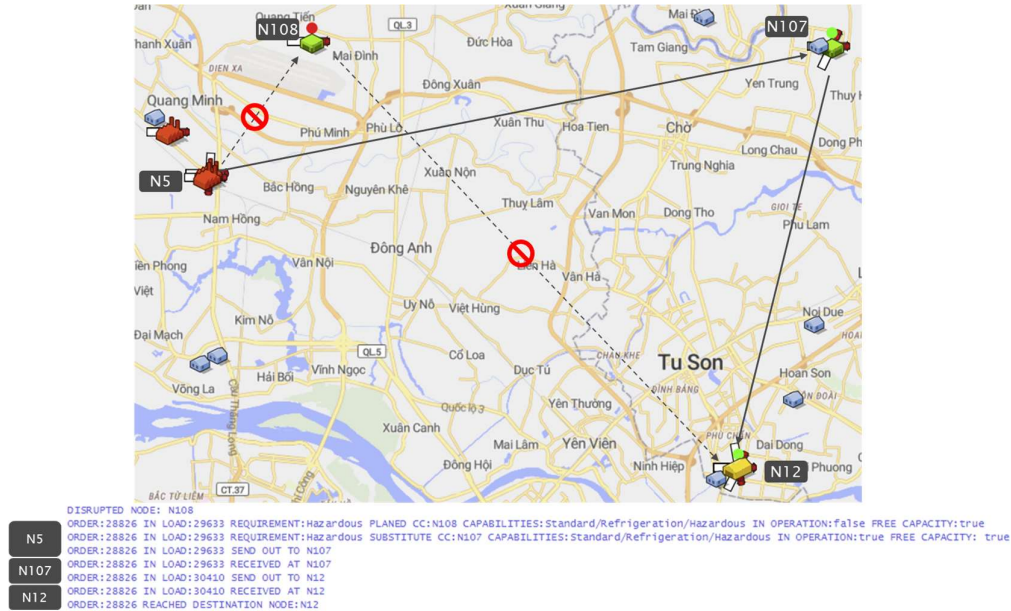


Figure 2: Fundamental reachability demonstration

When N108 is disrupted, N5 must identify an alternative. The simulation output shows order 28826 initially wrapped into load 29633 for N108. With N108 out of service, N5 evaluates N107 by checking capability, status, and capacity. This illustrates how the protocol supports

dynamic rerouting by considering constraints like node functionality and utilization. At N107, the order would be unwrapped, re-consolidated, and included in load 30410 for delivery to N12.

Ensuring reachability during disruptions typically leads to higher costs. As shown in Figure 3, cumulative transit times increase when disruptions occur. These values reflect only in-transit durations, excluding node lead times. In steady-state conditions, shipments follow optimal routes based on time, cost, and emissions. Disruptions, however, require alternative paths to maintain reachability, often resulting in additional time, cost, and emissions.



Figure 3: Orders transit time mapping

As previously discussed in the context of rerouting, the requirements field of a load plays a critical role in identifying appropriate substitute nodes. Similarly, this field is essential for effective consolidation processes. Nodes are assumed to consolidate orders to maximize utilization of transportation resources. Consolidation is carried out based on matching requirements, shared destinations, and dimensional compatibility. Specifically, consolidated shipments must not exceed a total volume of 2 TEU. Figure 4 provides an illustrative console output demonstrating how two loads were successfully consolidated according to these parameters.

```

CONSOLIDATED LOAD:25850 SIZE:2
NODE:N42 ORDER:102 Refrigeration 06 Thăng Long, Phường 4, Tân Bình, Hồ Chí Minh, Vietnam 1.0
NODE:N42 ORDER:558 Refrigeration 06 Thăng Long, Phường 4, Tân Bình, Hồ Chí Minh, Vietnam 1.0
CONSOLIDATED LOAD:25867 SIZE:12
NODE:N43 ORDER:274 Standard 10591 Red Bluff Rd, Pasadena, TX 77507, USA 0.155
NODE:N43 ORDER:294 Standard 10591 Red Bluff Rd, Pasadena, TX 77507, USA 0.155
NODE:N43 ORDER:310 Standard 10591 Red Bluff Rd, Pasadena, TX 77507, USA 0.155
:
:
:

```

Figure 4: Console output consolidation

Another critical feature supporting reachability is the protocol's ability to handle shipment fragmentation. In cases where network segments lack the capacity to accommodate a 2 TEU shipment, splitting the shipment into smaller units becomes necessary to preserve network inclusivity within the reachability graph. Figure 5 illustrates a console output where an order is divided into two parts to conform to the capacity limit of a 1 TEU transportation unit. Each part is wrapped and transported as an independent load. To enable reassembly at the destination, the "Fragment" field in the link header specifies the original order number, the sequence of the fragment, and the total number of fragments. Dimensions and weight are proportionally allocated to each fragment..

```

SPLIT ORDER:26248 DIMENSIONS:2.0 WEIGHT:255.6838860223501
LOAD:26252 SPLIT ORDER:26248/2/2 DIMENSIONS:1.0 WEIGHT:127.84194301111751
LOAD:26253 SPLIT ORDER:26248/1/2 DIMENSIONS:1.0 WEIGHT:127.84194301111751
SPLIT ORDER:26487 DIMENSIONS:2.0 WEIGHT:163.53965496625017
LOAD:26491 SPLIT ORDER:26487/2/2 DIMENSIONS:1.0 WEIGHT:81.76982748312508
LOAD:26492 SPLIT ORDER:26487/1/2 DIMENSIONS:1.0 WEIGHT:81.76982748312508

```

Figure 5: Console output splitting

5 Conclusion

This paper contributes to PI research by addressing a fundamental gap: the absence of operational mechanisms to solve the reachability problem. While prior research has largely concentrated on the optimality problem, how to consolidate, route, or assign resources within an already functional PI, this study takes a necessary step back. We propose and evaluate the PILP, a standardized protocol inspired by the IP, designed to enable shipments to be dynamically routed across decentralized and fragmented logistics systems.

The PILP is built on the principle of digitally wrapping shipment and load information in standardized headers that contain universally interpretable data essential for routing. This structure allows nodes to forward shipments based on a shared understanding of protocol-defined fields.

However, as most research, the approach has some limitations. First, it assumes full protocol adoption across nodes. Second, it depends on the future development of supporting protocols, for end-to-end routing, cost estimation, node state communication, etc. Third, it lacks a concrete system-level implementation strategy, currently relying on the assumption that a CPS would manage execution. Adoption challenges also persist. Unlike the Internet's early days, logistics is not a white space, it has entrenched processes that are suboptimal yet functional, making change more difficult.

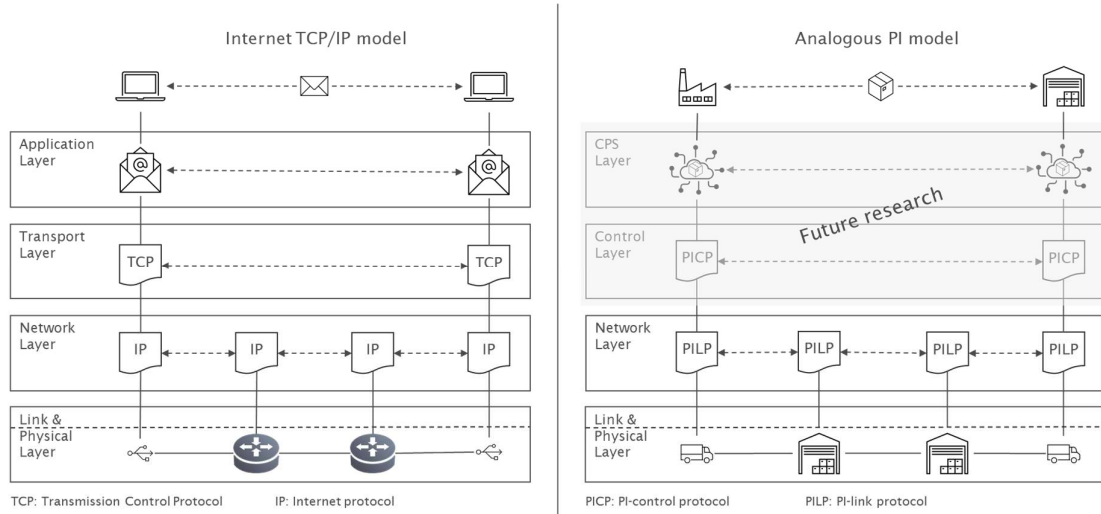
Thus, future research should extend this foundational work by developing complementary protocols and testing implementations in real-world settings. However, the PILP offers a critical building block toward a resilient, interoperable, and scalable PI.

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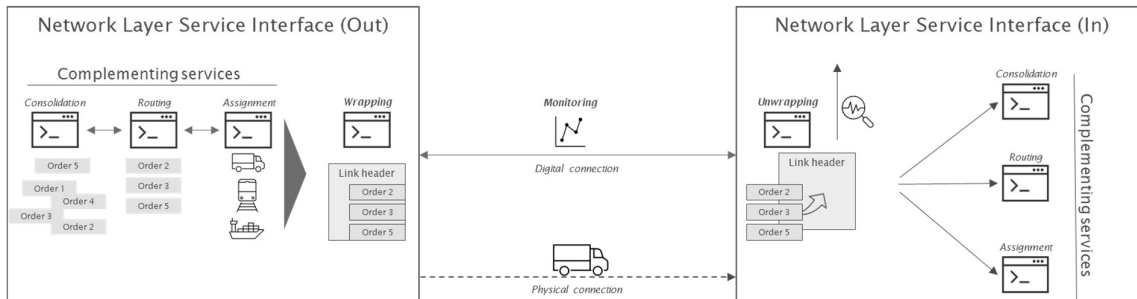
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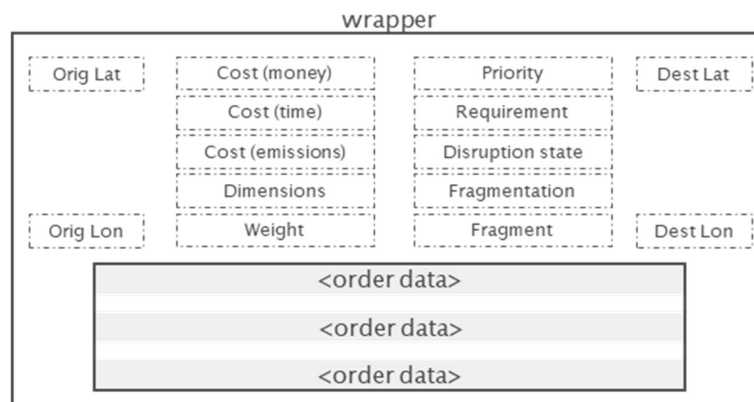
Appendix 1: Internet TCP/IP model and analogous PI layer model



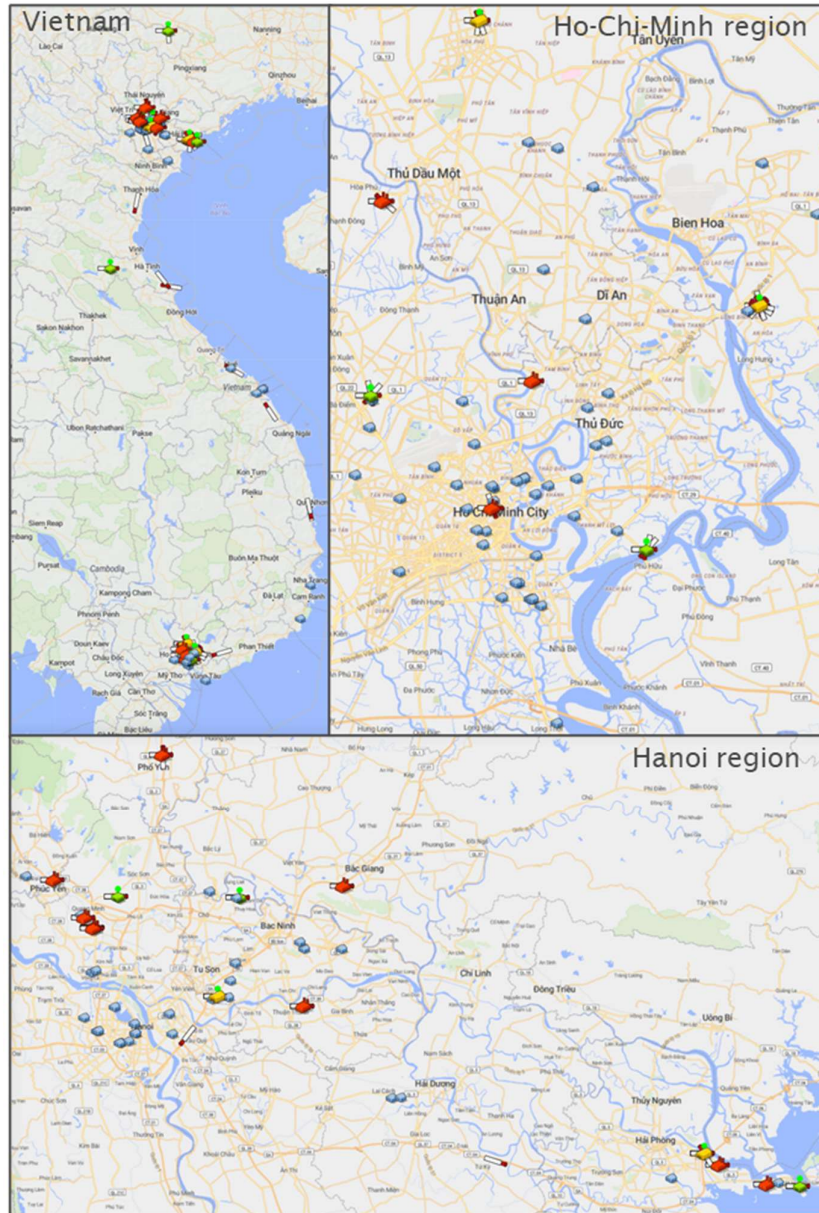
Appendix 2: Network layer service interface operations



Appendix 3: PI-link protocol package



Appendix 4: Network Vietnam and economic regions



Digital twins for inland waterways: Innovative approaches to monitoring and forecasting water levels, navigability, and infrastructure maintenance.

Tammo Märten¹, Björn Krämer¹ Ebrahim Ehsanfar¹ and Sohith Dhavaleswarapu¹

1. Fraunhofer Institute for Material Flow and Logistics IML, Dortmund, Germany

Corresponding author: tammo.maertens@iml.fraunhofer.de

Abstract: This paper deals with the application of digital twin technology in new and innovative ways for the upscaling of inland waterway management in terms of the monitoring and forecasting of water level, navigability, and infrastructures maintenance. Developed as part of the Horizon Europe project CRISTAL, the Water Level Twin, Buoy Twin, and Lock Twin were implemented. All bring forth important data insights from predictive modeling of water levels to real-time environmental monitoring by smart buoys and proactive maintenance management of locks by acoustic sensors. All of these developments aid improved decision-making for operators to improve security and efficiency in inland waterway transportation. Integration of machine learning models facilitates accurate forecasting of navigability, addressing challenges introduced by fluctuating water levels and environmental factors. This research reveals the potential for digital twins to transform inland waterway infrastructure management so that it is more climate change resilient and sustainable. The findings validate the effectiveness of digital twin systems in providing actionable intelligence for infrastructure operators, culminating in the creation of intelligent transport networks.

Keywords: *Physical Internet, Digital Twins, Machine Learning, Inland Waterway Transport, Prediction Models, Intelligent Buoys, Digitalised Locks, Predictive Maintenance.*

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

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

1 Introduction

The combination of digital technology with essential physical infrastructure systems has transformed the planning, observation, and management of key transportation networks globally. Digital twins (DT) represent a particularly innovative and useful technology for the resilience and sustainability of inland waterway systems, which are increasingly challenged by climate change and aging asset infrastructure. This paper discusses innovative implementations of digital twins in inland waterways, based on monitoring and forecasting water levels, navigability, and infrastructure maintenance as part of the Horizon Europe project CRISTAL.

Digital twins imply a significant transformation in the design, development, and management of physical assets and systems in a growing digital environment. VanDerHorn and Mahadevan (2021) define a digital twin as "a digital representation of a physical entity that tracks lifecycle data and live status that are connected in an ongoing manner." This connection allows for both digital and physical twins to share data in real-time to monitor, simulate, and make decisions based on that information. Although the idea first surfaced in the 1970s and 1980s in the automotive and aerospace industries, Michael Grieves did coin the term "digital twin" with his presentation on product lifecycle management at the University of Michigan in 2003 (Grieves and Vickers, 2016).

The evolution of digital twins has gone through a number of stages, ranging from simple simulation models to advanced systems possessing autonomous, self-learning capabilities (Qi et al., 2021). Kritzinger et al. (2018) proposed a classification framework for developing digital twins which distinguishes between digital models (no automatic data exchange), digital shadows (one way data flow from the physical to digital), and true digital twins (automated data exchange in both directions). This classification supports understanding of the varied implementation where maturity differs in applications.

A digital twin system consists of different types of technologies. At its essence, a digital twin refers to three main elements: the physical object in the real world, a virtual representation of that object in a digital space, and the digital connections between the two objects. These connections usually involve multiple layers of data acquisition technology, including IoT sensors, remote sensing platforms, and telemetry, that allow for real-time monitoring and synchronizing capabilities that define true digital twins. (VanDerHorn and Mahadevan, 2021) Digital twin technology has been applied across all infrastructure sectors. In urban planning, digital twins help to improve infrastructure projects and services, by modeling and simulating transport networks and public services. Additionally, digital twins can offer great value in transportation by modeling traffic flows to enhance traffic management and deploy predictive algorithms (Rudskoy et al., 2021). In construction and building, Thuhaise et al. (2023) describe multiple uses of digital twins including projects being managed in a more efficient manner and being monitored, predictive maintenance, and the collection and visualization of real-time data. Transportation infrastructure is a promising domain for digital applications. In this context Di Wu et al. (2025) analysed that most digital twin system in transportation infrastructure can be classified by the area of use, which are 1) monitoring and control, 2) simulation and analysis and 3) predictive maintenance and optimization.

For inland waterway transport (IWT) a good example for the use of digital twins is the study of Wu et al. (2021). Their study presents a novel application of digital twin technology and 3D video fusion for inland waterway safety management. The method consists of drone photography, Building Information Modeling (BIM), multi-channel video, and Internet of Things (IoT) sensors to establish a full-fledged 3D virtual environment of inland waterways. The digital twin can provide a "God's eye view" of the situation, support automated video patrols, and enhance emergency response.

Digital twins offer advantages for inland waterway infrastructure. An example are predictive maintenance approaches, that identify possible failures to the infrastructure prior to actual failure. Digital twins continuously assess sensor readings against historical behavior and theoretical models to detect minute variations that may signal the start of a problem. This is advantageous because digital twins support targeted actions to reinstate service by avoiding disruption and reducing maintenance costs. (Jahangir et al., 2024, p.164)

Linked to predictive maintenance is the CRISTAL project. The CRISTAL (Climate Resilient and environmentally sustainable transport infrastructure, with a focus on inland waterways) Project represents an important European initiative to improve the resilience and sustainability of inland waterway transport (IWT) infrastructure. Funded by the European Commission through the Horizon Europe funding programme (Grant No. 101069838), the Project consists of 15 partners from 9 countries that are working on innovative technologies to monitor transport chains and integrating river transport into multi-modal systems. One of the project's key objectives is "the development of inland waterway transport (IWT) and its infrastructure". The development of IWT addresses the issues, risks and uncertainty of climate change on the reliability and capacity of inland waterways across Europe. (Łukasiewicz, 2022)

Digital twin technology plays a central role in the CRISTAL Project's approach to enhancing inland waterway resilience. There are three digital twins (DT) with different functionalities and focuses in the CRISTAL project. The DT Water Level calculates water levels in advance and combines these with the navigability of the river section, the DT Buoy focusses on the

transmission of data such as wind speed and water height and the DT Lock depicts a lock and displays connected sensors and their results.

Digital Twin “Lock”

The Digital Twin (DT) developed for locks utilizes advanced acoustic sensors to monitor the status of lock gates and detect potential malfunctions in their early stages. By analyzing the data collected from these sensors, proactive maintenance measures can be implemented, which significantly mitigates shipping delays. Furthermore, radar technology is employed to examine wall structures, enabling a thorough assessment of the stability and safety of the lock infrastructure. Both sensor technologies enable predictive maintenance, as a prediction probability for a malfunction is made and, for example, with the AE system, a progression of this value is visualised in the DT.

The Digital Twin “Lock” provides a possibility to attach informational documents related to each lock, such as notices of closures due to repairs. It also integrates sensor data regarding the condition of lock gates and walls. This comprehensive approach allows for the recording and visualization of acoustic sensor data from lock gates, facilitating the transmission of pertinent information and alerts to users and interconnected systems. Consequently, the likelihood of mechanical failures can be assessed digitally at an early stage, preventing urgent interventions when issues arise. Current developments are focused on employing a dedicated sensor system that analyzes and interprets acoustic signals to monitor lock gates over an extended period.

The results obtained from these assessments can be transferred to the digital twin, where they can be analyzed in conjunction with visual displays, triggering various alarm scenarios for higher-level systems and users. This capability enables maintenance actions to be carried out before a complete lock failure occurs (predictive maintenance based on sensors), thereby preventing disruptions in shipping traffic.

Future applications may explore automatic analyses that establish connections between different lock types. For instance, these connections could be utilized to adapt locks with similar characteristics, such as construction year and gate specifications, providing early warnings of potential issues in comparable infrastructures. In addition to monitoring lock gates, there is the capability to examine the walls using radar technology, which allows for effective scanning of wall structures and identification of possible anomalies.

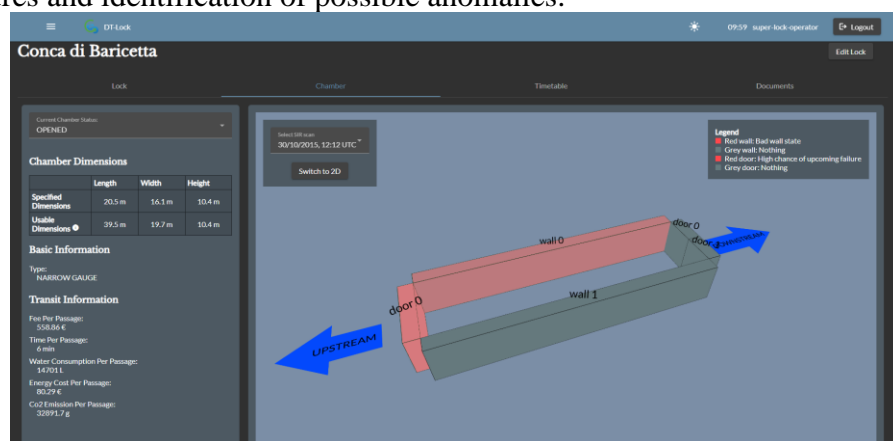


Figure 1 DT Smart Monitor Lock – Lock Inspect

The findings from these analyses are also presented in the Digital Twin and made accessible to infrastructure managers. The wall structures are categorized into different quadrants, with various views such as images and videos provided. This approach enables a closer inspection of the underlying structures, facilitating assessments of wall stability by identifying indicators like water inclusions, air bubbles, or roots that may signal alterations in the original structure, such as concrete degradation. Early detection through this assessment allows for timely repair actions.

Given that repairs typically entail closure periods, the Digital Twin for locks incorporates functionality to manage this aspect as well. Users can specify the duration of closures and integrate corresponding measures, including notifications regarding anticipated disruptions leading up to the actual closure. This information is subsequently relayed to a higher-level planning platform for shipping traffic, ensuring that relevant notices and warnings are disseminated effectively. Due to the open and flexible architecture of the digital twins, it is also possible to connect other sensor technologies and data sources. This would increase the range of additional information and could also be economically viable, for example by measuring the time of ship transfers and adding a cost factor.

Additionally, the Digital Twin “Lock” allows for the storage of supplementary documents and information pertaining to the lock, repair measures, and more.

Digital Twin “Buoy”

The Digital Twin “Buoy” is an innovative software that connects to smart buoys to collect a wide range of environmental metrics, including water depth, temperature, flow speed, and ice cover thickness. This data is essential for planning navigation routes, particularly in challenging conditions like low water levels or ice, which can impede navigability.

The primary goal of the Digital Twin “Buoy” is to gather diverse environmental data, enabling maritime operators to assess current conditions and make informed predictions about future developments. The system also visualizes this data, covering parameters like wind speeds and temperatures, which are crucial for effective route planning. Additionally, the digital twin system provides insights on ice thickness during winter, impacting shipping traffic. It aims to predict future water level changes and navigability, aiding maritime operators in preparation.

A standout feature is the real-time monitoring of buoy locations via GPS, ensuring they remain anchored and safe. This capability allows for efficient tracking and recovery efforts, with visualizations on an interactive map to assist maritime traffic managers in issuing warnings to nearby shipping traffic.

In a future application, a connection to the Digital Twin ‘Water Level’ is conceivable in order to enable a prediction of water levels and ice problems. However, the first step is to collect the relevant data in bulk in order to have the required basis. Here, too, this first form of DT.

In summary, the “Buoy Digital Twin” is a sophisticated tool that not only enhances the understanding of environmental conditions affecting navigation but also provides crucial support for planning and executing safe shipping operations in varying conditions. Through its advanced data collection, visualization, and monitoring capabilities, it plays a pivotal role in the future of maritime navigation and safety.

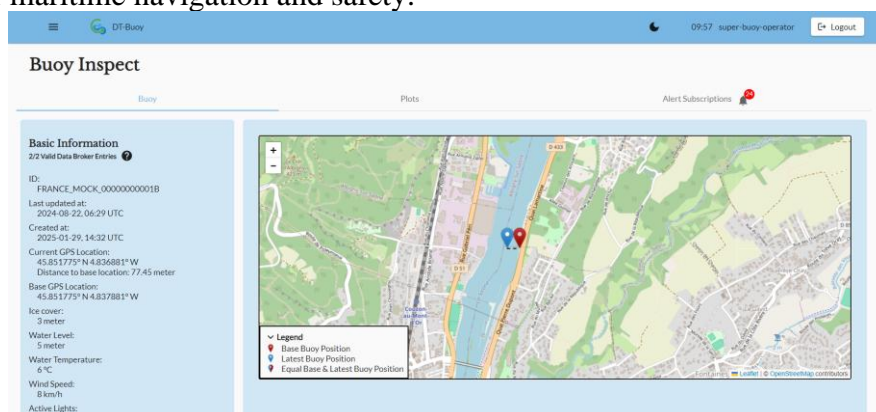


Figure 2 DT Smart Monitor Buoy – Deviating Position

Digital Twin “Water Level”

Within the broader digital twin ecosystem developed for inland waterway management, the Water Level Digital Twin stands out as one of the most advanced and operationally significant modules. Its primary function is to address the challenge posed by fluctuating river depth—one of the key constraints in ensuring navigability and reliability of inland vessel traffic. Temporary

or seasonal depth reductions can lead to route interruptions, underutilized cargo capacity, or even complete inaccessibility of certain river segments. Traditional monitoring systems offer limited foresight, often leaving planners and operators without the lead time necessary to adapt. The Water Level Twin moves beyond real-time observation by introducing a predictive layer into the system. Unlike other digital twins focused on fixed infrastructure elements, such as locks and buoys, this module is designed to forecast future water conditions at selected critical points along the river network. It integrates historical hydrological measurements, real-time water level and discharge observations, and meteorological forecasts to anticipate short-term developments in river depth. These forecasts are particularly important at shallow points, where minor changes in water level can significantly impact navigability for vessels with larger drafts. For each critical location, a dedicated predictive model is trained to estimate daily river depth values and evaluate the probability of safe passage for different vessel classes. The models are tailored to reflect the local hydrological characteristics and are continuously updated as new data becomes available. The output is not limited to numerical forecasts: the system also provides direct navigability assessments by comparing forecasted depth values with minimum draft requirements for each ship class.

All relevant outputs are integrated into a dedicated interface (Figure 3), designed for use by waterway operators, port authorities, and logistics planners. One of its central features is a navigability matrix, which visualizes forecasted conditions using a color-coded risk scale—green for navigable, red for restricted. This matrix helps users quickly identify time windows and vessel types at risk. Additional charts display the temporal evolution of water levels and discharge at each point, while contextual indicators, such as current flow rates and recent fluctuations, enhance interpretability. Importantly, the Water Level Twin does not operate in isolation. It is designed to function as part of an interconnected system of digital twins, alongside modules for locks, vessels, and environmental sensing. This modular yet integrated architecture enables a coordinated view of inland waterway operations and supports strategic decision-making at both local and network-wide scales. Rather than reacting to emerging bottlenecks, operators can now proactively plan vessel movements, adjust load factors, or reallocate capacity based on reliable short-term forecasts.

The methodology used for water depth forecasting and navigability risk estimation is described in chapter 3. It includes a comparison of machine learning models, model selection criteria, and the approach used to translate forecasts into navigational feasibility assessments per vessel class.

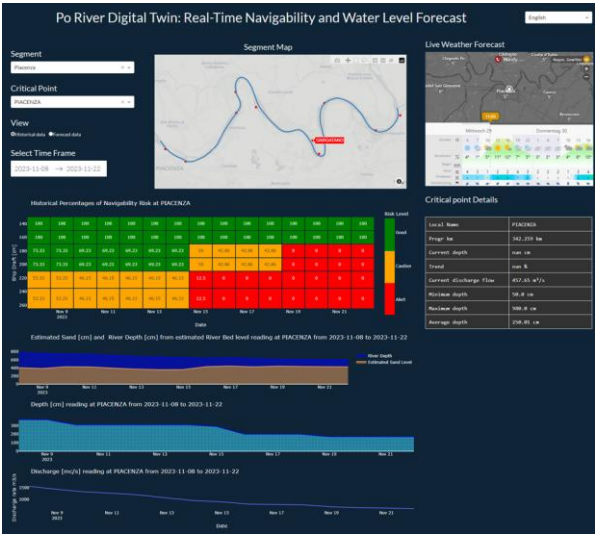


Figure 3 Interactive interface displaying forecasted water depths, navigability status by vessel class, and hydrological trends

2 System Architecture

Before the implementation of the digital twins began, the project, or more precisely the responsible work package, first dealt with the technical concept and the associated issues of a

digital twin. The subject of the scientific investigations were topics relating to IoT devices and their connection and communication, comparable developments of DT, e.g. in the SPHERE (European Commission) research project and the topic of architectures of digital twins in general and with a focus on security aspects. Full information and further details can be found in Deliverable 5.1 ‘Technical Concept of a Digital Twin’ of the CRISTAL project. With regard to the architecture, it was found that layer models in a wide variety of forms essentially play a role for DT. In 2022, Boyes and Watson (Boyes & Watson 2022) compiled and listed several variants, starting with a 3-layer architecture through to a 6-layer implementation with the physical, ingestion, persistence, inference, service and consumption layers (Mostafa et al. 2021). Of course, there are other approaches and, as time goes on, further concepts will develop, especially depending on the requirements and the form in which the digital twin is to be created. Above all, the ‘intelligence’ of the DT and the way in which real time data is processed should be considered.

The requirements were analyzed and identified before the project entered the implementation phase in this work package. Doing the requirements engineering, the requirements have been defined with the help of the methodology VOLERE, which can be found in the middle of an artefact- and a process-oriented approach. The prioritization methodology has been MoSCoW in order to obtain an assessment of the importance of the respective functionalities from the outset. Based on the exchange with the teams of the three different pilots, the technology provider and the higher-level platform different use cases have been defined as well.

Based on all the information at the beginning of the project, the findings of the state-of-the-art analysis and the developed requirements a 4+1-layer architecture (Figure 4) has been chosen with a “Data Visualization Layer”, a “Data Processing Layer”, a “Semantic Layer”, a Security Layer” and a “Data Acquisition Layer” which can be found outside the DT because with the “Data Broker” there is a separate solution for exchanging the data between the DT and the sensor technologies.

The aim was to develop an architecture that was as open and customisable as possible in order to create services that were as scalable as possible. There is a loose coupling between the backend and the frontend, which makes it relatively easy to replace the frontend, for example. In addition, the DTs are able to receive and send data, depending on the case, and the interfaces are designed in such a way that they are also easy to expand and new ones can be added.

In the course of the project, the pilots and technology providers made further adjustments to take account of the findings. The changes to the requirements for the digital twins were also incorporated and fed back into the architecture. For example, communication with the front end also takes place with the help of web sockets in order to better fulfil real time requirements.

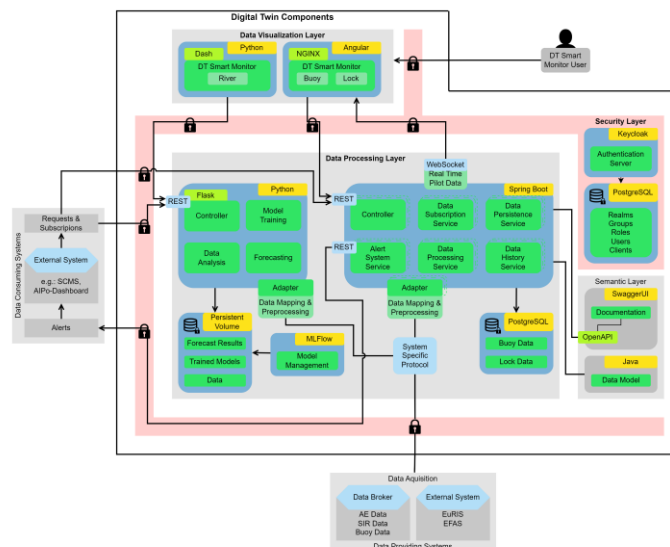


Figure 4 Updated Digital Twin Software Architecture

3 Machine learning water level prediction

This segment introduces a forecasting framework for inland waterway navigation that leverages machine learning to predict water depth at any point along the waterway and assess navigability at that location. In this study, data from 158 critical shallow points on the River Po in northern Italy are used to estimate navigation risks for different ship classes based on their draft requirements. These predictions form the core of the Digital Twin Water Level designed to support river transport operations under varying hydrological conditions.

The framework is applied to all 158 shallow points—areas where low water levels are most likely to impede navigation. For demonstration, the paper focuses on three representative sites: Piacenza, Monte P.Te Revere, and Cavanella, which are located upstream, midstream, and downstream, respectively, offering a better view of the model’s performance across diverse river segments.

The key objectives of this segment are to describe the data sources and structure used for training and evaluating the machine learning models; to outline the forecasting setup for the daily water level predictions and to explain how the predicted depths are used to assess navigational feasibility for various ship classes. A primary contribution related to this topic is presented in (Villani et al. 2024).

Data Sources and Scenario Setup

The forecasting models are trained using a combination of hydrological, geographical, and logistical datasets. The core hydrological variables include historical time series of river depth, discharge rates, and upstream water levels, primarily obtained from the Italian River Agency (AIPO). These variables serve as both input features and forecasting targets in the model.

The River Po is divided into several navigable branches, each associated with a group of these points. The Figure 5 shows this segmentation, highlighting the structural layout of the waterway used in this study.



Figure 5 Segments of the River Po located between the inland waterway ports, with critical points plotted as dots.

Each branch represents a stretch of the river where navigability is monitored and managed independently, making branch-level forecasts relevant for local decision-making.

To translate predicted water depths into navigation insights, the model incorporates a vessel classification system based on draft—the minimum required water depth for safe passage. The Table 1 summarizes the ship classes and their respective draft-to-tonnage ranges.

Table 1 Classification of vessels by draft depth and corresponding cargo capacity ranges for Class IV and Class V ships.

DRAFT (CM)	CLASS IV(TON)		CLASS V(TON)	
	From	To	From	To
140	370	620	790	880
160	620	750	880	1,060
180	750	870	1,060	1,230
200	870	1,000	1,230	1,410
220	1,000	1,130	1,410	1,600
250	1,130	1,320	1,600	1,860

This classification enables the model to estimate navigational risk for each ship type by comparing forecasted depths with the draft thresholds. For each shallow point and time step, a probability of safe passage is calculated, forming the basis for proactive navigation planning.

Forecasting Methodology and Model Selection

Each model is trained on a multivariate time series comprising three hydrological features: (1) river depth at the forecast location (cm), (2) local discharge rate (m³/s), and (3) upstream water level relative to sea level (cm), obtained from the nearest upstream station. These variables are selected for their strong influence on fluvial dynamics and navigation conditions. Prior to training, the data are normalized and structured into fixed-length sliding windows with a 14-day lookback period to capture relevant temporal patterns.

The river depth forecasting task is approached as a multivariate time series regression problem, with the aim of predicting daily water depth at critical shallow points along the waterway over a 14-day forecast horizon.

To evaluate predictive performance, four model classes are implemented. These include Long Short-Term Memory (LSTM) networks, which are capable of modeling long-range temporal dependencies; Gated Recurrent Units (GRU), a computationally simpler variant of LSTM; the Long- and Short-Term Time-series Network (LSTNet), which integrates convolutional and recurrent layers along with skip connections and an autoregressive component for improved multiscale learning; and Vector AutoRegression (VAR), a classical linear time series model used as a baseline. Each model is trained using an 80%–20% training-validation split, with the final 14 days of the dataset held out for testing.

Compared to standard LSTM, LSTNet offers a hybrid architecture that captures both short-term fluctuations via convolutional layers and long-term temporal dependencies via recurrent units, with additional skip connections and an autoregressive component to better model periodicity and linear trends (Lai et al., 2018). In this study, the innovation lies in adapting the LSTNet structure to multivariate hydrological data and tuning it for spatially distributed shallow points in inland waterways. This includes custom preprocessing steps, adjusted sequence windows per location, and domain-specific integration into a digital twin pipeline for river depth forecasting and navigational risk assessment.

Model performance is assessed using the Root Mean Square Error (RMSE), measured in centimeters, to quantify the deviation between predicted and actual depth values. To enhance the performance of the LSTM model in particular, a hyperparameter optimization process is carried out using the FLAML AutoML framework (Wang et al., 2021). The search space includes the number of LSTM units, number of layers, activation function (ReLU or Tanh), batch size, and number of training epochs. The optimal configuration for each location results in a three-layer bidirectional LSTM followed by a dense output layer.

The trained models generate daily forecasts of river depth at each critical point, which are then passed into the navigation risk estimation framework. This step translates the forecasted depth values into probabilistic assessments of navigability for different ship classes, enabling operational decision-making in inland waterway transport.

The likelihood of navigability at a critical river point is assessed using a statistical method based on historical river depth data and forecasted values. The probability is calculated using the following formula:

$$P_{cr.point}^{(nav)} = \frac{\text{Number of days where Depth} \geq \text{Minimum Depth Class and } Q \leq Q_{obs}}{\text{Total number of days where } Q \leq Q_{obs}}$$

This formula estimates the probability at each critical river point that the river is navigable for a given ship class at a specific observation point. Here, the numerator counts the number of

historical days when the water depth exceeded the required minimum draft for navigation (e.g., 140 cm in current setting) and the river depth required for the ship class Q was less than or equal to the observed or forecasted depth Q_{obs} . The denominator is the total number of historical days with depth $Q \leq Q_{obs}$. This probability, calculated for each ship class, is then used to assess navigation feasibility over a 14-day forecast horizon at locations.

Experiment Setup

The models are evaluated using daily data from Piacenza, Monte P.Te Revere, and Cavanella. For each site, the final 14 days are used as the test set, while the remaining records are split 80–20 into training and validation subsets. Input sequences include recent values of river depth, discharge, and upstream water level.

To ensure robustness, a 20-fold cross-validation is applied to the training and validation sets. Performance is averaged across folds to account for data variability and improve generalizability. Final model accuracy is measured using RMSE on the 14-day test horizon. Forecasted depths are then used to estimate navigability probabilities for various ship classes, enabling practical, risk-based decision support.

Results

This sub section presents the performance of the forecasting models across the three selected shallow points along with the corresponding navigability assessments. Accuracy is measured using RMSE (cm), and training time is included for context.

As shown in Table 2, LSTNet consistently delivers the best forecasting accuracy, achieving the lowest RMSE across all locations: 13.78 cm in Piacenza, 25.21 cm in Revere, and 23.75 cm in Cavanella. It also balances performance with moderate training time.

Table 2 Performance Comparison of Forecasting Models (Daily Data)

Model	Piacenza (RMSE)	Revere (RMSE)	Cavanella (RMSE)	Training Time (s)
LSTM (Vanilla)	28.06	27.13	29.41	High
LSTM (Tuned)	14.48	19.69	24.26	Moderate
GRU	14.67	26.99	24.42	Moderate–High
LSTNet	13.78	25.21	23.75	Moderate
VAR	26.77	36.09	37.03	Very Low

Table 3 Performance Metrics Across Multiple Draft Depths evaluated on the Piacenza dataset using the LSTNet model

Class	True Negative	False Positive	False Negative	True Positive	Accuracy	Precision	Recall	F-measure
draft_140cm	129	12	20	1156	0.98	0.99	0.98	0.99
draft_160cm	364	20	41	892	0.95	0.98	0.96	0.97
draft_180cm	594	28	43	652	0.95	0.96	0.94	0.95
draft_200cm	757	31	41	488	0.95	0.94	0.92	0.93
draft_220cm	878	31	50	358	0.94	0.92	0.88	0.90
draft_250cm	1039	16	49	213	0.95	0.93	0.81	0.87

As shown in Table 3, the confusion matrices elements generated on Piacenza validation set as an example, for each draft depth (140cm, 160cm, 180cm, 200cm, 220cm, and 250cm) and the corresponding performance metrics (accuracy, precision, recall, and F1-score) demonstrate strong predictive performance of the model for navigability classification. The matrices reveal a high true positive and true negative rate for each draft class, with very few false positives and false negatives. This is further supported by the consistently high values of accuracy (above 95% for most drafts), precision, and recall across all depths. Notably, the F1-scores, which balance precision and recall, remain high, indicating the model's effectiveness in handling the

class imbalance and making accurate predictions. These results suggest that the model is reliable for forecasting navigability at different draft depths, making it a robust tool for risk-based decision support in the digital twin water level.

The practical value of the forecasts is demonstrated through the navigational risk assessment, where predicted depths are compared against vessel draft thresholds. Figure 6 show the probability of safe navigation over the 14-day forecast window for Revere shallow point as an example. Green bars indicate days with safe shipping, while red marks highlight risk periods for ships with higher draft requirements.

	2021-10-24	2021-10-25	2021-10-26	2021-10-27	2021-10-28	2021-10-29	2021-10-30	2021-10-31	2021-11-01	2021-11-02	2021-11-03	2021-11-04	2021-11-05	2021-11-06
140	99.258392	99.258392	99.185598	99.185598	99.061265	99.061265	98.905530	98.905530	98.905530	98.674110	98.674110	98.905530	99.061265	99.258392
160	96.370023	96.370023	96.013716	96.013716	95.405138	95.405138	94.642857	94.642857	94.642857	93.510119	93.510119	94.642857	95.405138	96.370023
180	85.284934	85.284934	83.840549	83.840549	81.373518	81.373518	78.283410	78.283410	78.283410	73.691556	73.691556	78.283410	81.373518	85.284934
200	69.398907	69.398907	66.395199	66.395199	61.264822	61.264822	54.838710	54.838710	54.838710	45.289602	45.289602	54.838710	61.264822	69.398907
220	44.067135	44.067135	38.576940	38.576940	29.199605	29.199605	17.453917	17.453917	17.453917	0.000000	0.000000	17.453917	29.199605	44.067135
250	8.938329	8.938329	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	8.938329

Figure 6 Predicted navigability probabilities over a 14-day forecast horizon at Revere

These insights are particularly important for Class IV and V vessels, which require depths between 140–250 cm depending on tonnage.

4 Conclusion

In conclusion, this paper provides an overview of the applications of digital twin technology in inland waterway management, with specific attention paid to the CRISTAL project. The establishment of the Water Level DT, Buoy DT, and Lock DT not only illustrates the potential of digital twins but also their capability to advance the monitoring, predicting, and maintenance of crucial infrastructure. These instruments provide real-time data and forecasting that allow operators to make knowledgeable decisions, hence improving the safety, efficiency, and resilience of inland waterway transport systems.

The Water Level DT, developed with robust machine learning functionalities, facilitates safe river depth prediction for ensuring navigability in the face of fluctuating water levels. Its predictive modeling is able to solve the problems caused by environmental uncertainty and climate change that assist operators in handling vessel movement management in advance along with cargo optimization capability.

Similarly, the Buoy DT enhances environmental monitoring by gathering different metrics and providing operators with useful information regarding navigation conditions. Monitoring environmental changes in real-time using smart buoys is essential for route planning and operational safety.

The Lock DT is a critical enabler of proactive maintenance management, utilizing acoustic sensors to monitor lock infrastructure. Reliable early detection of possible breakdowns not only minimizes shipping delay but also extends the lifecycle of critical assets, thereby lowering overall maintenance costs.

As digital twin technology continues to develop, its use on inland waterways will expand, and the possibilities for further innovations in the management of transport infrastructure will increase. Further research must be conducted to continue refining these models, making them more integrated and finding new ways to link them with new emerging technologies. Ongoing developments in digital twin systems hold great promise for the revolutionizing of inland waterway management, enabling such critical transportation routes to be both sustainable and efficient in fulfilling existing and future needs.

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Increasing Resilience of Intermodal Freight Transport Networks – Key Challenges in Disruption Handling and Requirements for Digital Solutions

John von Stamm, M. Sc.¹, Alina Behle, M. Sc.¹ and Jonas Dallwig, B. Sc.¹

1. FIR at RWTH Aachen University, Aachen, Germany

Corresponding author: john.vonstamm@fir.rwth-aachen.de

Abstract: The Eurozone faces growing economic and environmental challenges, with supply chain disruptions causing losses of over EUR 112.7 billion in 2021. Climate change, geopolitical risks, regulatory shifts, and infrastructure weaknesses strain intermodal freight transport, highlighting the need for digital solutions to enhance resilience and efficiency.

This paper examines key challenges in intermodal freight transport, including disruption triggers, network vulnerabilities, and inefficiencies in disruption management. Extreme weather, and capacity shortages impact both performance and sustainability. Using the Total Quality Framework (TQF), the research includes interviews with 23 stakeholders from 10 countries, focus workshops, and surveys. The analysis reveals shortcomings in real-time data integration, interoperability, and disruption response. Regulatory fragmentation and low digital maturity hinder resilience strategies. Addressing these gaps requires harmonized data frameworks, improved interoperability, and the use of collaborative digital platforms.

The Horizon Europe project ReMuNet leverages intelligent algorithms and digital platforms to enhance multimodal networks, optimize route planning, and improve disruption response, contributing to the vision of the Physical Internet.

Keywords: Physical Internet, Supply Chain Resilience, Disruption Management, Intermodal Freight Transport, Digital Logistics Platforms, Sustainable Logistics

Physical Internet (PI) Roadmap Fitness: ☐ PI Nodes (Customer Interfaces, Logistic Hubs, Deployment Centers, Factories), ☐ Transportation Equipment, ☒ PI Networks, ☒ System of Logistics Networks, ☐ Vertical Supply Consolidation, ☒ Horizontal Supply Chain Alignment, ☒ Logistics/Commercial Data Platform, ☐ Access and Adoption, ☒ Governance.

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

1 Introduction

The Eurozone faces growing economic and environmental challenges, with supply chain disruptions causing losses exceeding EUR 112.7 billion (Ollagnier et al., 2022). Climate change-driven disruptions are increasing, forcing companies to prioritise resilience (Bocksch, 2020; Brandt, 2021).

This paper builds on insights from the Horizon Europe project ReMuNet – Resilient Multimodal Freight Transport Networks, which enhances resilience, sustainability, and adaptability in logistics using digital technologies. It promotes standardisation, collaboration, and SME integration, fostering a more connected and sustainable freight network (von Stamm et al., 2024). Organisational challenges and low digital maturity hinder disruption management, causing delays and financial losses. Strengthening resilience requires robust systems, flexible responses, and adaptive learning. This paper assesses the current intermodal freight ecosystem, identifies challenges, and outlines digital solutions to enhance resilience.

2 Background Information and Definitions

2.1 Resilience of Freight Transport Networks

The term “resilience” originates from the Latin word “resilire”, meaning “to rebound” or “to spring back”. It is generally defined as the ability to quickly return to a previous positive state after encountering problems (Cambridge Dictionary, 2024b). “Resilience determines the persistence of relationships within a system and is a measure of the ability of these systems to absorb changes of state variables, driving variables, and parameters, and still persist” (Holling, 1973). A resilient system can absorb disruptions, adapt to changes, and recover quickly while maintaining its core functions (Clement et al., 2021; Holling, 1973). Key characteristics include adaptability, flexibility, agility, redundancy, robustness, and learning (De Marchi et al., 2023; Morisse and Prigge, 2017). Resilience focuses on short-term functionality and recovery, complementing long-term sustainability goals (Brundtland et al., 1987). In the context of freight transport, “a resilient freight transport network minimises disruption-related impacts on network performance in terms of both intensity and duration, along with minimising the system recovery time” (von Stamm et al., 2024).

2.2 Disruptive Events in Intermodal Freight Transportation

Since resilience refers to the ability to recover from a disrupted system state, a “disruption” can be defined as an “action that prevents something, especially a system, process, or event, from continuing as usual or as expected” (Cambridge Dictionary, 2024a). In relation to the logistics sector, a disruptive event can therefore be defined as any planned or unplanned interruption or change to the operation of a transport network that causes effects such as delays, blockages or closures (Schiffling et al., 2024). The effects of these disruptive events can vary in terms of geographical extent and duration. Depending on their operational focus, disruptions can occur in the physical infrastructure, but also at the interface between the physical infrastructure and the information level where (digital) information exchange happens (Schiffling et al., 2024). Disruptions can be categorised into nine dimensions shown in figure 1.

Natural Disaster	Technological Failure	Regulatory Changes	Security Incidents	Accidents
<ul style="list-style-type: none"> • Earthquake • Flood 	<ul style="list-style-type: none"> • Power Outage • Signal Failure 	<ul style="list-style-type: none"> • Customs Procedures • Environmental Regulations 	<ul style="list-style-type: none"> • Cyber Attack • Terrorism 	<ul style="list-style-type: none"> • Road traffic Collision • Derailment
Health Emergencies	Capacity Shortages	Geopolitical Crisis	Extreme Weather	Economic Slowdown
<ul style="list-style-type: none"> • Human Pandemic • Animal Disease 	<ul style="list-style-type: none"> • Truck Driver Shortage • Infrastructure Constraints 	<ul style="list-style-type: none"> • War • Trade Dispute 	<ul style="list-style-type: none"> • Drought • Extreme Cold 	<ul style="list-style-type: none"> • Recession • Low Consumer Confidence

Figure 1: Categories of Disruption and its causes (based on Schiffling et al., 2024)

2.3 Freight Transport Modes

The “transport mode refers to the way in which [...] goods can be transported“ (European Commission, 2025). Multimodal and intermodal transport both involve multiple transport modes but differ in the coordination and management of these modes. Multimodal transport refers to the movement of goods using at least two different modes of transport under a single transport contract (Gronalt et al., 2019). In intermodal transport on the other hand each transport segment has to be organised with an individual contract (Rodrigue, 2018). In practice, the first and last legs are typically handled by road freight, the main leg by mass transport modes like rail or ship, with terminals serving as transfer points. In this paper, both terms are considered interchangeable when discussing the combination of different modes of transport.

2.4 Solution Hypothesis

The authors hypothesise that contributing to network resilience while maintaining sustainability can be achieved by optimally leveraging the strengths of different transport modes in intermodal freight transport networks. A significant contribution can be achieved by leveraging digital technologies, such as the Physical Internet (PI), to enhance responsiveness and adaptability, enabling improved cross-stakeholder communication and fostering collaborative solutions.

3 Methodology

This research applies the Total Quality Framework (TQF), a comprehensive approach ensuring valid and useful qualitative study designs (Roller and Lavrakas, 2015). TQF follows three phases: Data Collection, Analysis, and Reporting (figure 2).

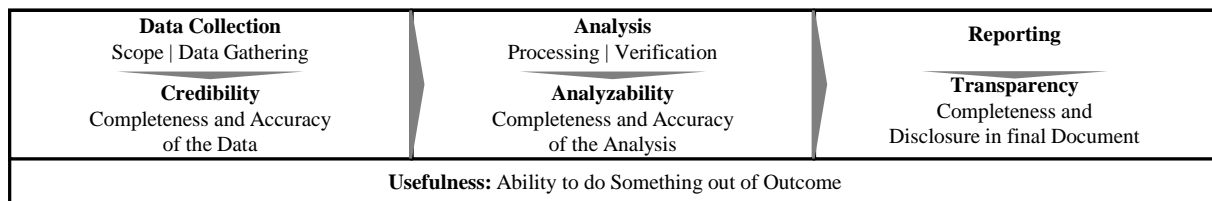


Figure 2: Total Quality Framework (based on Roller and Lavrakas, 2015)

3.1 Data Collection

The scope of this research is to identify key disruption triggers and their impacts on the intermodal transport network. With further consideration of the existing challenges in the logistics industry, requirements are first derived from the findings of the disruptions and challenges. These are then used to identify potentials for intermodal network resilience. For this purpose, semi-structured interviews and workshops were conducted with 23 key stakeholders from ten European countries, including (digital) logistics service providers, carriers (road, rail, inland waterways), freight forwarders, multimodal operators, and terminal operators (see Annex I). An online survey complemented the interviews, validating key aspects (see Annex II). Both methods focused on four main topics (table 1): stakeholder profiles, logistics disruptions, industry challenges, and potential solutions or requirements.

Table 1: Topic specific question focus

General	What are the main activities of the company and what are its economic key value propositions?
	Which customer segments does the company serve and what data is exchanged?
Disruptions	Which disruptions affect the company the most or most frequently and what challenges does it face in overcoming them?
Challenges	What are the main challenges that the company faces in its operations and how have they been addressed so far?
Needs and Requirements	How can digital solutions contribute to better disruption management and what has hindered implementation so far?

3.2 Analysis and Reporting

After data gathering, statements were analysed using an inductive approach. Thematic analysis identified recurring issues, providing a structured yet flexible interpretation. Results were systematically structured within the research framework. Disruption triggers, impacts, and challenges were analysed, leading to derived needs and requirements. Finally, potentials for enhancing intermodal transport resilience were identified. Informed consent was obtained, and confidential disclosures were excluded, ensuring ethical integrity and trust.

4 Disruptions in Intermodal Transport

The triggers for disruptive events identified in the expert interviews and workshops were analysed considering the categorisation of Schiffling et al. (2024). Impacts were mapped to the elements of the transport network, depending on whether a disruption affects a node, an edge or the entire network (figure 3).

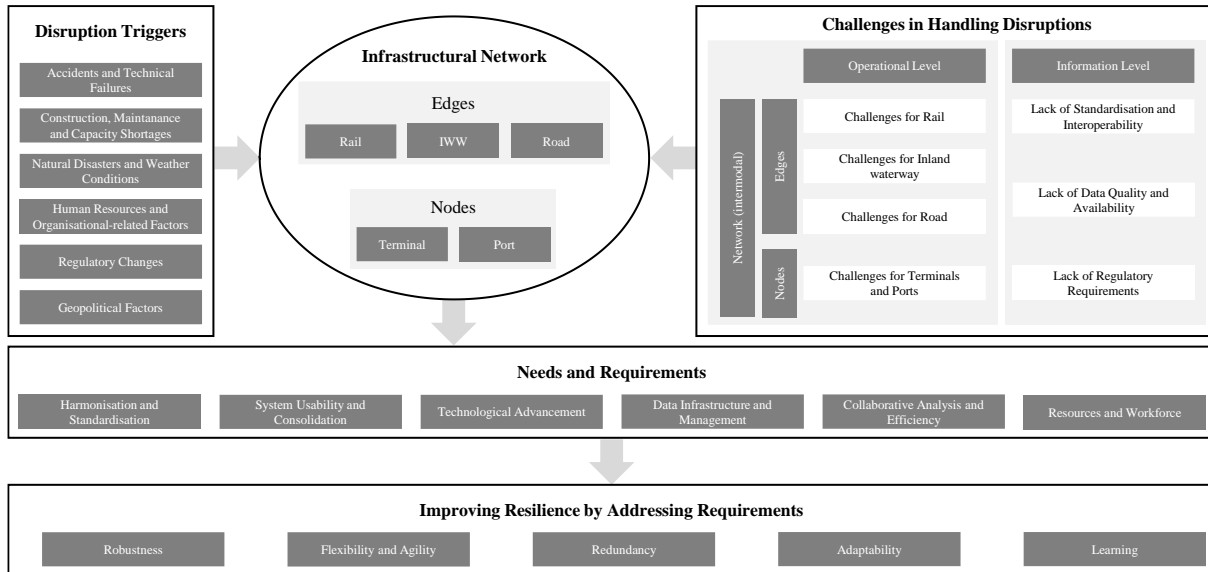


Figure 3: Key Challenges in Disruption Handling and Requirements for Digital Solutions

Physical infrastructure triggers include accidents and technical failures like signal or point malfunctions, causing closures and reduced capacity, especially in rigid systems such as rail and inland waterways (IP 3, 9, 13, 16). Construction and maintenance often disrupt operations through delays, line closures or port congestion (IP 16, 19). Capacity is further strained by equipment damage or staff shortages (IP 9, 16). Natural disasters are increasingly disruptive due to climate change (IP 8, 9, 13). **Organisational triggers** stem from human resource issues like strikes or protests, blocking key routes and terminals (IP 16). Geopolitical factors such as conflicts, sanctions, or political shifts hinder corridors and impair infrastructure, as seen in the Ukraine war and tensions in grain trade (IP 4, 16). Non-EU memberships or diverging policies interrupt inland waterway continuity (IP 6). Regulatory disruptions arise from shifting legal frameworks, inconsistent border checks or trade rules, causing inefficiencies (IP 6, 16). For instance, COVID-19 restrictions heavily limited road freight, while Brexit added customs delays (IP 15, 9).

5 Challenges for Intermodal Transport Stakeholders

Beyond disruptions, various challenges hinder transport efficiency and resilience. Challenges specific to edges, nodes, and the network are analysed, along with those related to information standardization, interoperability, data quality, and regulations (figure 3).

5.1 Challenges affecting Edges

5.1.1 Rail Transport

The rail network is highly **inflexible**, making re-routing difficult during disruptions, which often escalate quickly into widespread delays and congestion (IP 3). A single incident can trigger cascading effects, and restoring normal operations takes significant time: “If there's a disruption during transportation, it has a huge impact on the entire transport network. [...] The problems scale up to even bigger problems in a very short time [...] it takes a long time to get the systems back to normal operation.” (IP 3). **Capacity** is already exhausted leaving no room

for additional freight or surges in demand, underscoring the urgent need for infrastructure upgrades (IP 5). According to IP 5 „the rail is completely utilised; you can't put any more on the rail at the moment” (IP 5). Cross-border transport is further complicated by **regulatory fragmentation and the lack of interoperability**. Unlike road freight, rail requires country-specific locomotive licenses, driver certifications, and language skills, which add complexity and reduce competitiveness (IP 16). Inconsistent train identification also poses a barrier as operational train numbers differ between operators and countries, making tracking difficult (IP 12). A unified European train ID has been proposed to address this, but no solution has yet been implemented (IP 12).

5.1.2 Inland Waterway Transport

Inland waterway transport suffers from **restricted flexibility** due to its fixed infrastructure and closed system design (IP 3). Waterways offer less adaptability than road transport, as vessels cannot deviate freely or dock anywhere. They rely on ports and locks as access points, limiting operational flexibility (IP 3). This strict **reliance on existing structures** renders the system vulnerable to disruption and delay. In the event of unforeseen circumstances, such as technical failures, flooding or low water levels, it is not possible to divert ships at short notice. This restricts the ability to react and makes operations more challenging (IP 3). **Outdated infrastructure** is a major obstacle to inland waterway transport (IP 3). Many locks, signalling systems, and draught measures are no longer fit for purpose and lack proper maintenance or modernisation (IP 3). The **coordination of international efforts** is a major challenge for cross-border waterways: “The issue for us is not only that the [...] national territory plays a role in navigability, but also all the downstream member states” (IP 6). Varying regulations and infrastructure conditions across countries, especially on waterways like the Danube, make reliable navigation dependent on political decisions downstream (IP 6).

5.1.3 Road Transport

The reliance on road transport as a **contingency for rail transportation** presents challenges (IP 8). Rail disruptions drive up road demand, requiring up to three times more lorries. This shift strains capacity and hinders sustainability (IP 8), as road transport emits 7.5 times more greenhouse gases per ton-kilometre than rail (Statista, 2024). Road transport is highly sensitive to **fluctuations in the economic cycle** (IP 2). During downturns, increased supply lowers transport prices, drawing customers from rail to road. Road freight’s price sensitivity makes it less stable and more vulnerable to short-term economic shifts (IP 2).

5.2 Challenges affecting Nodes (Terminals/ Ports)

Capacity bottlenecks often emerge at these nodes rather than along the transport routes (IP 19). When terminals become congested, cargo cannot be moved in or out efficiently, limiting the system’s overall performance. **Slot management** is another major issue. Terminal time slots are not integrated into the centralized rail network and remain uncoordinated by infrastructure providers (IP 2). Although IP 12 emphasizes the need to align terminal slots with main transport routes, such harmonization is difficult due to jurisdictional limitations (IP 12). Delays or train cancellations at terminals reduce resource utilization and trigger knock-on effects across the entire network (IP 3). **Coordination and communication** gaps further affect efficiency. While construction and maintenance projects are announced in advance, their full implications are not always clearly communicated (IP 2). IP 21 also notes unrealistic expectations during planning: companies often place orders without understanding operational constraints, leading to misalignment and frustration when outcomes fall short of expectations. Finally, **regulatory and administrative issues** add to the strain. Missing documentation or import permits can hold up containers in ports, resulting in delays and costly demurrage fees (IP 4).

5.3 Challenges on Network Level

The intermodal nature of modern logistics networks brings flexibility but also creates **dependencies** that can amplify disruptions. Smooth operations rely heavily on infrastructure managers, whose response speed is crucial during disruptions: “We are massively dependent on the reaction speed of the infrastructure operators” (IP 16). Delays in restoring services can cause cascading effects across transport modes, highlighting the need for coordinated and timely responses to ensure network resilience. Moreover, **capacity limits**, particularly at ports, have network-wide implications. When ports reach full capacity ships queue outside ports, and logistics providers struggle with unreliable schedules (IP 19). During peak periods, this can significantly reduce overall productivity as transport plans become unreliable and challenging to plan: “There might be capacity available [on other modes of transport], but smooth access to that is in most cases the most challenging thing” (IP 8). Gaining access often requires complex coordination and extensive negotiations with partners, while rising demand during disruptions aggravates the situation (IP 8). Furthermore, there is an **insufficient level of redundancy** regarding modal shifts in intermodal transport (IP 9). Although resilience through modal shifts is desired, it is rarely feasible in practice: “That sort of resilience is wished for today. But unfortunately, I should say it is not available” (IP 9). The capacity of the rail network is frequently constrained, with freight transport frequently receiving a lower priority than passenger transport. In the absence of redundant infrastructure, intermodal logistics is unable to provide reliable alternatives for affected cargo (IP 9). Furthermore, the lack of redundancy is intensified by the **inflexibility of inland waterways and rail systems** (IP 3), as both inland waterways and railways are closed systems with limited flexibility. This results in a significant impact even from minor disruptions, which often spread across the entire network and create broader operational challenges that require a considerable amount of time to resolve (IP 3).

5.4 Challenges on Information Level

In addition to the challenges of the transport network at the infrastructure and organisational level described above, there are also numerous challenges at the information level. These challenges affect the entire network and impair the efficiency of key transportation processes.

5.4.1 Lack of Standardisation and Interoperability

The **fragmentation of standardisation among stakeholders** hinders interoperability, efficiency, and transparency in freight transport (IP 11). Different modes follow separate standards without a harmonised framework (IP 7), making integration complex and costly (IP 7, 9, 21). Furthermore, SMEs struggle with limited resources to meet complex standards (IP 22) although, according to the survey, data standardisation and automation is the most important requirement among SMEs. Only 43% of stakeholders use standardised data exchange formats. Therefore, basic functions like appointment scheduling and cargo visibility suffer from missing communication protocols, causing inefficiencies (IP 14). Efforts toward standardisation are further hindered by national regulations and diverse systems (IP 12), forcing bespoke integrations (IP 19). Furthermore, **system incompatibility and interoperability issues** disrupt data flow and visibility (IP 7). Outdated systems and varying software setups block modern API use (IP 15), and manual interfaces and incompatible logic reduce efficiency (IP 11, 16, 19). **Data exchange format fragmentation** further leads to inconsistent formats, manual mapping, and compliance issues (IP 12, 13, 19). Legacy systems like EDI are still widespread (IP 3). **Manual data handling and transfer** causes inefficiencies, delays, errors, and limited automation due to media breaks and missing protocols (IP 2, 14, 19). Finally, **system diversity** results from customised IT systems (IP 11). Even identical software differs across users (IP 6, 11, 21), creating “many parallel [non-interoperable] systems” (IP 6).

5.4.2 *Lack of data quality & availability*

Inaccurate and inconsistent data affect operational efficiency, planning, and decision-making. Data quality issues often arise from incomplete, outdated, or misaligned information, (IP 3, 7, 14, 15): “This kind of data lead to errors in documentations, sometimes in misinterpretations, and subsequently to the delays” (IP 13). Further, **unreliable and incomplete tracking information** limits shipment visibility due to real-time data gaps and inconsistencies between transport modes, reducing the reliability of tracking systems (IP 7, 8, 14). Challenges with **data availability** arise from issues of data quality, access and reliability. Inconsistent data disrupts forecasting, especially for medium- to long-term planning (IP 7). Administrative barriers and unreliable communication with stakeholders increase uncertainty (IP 22). **Barriers to data sharing and transparency** weaken efficiency and digital adoption. Many stakeholders hesitate to share data due to trust, confidentiality, or control concerns (IP 1, 2, 11, 12, 19, 22). As a result, decisions rely on outdated or planning-only data, limiting real-time insight (IP 11). **Manual processes and the lack of automation** remain widespread. Despite AI advances, manual effort dominates, especially in document handling, which is still often paper-based, increasing inefficiencies and system fragility (IP 3, 8). **Route planning and rerouting** suffer from unreliable data, lack of transparency, and limited alternative options during disruptions. Inadequate planning data and poor stakeholder coordination therefore make adjustment measures difficult, increasing delays (IP 1, 8, 11, 14). **Capacity planning** is challenged by inaccurate data and fluctuating demand (IP 1, 2). Planners often operate under the assumption of unlimited capacities, which leads to inefficiencies and suboptimal decision-making when actual constraints emerge (IP 1).

5.4.3 *Lack of regulatory Requirements*

Complexity and frequent changes in regulatory frameworks burden the transport sector through excessive bureaucracy, frequent adjustments, and resource-intensive compliance (IP 13, 22). Legal complexities slow operations and discourage innovation, especially for those unfamiliar with the regulatory environment, reinforcing reliance on traditional methods (IP 7, 13). This constant need for vigilance drains resources and reduces the sector's efficiency (IP 13). **Uncertainty about future regulatory decisions** makes long-term planning difficult. Operators often cannot foresee upcoming regulations, increasing risk and complicating strategic decisions (IP 7). The **lack of harmonisation in cross-border regulatory frameworks** further creates inefficiencies due to inconsistent national standards. Border disruptions, unclear responsibilities, and unpredictable customs decisions cause delays and operational challenges (IP 4, 8, 14, 15). Inconsistent rail processes and customs classifications further complicate international logistics. Finally, the **lack of standardised terminology and processes** hampers coordination. Varying terms for the same actions lead to confusion and inefficiencies: “different terms for the same action bring in a lot of challenges” (IP 9)”. The absence of universal standards increases integration costs and limits interoperability (IP 7, 9). Even within the EU, inconsistent documentation standards result in outdated and inefficient cross-border procedures (IP 14).

6 Needs and Requirements to improve Disruption Handling

The disruptions and associated challenges in combined transport give rise to specific needs and requirements that aim to increase the resilience of the transport system. These requirements are divided into six central categories: harmonisation and standardisation, system usability and consolidation, technological advancement, data infrastructure and management, collaborative analysis and efficiency, and resources and workforce (figure 3). **Harmonisation and standardisation** are key to improving resilience in combined transport. Stakeholders call for

uniform terminology, data formats, and interoperable systems to enable efficient collaboration (IP 9). Revised rerouting regulations and standardised crisis procedures, including clear rules for prioritisation, can enhance coordination in emergencies (IP 8, 22). The establishment of a neutral platform could prove to be a pivotal element in this process, as clear rules regarding the prioritisation of entities in exceptional circumstances has the potential to mitigate the negative effects of chaos and enhance the overall performance of the system (IP 22). **Data infrastructure and management** is crucial for flexibility and transparency. A neutral, accessible data pool enables informed, real-time decisions (IP 1, 14, 18). To this end consistent end-to-end data improves transparency across supply chains (IP 14), while automated data exchange reduces inefficiencies and enables faster responses to disruptions (IP 9, 13). IP 5 explains that real-time data is “essential” to respond flexibly to disruptive events. AI-based systems and predictive models, as proposed by IP 9 and IP 13 enable the development of alternative plans at an early stage. These forward-looking approaches allow risks to be better managed and decisions to be made on a more informed basis (IP 18). A unified interface for all stakeholders would further boost integration (IP 12, 18). For systems to function effectively, **usability and consolidation** are key. The interviewees stress the need for consistent use of existing digital tools and for systems that are intuitive and user-friendly (IP 15). Furthermore, **collaborative analysis** enables coordinated action and improved efficiency. While many actors seek data, they often hesitate to share it. A transparent exchange where all parties contribute, and benefit is seen as a step toward mutual resilience which can only be reached by a joint discussion in which all participants transparently share their data (IP 3). Efficiency should thus be pursued as a collective aim, not just an internal one (IP 3, 5, 13). **Technological advancement** is thus central to overcoming the limitations of existing systems and to integrate the various and often complex system landscapes. This includes the necessity for real-time data availability and modern data exchange, such as the development and implementation of uniform standards that enable compatibility between old and new systems (IP 22). The interviewees therefore call for modular, integrable technologies, and long-term strategies for digital modernisation (IP 3, 22). Fear of mishandling sensitive customer data and navigating compliance requirements are significant sources of apprehension (IP 19). Therefore, the interviewees stress the need for secure cloud environments and compliance frameworks to safeguard sensitive data and build trust in digital systems (IP 13, 14, 19). However, the introduction of advanced technologies is impeded by high implementation costs (IP 13) and reservations regarding data sharing (IP 2, 3, 11, 12, 22, 22).

7 Potentials for improving Intermodal Network Resilience

Improving resilience in intermodal networks depends on strengthening robustness, flexibility and agility, redundancy, adaptability, and learning. **Robustness** involves stable structures and secure processes that absorb initial disruptions. Cybersecurity, harmonised regulations, and standardised data systems build reliability, while user-friendly information systems ensure consistent data access across stakeholders. **Flexibility and agility** enable quick reactions and fast recovery. Real-time awareness, efficient data exchange, and usable systems support dynamic rerouting during events like route closures. Advanced technologies like rerouting algorithms help maintain operations when disruptions such as route closures occur. **Redundancy** provides backup options through additional resources, infrastructure, and processes. It ensures continuity when parts of the network fail, for instance by enabling rerouting or switching between modes. A resilient network requires mature technologies, accurate and up-to-date information, and standardised communication protocols to manage disruptions without major losses. **Adaptability** refers to the system’s ability to evolve with change. Harmonised regulations are key to allowing controlled adjustments without causing

further fragmentation. Adaptability ensures that networks can respond not only to one-time disruptions but also to long-term shifts in conditions or requirements. **Learning** from disruptions is essential to build future resilience. This involves collecting data, applying standardised analysis methods, and using advanced digital tools to identify causes and improve preparation. Staff training and consistent equipment maintenance are basic requirements for embedding resilience in practice. Recovery must be followed by collaborative evaluation processes to strengthen response strategies over time.

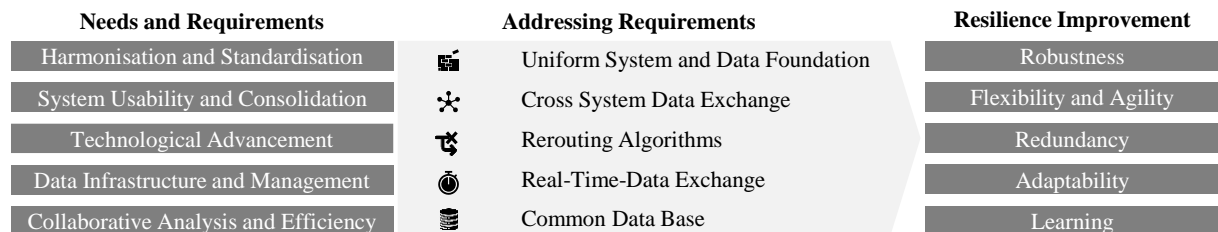


Figure 4: How addressing needs and requirements can improve resilience

Pursuing the same long-term goal digital technologies in multimodal transport not only improve resilience but also environmental sustainability by optimising operations, reducing emissions and promoting resource efficiency.

8 Conclusion and Implications for future Research

The growing economic and environmental pressures within the Eurozone underline the urgent need for more resilient and efficient intermodal freight transport systems. This paper highlights a broad range of vulnerabilities that currently undermine resilience, including the increasing frequency of extreme weather events, infrastructure bottlenecks, geopolitical instability, and low levels of digital integration. These factors not only impair performance but also limit the sector's ability to respond flexibly to disruptions.

Several key challenges were identified: outdated and inflexible infrastructure, lack of redundancy, regulatory fragmentation, and an insufficient level of digital maturity across stakeholders. Furthermore, the absence of standardised data formats, poor interoperability, and limited real-time data availability severely hinder effective disruption management. Manual processes, fragmented IT landscapes, and a general lack of trust and transparency in data exchange amplify inefficiencies and prolong recovery times during disruptive events.

To address these challenges, the study derives concrete needs and requirements: harmonised and standardised regulatory and data frameworks, usable and consolidated systems, technological advancements, improved data infrastructure and management and enhanced cross-stakeholder collaboration. Real-time data exchange, a common database for cross-system data exchange, predictive analytics, and AI-supported rerouting tools emerge as key enablers of a more agile and responsive transport system.

These findings align strongly with the long-term vision of the PI, promoting a modular, standardised, resilient and digitally interconnected logistics ecosystem and transforming today's fragmented transport systems into open, interoperable networks. Increasing resilience of intermodal freight transport networks is not only a response to today's disruptions but also a decisive step toward building the PI.

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Appendix

Annex I: Detailed Interview Partner List

IP	Role & Nationality	Business Activities	Why the Interview partner was selected
IP 1	4th Party Logistics Service Provider DLSP <i>Germany</i>	Optimisation service provider specialising in road transport, offering solutions to improve customers' transportation, warehousing, and handling processes, with a focus on transparency through their TMS platform	This company is a leading global provider of supply chain consulting, software, and fourth-party logistics (4PL) services. Insights on end-to-end logistics processes and technical requirements are especially relevant for the stakeholder analysis
IP 2	Terminals <i>Luxembourg</i>	Multi-use terminal operator managing train operations, container trading, and employing sustainable practices, including renewable energy and battery electric vehicle	This operator of a public intermodal terminal in Luxembourg can handle all intermodal transport units on an area of 33 hectares and uses innovative technologies like AI-applications to increase the efficiency of transshipment processes. The company offers valuable insights from the perspective of terminal operators and provides suggestions for the use of digital technologies.
IP 3	Carrier Terminals Infrastructure Manager/Operator <i>Germany</i>	Trimodal logistics company, specialising in container import/export via inland waterway, rail, and trucking, with a network of terminals across Europe	This company specialises in trimodal transportation connecting seaports with the European hinterland moving an annual freight volume of 2.1 million TEU within its network along the river Rhine. This partner therefore offers crucial industry information along all transport modes.
IP 4	NGO (Humanitarian Logistics) <i>Denmark</i>	Providing auxiliary support, coordinating logistics operations, and establishing warehousing hubs for efficient disaster response and conflict management	One of the largest humanitarian networks worldwide provides aid support to people affected by conflicts or disasters. Their extensive expertise in the field of humanitarian logistics contributes fundamentally to understanding the challenges and requirements of aid organisations in freight transport logistics.
IP 5	DLSP <i>Germany</i>	Digital logistics service provider specialising in road freight optimisation and additional services, (with potential for multimodal transportation)	This software-SME is one of Germany's most innovative logistics tech start-ups and has access to an extensive network of freight forwarders and transport companies. Their multi-tenant matching platform enables conducting event-based relay transports to circumvent disrupted infrastructure sections.
IP 6	Infrastructure Manager/Operator <i>Austria</i>	Operating an infrastructure provider, with a primary focus on container handling at a terminal, emphasising various modes of transportation and collaborating on urban logistics initiatives with an academic institution	This stakeholder operates one of the most important inland ports in the Rhine-Danube corridor and handles around 1200 cargo ships per year. The company offers a comprehensive service portfolio and has access to a large network of the most important hinterland logistics companies in Europe.
IP 7	Software Provider <i>Germany</i>	Providing logistic planning products, including route and tour planning, load optimisation, geo-management/geo-marketing solutions, intermodal component solutions, and customised software-as-a-service options for automated tour planning and delivery time estimation	As a European market leader in traffic and transport route planning. In addition, the company is involved in many innovative projects to further develop its state-of-the-art software solutions and support the logistics industry.
IP 8	Terminals	Creating a sustainable European network with assets like trucks, trailers, containers,	The company is one of the largest European transport companies focusing on multimodal

	Carrier <i>Netherlands</i>	vessels, and rail connections, and operating hub terminals for efficient customer service	transport by operating own terminals, transport vehicles, and loading units. This stakeholder provides crucial information on multimodal transportation and disruption management.
IP 9	Industry Association <i>Germany</i>	Promotion and development of sustainable freight transportation using different loading units, conduct research, studies, and consulting activities, and advocate for the adoption of combined transport within the freight transport sector	This partner is one of the most important non-profit membership associations in intermodal logistics. For 80 years this association has connected relevant actors of the Combined Transport sector and created a neutral communication and knowledge platform for research and development.
IP 10	Research & Consulting <i>Netherlands</i>	The establishment of an integrated grid network for supply chain partners, facilitating customisable data sharing, multimodal visibility services, and authentication-based link-driven data exchange for the generation of digital product passports.	As a leading Dutch research and consulting organisation this stakeholder holds extensive expert knowledge to facilitate seamlessly connected logistics systems that are more efficient, create new business opportunities and reduce emissions.
IP 11	Software Provider <i>Germany</i>	Digital logistics service provider offering a software for optimising transportation routes and data driven decision-making.	As a leading provider of artificial intelligence and mathematical optimisation systems, this stakeholder's software products support dispatchers and planners in calculating complex and time-critical logistics scenarios.
IP 12	Industry Association <i>Belgium</i>	Raising stakeholder awareness, consulting policy makers, and standardising combined transport operations, while representing intermodal operators as key actors in the integrated freight transport chain.	As one of the main industry associations in the European intermodal transport industry this stakeholder actively promotes Combined Transport, primarily towards European decision-makers and supports the daily functioning of this ecologically and economically sustainable mode of long-distance freight transport. The association has in-depth knowledge of existing standards, legal requirements and current challenges in intermodal transport and is familiar with the needs of its members due to its role as an interest representation body.
IP 13	Freight Forwarder <i>Greece</i>	Intermodal freight transport, facilitating smooth movement of goods across various modes of transportation, acting as intermediaries between shippers and carriers, and operating primarily in Europe	This SME freight forwarder specialises in road and sea transport organisation and provides – besides specific industry knowledge - detailed insight into the challenges faced by smaller logistics companies when implementing digital solutions.
IP 14	Software Provider Logistic Service Provider <i>France</i>	Product lifecycle software and collaborative platform provider for multiple industries, with a strong emphasis on mobility, manufacturing, aerospace, and defence.	As one of the largest software companies in Europe, this stakeholder has an extensive software and service portfolio for various industry segments. From the transport logistics perspective especially, the collaborative digital platform holds significant potential to address current business challenges in the transport sector.
IP 15	Software Provider Logistics Service Provider <i>Finland</i>	Software solutions for transparency, optimising parcel routing, acting as middleware between ecommerce stores and warehouses, and providing warehousing services for efficient picking and packing of goods	This logistics service provider helps e-commerce businesses to optimise their supply chain, speed up delivery times, and reduce costs with a modern 3PL service. With extensive experience in e-commerce shipment tracking and other logistics services this innovative SME contributes valuable information on digitalised supply chains.
IP 16	Carrier <i>Austria</i>	Rail transportation, including intermodal and wagon loading traffic	This company holds the operating licence for all railway lines in Austria and the EU. This railway undertaking operates freight transport both on its own infrastructure (with its own diesel locomotives) and on third-party infrastructure (with its own diesel and electric locomotives) and provides important information on rail cargo transports in the Rhine-Danube Corridor.

IP 17	Infrastructure Manager/Operator <i>Austria</i>	Owning and managing transportation infrastructure, including parking lots, rest areas, and rest stops, to facilitate smooth and convenient journeys for road users, particularly those engaged in road freight transportation, catering to car and truck drivers, as well as special transports	This infrastructure company is responsible for the planning, construction, operation and tolling of the Austrian motorway and motorway network. As an important road network operator in the Rhine-Danube corridor, this player supplements the stakeholder analysis with important information from the perspective of an infrastructure operator.
IP 18	Carrier Terminals Freight Forwarder <i>Switzerland</i>	Offering a cost-effective and sustainable transport chain for continental transports, utilising sea, inland waterway, rail, and road modes, optimising efficiency for longer routes, and providing cross-border transport services in Europe with seamless last-mile deliveries	This interview partner is one of the market leading combined transport operators in Europe. As a neutral combined transport operator, this company moves over 1 million road consignments annually and consolidates shipments from transport companies to complete trains utilising 9100 own wagon modules. As a major combined transport operator, this company offers important industry insights and provides significant support in identifying challenges around combined transport.
IP 19	Freight Forwarder <i>Switzerland</i>	Offering end-to-end transport solutions, including ocean freight, air freight, European land transport, contract logistics, customs services, and data management, operating as an asset-light company	This large company is the leading sea freight and air freight forwarder worldwide offering specialised transport solutions for major industries as a global logistics partner. Being one of the most important freight forwarding companies this partner provided important insights on freight transportation and the use of digital technologies.
IP 20	Consignor & Consignee <i>United States, Europe</i>	Production and distribution of consumer goods	This American multinational consumer goods corporation is one of the largest shippers in Europe and contributes important insights to the stakeholder analysis from a consignor/consignee perspective.
IP 21	Freight Forwarder <i>Germany</i>	Managing standardised transport orders, unitising them based on client software systems, handling various container types, good types, commercial types, capacities, departure and provision times, duration of stay, customs clearance, and release processes from terminals	As a maritime, port-neutral operator and specialist in port-to-door logistics, this company organises global supply chains in combined transport and bringing together the system strength of rail with the flexibility of trucking. As an important link between maritime ports and hinterland transportation, this stakeholder contributes significant industry experience to the analysis
IP 22	DLSP <i>Germany</i>	Neutral platform connecting intermodal actors and providing transport chain transparency and intermodal booking options	As a highly innovative SME and neutral platform for intermodal players, this stakeholder makes a decisive contribution to the analysis.
IP 23	Carrier Freight Forwarder <i>Germany</i>	Providing rail transport services, including locomotives, and rolling stock, transportation of hazardous goods, customs Clearance, train path orders, local operations, personnel, equipment, and combined transport	As a subcompany of the largest combined transport operator in Europe for road and rail transport, this stakeholder specialises in the transport of high-quality rail products in combined transport between the Netherlands and Germany. This partner contributes to the gain of knowledge with its perspective of a railway undertaking company.

Annex II: Quantitative Online Survey

Key	Section	#	Topic	Question type	Questions	Options (if applicable)	Optional	Dependencies
LOG_01	01_Logistics	1	Role in multimodal transportation	Multiple Choice	What roles does your organisation play in the transportation process?	1. Shipper 2. Carrier 3. Freight Forwarder 4. Multimodal Transport Operator (MTO) 5. Logistics Service Provider 6. Digital Logistics Service Provider 7. Support service provider or consultant 8. Software provider 9. Terminal operator 10. Infrastructure operator and/or manager		

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						11. Governmental entity 12. Other...		
LOG_02	01_Logistics	2	Relevant transport modes	Multiple Choice	Please select all modes of transport (co-)operated with/by or relevant to your organisation?	1. Road 2. Rail 3. Inland waterways 4. Maritime (both deep sea and short sea) 5. Air 6. None		
LOG_03	01_Logistics	3	# of transport modes per order	Single Choice	On average, how many different modes of transport does your organisation use per shipment?	1. None 2. 1 3. 2 4. 3 or more 5. I don't know/not relevant for our organisation		
LOG_04	01_Logistics	4	Impact of multimodality on efficiency	Likert	Do you think using more than one mode per shipment helps to improve efficiency?	1. Not at all 2. Slightly 3. Moderately 4. Very 5. Extremely 6. I don't know		
LOG_05	01_Logistics	5	Stages of the transport process	Multiple Choice	What stages of the transport process do your organisation's activities cover, serve or address?	1. Pre-haulage 2. Main-run 3. Post-haulage 4. None		
LOG_06	01_Logistics	6	Transport range	Multiple Choice	What transport distances are relevant to your organisation?	1. < 15 km, commonly referred to as "last mile" 2. 15 km - 300 km 3. 300 km - 600 km 4. 600 km - 900 km 5. > 900 km 6. None		
LOG_07	01_Logistics	7	Preference for relay traffic	Single Choice	In the case of multimodal transportation, would you prefer many short distance segments or few long-distance segments?	1. Many short distance segments (less than 300 km) 2. Few long-distance segments (more than 300 km) 3. I don't know		
TEN_01	02_TEN-T	1	Relevance of TEN-T corridors	Single Choice	Is the concept of the Trans-European Transport Network, also known as TEN-T corridors, relevant to your organisation?	1. Yes 2. No 3. I am not familiar with the concept of TEN-T corridors		
TEN_02	02_TEN-T	2	Introduction to TEN-T					TEN_01_03 required
COR_01	03_Corridor	1	Activities in North-Sea Baltic	Single Choice	Is your organisation active in the North Sea-Baltic TEN-T corridor?	1. Yes 2. No 3. No, but there are plans to expand into the corridor 4. I don't know		
COR_02	03_Corridor	2	Actors in North-Sea Baltic	Text	What are the relevant carriers operating in the North Sea-Baltic TEN-T corridor?			
COR_03	03_Corridor	3	Actors in North-Sea Baltic	Text	What are the relevant Logistics Service Providers (LSP) operating in the North Sea-Baltic TEN-T corridor?			
COR_04	03_Corridor	4	Actors in North-Sea Baltic	Text	What are the relevant terminals and/or companies operating the terminals in the North Sea-Baltic TEN-T corridor?			
COR_05	03_Corridor	5	Actors in North-Sea Baltic	Text	What are the relevant infrastructure managing or operating entities operating in the North Sea-Baltic TEN-T corridor?			
COR_06	03_Corridor	6	Actors in North-Sea Baltic	Text	What are the relevant governmental agencies operating in the North Sea-Baltic TEN-T corridor?			
COR_07	03_Corridor	7	Activities in Rhine-Danube	Single Choice	Is your organisation active in the Rhine-Danube TEN-T corridor?	1. Yes 2. No 3. No, but there are plans to expand into the corridor 4. I don't know		
COR_08	03_Corridor	8		Text	What are the relevant carriers operating in the Rhine-Danube TEN-T corridor?			
COR_09	03_Corridor	9		Text	What are the relevant Logistics Service Providers (LSP) operating in the Rhine-Danube TEN-T corridor?			
COR_10	03_Corridor	10		Text	What are the relevant terminals and/or companies operating the terminals in the Rhine-			

					Danube TEN-T corridor?			
COR_11	03_Corridor	11		Text	What are the relevant infrastructure managing or operating entities operating in the Rhine-Danube TEN-T corridor?			
COR_12	03_Corridor	12		Text	What are the relevant governmental agencies operating in the Rhine-Danube TEN-T corridor?			
TEN_03	02_TEN-T	3	Activities in TEN-T corridors	Multiple Choice	In which TEN-T corridors does your organisation operate?	a. Yes b. No c. No, but expansion plans d. Don't know 1. Baltic-Adriatic Corridor 2. North Sea-Baltic Corridor 3. Mediterranean Corridor 4. Orient/East-Med Corridor 5. Scandinavian-Mediterranean Corridor 6. Rhine-Alpine Corridor 7. Atlantic Corridor 8. North Sea-Mediterranean Corridor 9. Rhine-Danube Corridor 10. None		
BM_01	04_Business Model	1	Key activities	Multiple Choice	What are your organisation's key activities?	1. Transportation management: managing and executing the physical transportation of goods across various transport modes 2. Logistics coordination: organising and managing all aspects of the shipping process, including route selection and carrier contracting 3. Scheduling and coordination: managing schedules for shipments to maximise throughput and minimise downtime 4. Loading and transshipment: executing the loading, unloading, and transfer of cargo 5. Shunting: moving and organising railway cars to assemble or disassemble trains 6. Commissioning: preparing and verifying systems, equipment, or facilities for operational use, ensuring they meet specified requirements and are ready for service 7. Customs and compliance: handling documentation and ensuring compliance with international trade regulations 8. Safety and security management: implementing and monitoring security protocols and safety practices within facilities 9. Maintenance and upkeep: conducting regular maintenance of infrastructure and equipment 10. Container handling: provision or repair and maintenance of containers 11. Storage and warehousing: storing of goods in designated facilities to ensure their safekeeping, inventory management, and timely distribution 12. Traffic management: planning and controlling the flow of vehicles 13. Consulting and support: offering expert advice on digital transformation and operational optimisation 14. Technology development: creating digital solutions for logistics processes 15. Platform development: building and maintaining digital platforms for logistics processes 16. Data analytics services: analysing logistics data 17. Cybersecurity services: ensuring digital platforms and data exchanges are secure from cyber threats 18. Customer relationship management: developing and maintaining strong relationships with customers to ensure satisfaction and repeat business 19. Training and development: offering training services to upskill employees in transport and logistics firms		

						20. Stakeholder engagement: communicating and collaborating with all parties involved 21. Other...		
BM_02	04_Business Model	2	Customer segments	Multiple Choice	For whom does your organisation create value?	1. Shipper 2. Carrier 3. Freight Forwarder 4. Multimodal Transport Operator (MTO) 5. Logistics Service Provider 6. Digital Logistics Service Provider 7. Support service provider or consultant 8. Software provider 9. Terminal operator 10. Infrastructure operator and/or manager 11. Governmental entity 12. Other... 11. Other		
BM_03	04_Business Model	3	Information exchange	Multiple Choice	With which roles do you exchange information as you create value? What is the direction of information flow?	a. Yes, receive from b. Yes, send to c. Yes, receive from and send to d. No e. Don't know 1. Shipper 2. Carrier 3. Freight Forwarder 4. Multimodal Transport Operator (MTO) 5. Logistics Service Provider 6. Digital Logistics Service Provider 7. Support service provider or consultant 8. Software provider 9. Terminal operator 10. Infrastructure operator and/or manager 11. Governmental entity 12. Other...		
BM_04	04_Business Model	4	Information exchange	Likert	Which information streams does your organisation receive, pass on or both receive and pass on?	a. Receive b. Receive and pass on c. Pass on d. Neither e. Don't know 1. Regulatory and compliance requirements and documentation (customs, insurance) 2. Cargo requirements and documentation (cargo information, transport unit requirements, handling equipment, contact details, safety requirements) 3. Transport requirements and documentation (Transport order, booking confirmation, Shipment specifications [mode of transport, transshipments], schedules [origin and destination, ETD, ETA], Transshipment equipment) 4. Payment and billing information (billing instructions, Invoicing, handling and transshipment rates, freight rates, storage rates) 5. Track-and-Trace information (Position, Change notification, Condition report, transshipment tracking, shipment status) 6. Routing conditions (weather and traffic forecast, infrastructure status, Terminal status, Transshipment spot availability, Storage space availability, capacity constraints) 7. Sustainability indicators 8. Incident and exception reporting		
BM_05	04_Business Model	5	Logistics-specific IT systems	Single Choice	Does your organisation use a Transport Management System (TMS)?	1. Yes 2. No 3. I don't know		
BM_06	04_Business Model	6	Logistics-specific IT systems	Single Choice	Which TMS system does your organisation use?	1. SAP 2. Oracle 3. Alpega 4. Transporeon 5. Impargo 6. In-house 7. Other (free text)		BM_05_01 required
BM_07	04_Business Model	7	Logistics-specific IT systems	Single Choice	Does your organisation use a Warehouse Management System (WMS)?	1. Yes 2. No 3. I don't know		
BM_07	04_Business Model	7	Logistics-specific IT systems	Single Choice	Which WMS system does your organisation use?	1. SAP 2. Oracle 3. Körber 4. Manhattan Associates 5. Luminate 6. In-house 7. Other (free text)		BM_07_01 required

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BM_08	04_Business Model	8	Logistics-specific IT systems	Single Choice	Does your organisation use a Enterprise Resource Planning System (ERP)?	1. Yes 2. No 3. I don't know		
BM_08	04_Business Model	8	Logistics-specific IT systems	Single Choice	Which ERP system does your organisation use?	1. SAP 2. Oracle 3. Sage 4. NetSuite 5. Epicor 6. In-house 7. Other (free text)		BM_08_01 required
BM_09	04_Business Model	9	Logistics-specific IT systems	Single Choice	Does your organisation use a Customer Relationship Management System (CRM)?	1. Yes 2. No 3. I don't know		
BM_09	04_Business Model	9	Logistics-specific IT systems	Single Choice	Which CRM system does your organisation use?	1. Salesforce 2. Monday sales 3. Nimble 4. HubSpot 5. Pipedrive 6. In-house 7. Other (free text)		BM_09_01 required
BM_10	04_Business Model	10	Logistics-specific IT systems	Single Choice	Does your organisation use a Supply Chain Management System (SCM)?	1. Yes 2. No 3. I don't know		
BM_10	04_Business Model	10	Logistics-specific IT systems	Single Choice	Which SCM system does your organisation use?	1. SAP 2. Oracle 3. MS Dynamics 4. Plex 5. IFS 6. In-house 7. Other (free text)		BM_10_01 required
BM_11	04_Business Model	11	Logistics-specific IT systems	Single Choice	Does your organisation use a Asset Tracking System?	1. Yes 2. No 3. I don't know		
BM_11	04_Business Model	11	Logistics-specific IT systems	Multiple Choice	Which asset tracking system does your organisation use?	1. RFID 2. GPS 3. Barcode 4. NFC 5. Other (free text)		BM_11_01 required
BM_12	04_Business Model	12	Logistics-specific IT systems	Single Choice	Does your organisation use a Terminal Operating System (TOS)?	1. Yes 2. No 3. I don't know		
BM_12	04_Business Model	12	Logistics-specific IT systems	Multiple Choice	Which TOS does your organisation use?	1. Navis 2. CyberLogitec 3. GullsEye 4. Autostore TOS 5. ContPark 6. Interman (B. Rekencentra) 7. Inform 8. Berghof BLU 9. In-house 10. Other (free text)		BM_12_01 required
BM_13	04_Business Model	13	Data exchange formats	Multiple Choice	What formats does your organisation use to exchange data?	1. Standardised electronic data exchange formats (EDI/EDIFACT) 2. Office formats (.xls(x), .doc(x), .ppt(x)) 3. Comma-separated values (.csv) 4. .xml 5. .txt 6. PDF 7. E-Mail 8. Telefax 9. Paper 10. Other (free text)		
BM_13	04_Business Model	13	Revenue streams	Multiple Choice	Who is the primary entity responsible for financing or paying for the value or service provided by your organisation?	1. The customer itself 2. The state or government 3. No one 4. Another role		
BM_14	04_Business Model	14	Revenue Streams/Business Models	Multiple Choice	What describes your organisation's business model best?	1. Direct Sales Model: Products or services are sold directly to consumers without intermediaries 2. Subscription Model: Customers pay a recurring fee (monthly, yearly, etc.) to access a product or service 3. Marketplace Model: The company takes a commission or fee on transactions made between buyers and sellers on the platform 4. Freemium Model: Basic services are offered for free, while premium features, advanced functionalities, or additional content are available for a fee 5. Advertising Model: Revenue is generated through advertisements placed on the company's platform, paid for by advertisers who want to reach the platform's audience 6. Other...		
PLA_01	05_Platforms	1	Potential of a digital platform on multimodality efficiency	Likert	Do you think a digital platform could help orchestrate multimodal	1. Not at all 2. Slightly 3. Moderately 4. Very		

[Increasing Resilience of Intermodal Freight Transport Networks – Key Challenges in Disruption Handling and Requirements for Digital Solutions Research Contribution]

					transportation more efficiently?	5. Extremely 6. I don't know		
PLA_02	05_Platforms	2	Utilisation of digital platforms	Single Choice	Does your organisation already use a digital platform for collaboration with its partners and customers?	1. Yes 2. No		
PLA_03	05_Platforms	3	Platforms in use	Multiple Choice	Which digital platform does your organisation use for collaboration with partners and customers?	1. Transporeon 2. Sennder 3. Cesar-Next 4. Insta-Freight 5. Forto 6. Shippeo 7. FreightHub 8. Quicargo 9. Other (Free text)		PLA_02_02 required
PLA_04	05_Platforms	4	Integrated solution	Single Choice	Would you prefer a digital platform that is integrated into your existing digital infrastructure or an independent stand-alone solution that works via interfaces with existing IT services?	1. Integrated system 2. Standalone solution 3. No preference		
PLA_05	05_Platforms	5	Information streams via digital platforms	Likert	How important is the processing of information streams via a digital platform?	a. Must b. Should c. May d. Should not e. Must not f. No preference 1. Regulatory and compliance requirements and documentation (customs, insurance) 2. Cargo requirements and documentation (cargo information, transport unit requirements, handling equipment, contact details, safety requirements) 3. Transport requirements and documentation (Transport order, booking confirmation, Shipment specifications [mode of transport, transshipments], schedules [origin and destination, ETD, ETA], Transshipment equipment) 4. Payment and billing information (billing instructions, Invoicing, handling and transshipment rates, freight rates, storage rates) 5. Track-and-Trace information (Position, Change notification, Condition report, transshipment tracking, shipment status) 6. Routing conditions (weather and traffic forecast, infrastructure status, Terminal status, Transshipment spot availability, Storage space availability, capacity constraints) 7. Sustainability indicators 8. Incident and exception reporting		
PLA_06	05_Platforms	6	Concerns regarding information exchange	Multiple choice	Which concerns do you have when exchanging information via a digital platform?	1. Data security 2. Data privacy 3. Data integrity/Authentication 4. (Regulatory) Compliance 5. Technical issues 6. Interoperability 7. Standardisation 8. Other (free text)		
NEE_01	06_Needs	1	Needs	Ranking	Please rank the following needs according to their importance to your organisation from highest to lowest:	1. Data standardisation and automation 2. Integrated digital solutions 3. Facilitated data exchange and collaboration 4. Streamlined transport regulations 5. Advanced analytics and forecasting tools		
NEE_02	06_Needs	2	Needs	Single Choice	Do you can think of additional needs that need to be addressed when designing a digital platform?	1. No 2. Other (free text)		
GEN_01	07_General	1	Gender	Single Choice	Which gender do you identify with?	1. male 2. female 3. non-binary	x	
GEN_02	07_General	2	Job Level	Text	What is your current job level in your organisation?	Free text	x	
GEN_03	07_General	3	Number of employees	Single Choice	How many employees does your organisation have?	1. up to 9 2. 10 to 49 3. 50 to 249 4. from 250	x	
GEN_04	07_General	4	Annual revenue	Single Choice	How much is your estimated annual revenue in euros (€)?	1. up to € 2 million 2. up to € 10 million 3. up to € 50 million 4. more than € 50 million	x	
GEN_05	07_General	5	Participation	Single Choice	Are you interested in contributing to our	1. Yes 2. No		

					project by participating in an expert interview or stakeholder workshop?			
GEN_06	07_General	6	Participation	Text	Please enter your contact email address	Free text		GEN_05_01 required

Readiness Indicators for Physical Internet in Supply Chain

Naruphon Gunhawan¹, Apichat Sopadang², Ruth Banomyong³, Salinee Santiteerakul²

¹Graduate Program in Industrial Engineering, Department of Industrial Engineering, Faculty of Engineering, Chiang Mai University, Chiang Mai, 50200, Thailand.

²Supply Chain Engineering Management Research Unit, Department of Industrial Engineering, Faculty of Engineering, Chiang Mai University, Chiang Mai, 50200, Thailand.

³ Center of Excellence in Connectivity, Thammasat University, Bangkok, 10200, Thailand

Corresponding author: naruphon_g@cmu.ac.th

Abstract: *The Physical Internet (PI) is an emerging paradigm that enhances supply chain efficiency, adaptability, and sustainability through modular, standardized, and digitally connected systems. However, implementation remains limited due to gaps in technological readiness, organizational capability, and regulatory coherence. This study aims to identify practical readiness indicators to support PI adoption. A systematic literature review and thematic analysis were conducted, structured around the five development areas defined in the 2024 ALICE Roadmap: PI Nodes, PI Networks, the System of Logistics Networks, Access and Adoption, and Governance. The analysis yielded 15 key readiness aspects, which were translated into measurable key performance indicators (KPIs) across technical, organizational, and institutional domains. These indicators provide a structured foundation for assessing readiness, identifying gaps, and supporting strategic investment planning. This research contributes the first structured indicator set aligned with the ALICE model, enhancing the practical applicability of PI readiness assessment in diverse logistics contexts.*

Keywords: *Physical Internet, Supply Chain Management, Organizational Readiness, Modular Logistics, Digital Transformation*

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

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

1. Introduction

The Physical Internet (PI) is an innovative logistics paradigm designed to significantly enhance efficiency, flexibility, and sustainability in supply chain operations. Inspired by the digital internet, PI proposes a globally interconnected logistics network using standardized, modularized containers. Within this system, physical goods move autonomously, similar to how data packets travel seamlessly across digital networks [1]. By adopting principles of dynamic routing and real-time responsiveness, PI can lead to more effective resource utilization, reduced environmental impact, and enhanced overall supply chain resilience.

While PI holds great promise, its implementation presents considerable challenges. Successful adoption requires more than just technological advancements. It involves organizational readiness, stakeholder collaboration, robust information systems, and adaptive governance structures. A critical factor for the effective transition to PI is collaborative readiness. This dimension necessitates organizations to shift from competitive strategies to collaborative partnerships, emphasizing secure data sharing and intellectual property protection [2].

While interest in the PI is growing, most existing studies focus narrowly on technical aspects such as infrastructure digitalization or modular design, with limited consideration of organizational, governance, and sustainability factors. Moreover, current readiness assessment models are either too generic or lack PI-specific, measurable indicators. This fragmentation leaves a gap in both academic knowledge and practical implementation. To address this, the study introduces a KPI-based PI readiness indicator set aligned with the five development areas of the ALICE roadmap. By translating conceptual enablers into actionable metrics, the indicators support organizations in evaluating their readiness, identifying gaps, and prioritizing strategic investments. This research contributes the first multidimensional, PI-specific indicator set, advancing both theoretical understanding and practical guidance for PI adoption across diverse logistics systems.

2. Literature Review

The PI represents a transformative logistics paradigm, envisioning an open and interconnected global network designed for efficient and sustainable movement of goods, analogous to the data transmission methods of the digital internet. Core principles underpinning the PI include standardization, modularization, and collaboration, which are critical to realizing its vision of a seamless logistics ecosystem [3]

2.1 Organizational Readiness for PI

Initial studies on the PI primarily addressed foundational theoretical aspects such as modularization, standardization, and interconnectivity. Subsequent research has expanded these conceptual foundations, shifting towards practical applications demonstrated through pilot studies and real-world logistics initiatives. For instance, the implementation of PI principles at multi-modal logistics hubs in northern France resulted in notable reductions in CO₂ emissions and improved resource utilization [4]. Additionally, research within the chemical sector demonstrated that integrating PI with modular capacity systems can enhance both sustainability and resilience compared to traditional logistics approaches [5]. Nonetheless, successful adoption of PI involves significant organizational transformations beyond technological innovations alone. Existing research highlights critical dimensions of organizational readiness such as leadership support, strategic alignment, cultural adaptability, and collaborative capacity [6]. Despite broad agreement on these dimensions, current literature reveals considerable variability and lacks a standardized framework for systematically assessing readiness across different contexts. In particular, there is a noticeable gap regarding integrated assessment models capable of effectively bridging technological readiness with broader organizational capabilities [7]. Moreover, achieving the full potential of PI requires significant advancements in digital interoperability and physical infrastructure. This demands multidisciplinary collaboration, particularly given PI's close alignment with the goals of the circular economy [8]. Similarly, urban logistics research emphasizes the importance of collaborative frameworks aimed at reducing environmental impacts, further supporting the transformative potential of PI to create sustainable logistics networks [9].

However, a critical evaluation of current literature reveals an imbalance in research focus. Studies have predominantly addressed isolated technical components, such as infrastructure digitalization or modular container design, while largely overlooking essential dimensions related to organizational structure, governance mechanisms, and sustainability practices. Consequently, this fragmented approach has resulted in significant gaps within both the academic literature and practical implementation guidance.

The updated 2024 ALICE roadmap emphasizes five critical development areas for transitioning to a sustainable and scalable PI, including the transformation of logistics nodes, integration of multimodal networks, and the establishment of federated systems for interoperability. This aligns with the findings

from Hsu et al., which highlight the necessity of human-centric and sustainable practices in logistics under Industry 5.0, suggesting that active government support is vital for successful implementation [10]. Additionally, Ye et al. demonstrate that intelligent logistics, leveraging automation and IoT, can significantly enhance logistics performance, although effects vary regionally, indicating the need for tailored strategies [11]. Holmström et al. advocate for distributed control in collaborative networks, which can facilitate the effective integration of services and processes in logistics [12]. Furthermore, Yavaş and Ozkan-Ozen propose a framework for logistics centers in Industry 4.0, underscoring the importance of adapting traditional practices to meet modern demands [13]. Collectively, these insights underscore the roadmap's relevance in addressing existing gaps and guiding future research in logistics transformation.

In response to these gaps, this research develops an integrated PI Readiness Assessment Framework grounded firmly in the five ALICE roadmap dimensions. By translating theoretical readiness enablers into quantifiable and operational indicators, the framework provides a comprehensive diagnostic tool. This tool enables organizations to assess their current preparedness, pinpoint capability gaps, and prioritize strategic investments for effective PI implementation. This contribution advances the field by providing the first multidimensional, KPI-based readiness assessment model specifically tailored for the diverse environments associated with PI adoption.

3. Methodology

This study adopts a structured, five-phase methodology aligned with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework, which is widely recognized for enhancing transparency and reproducibility in systematic reviews. The review process includes the following steps: identification, screening, eligibility assessment, and inclusion. The review process includes the following steps: identification, screening, eligibility assessment, and inclusion, as summarized in Figure 1. The process begins by defining the research scope and selecting appropriate keywords, databases, and inclusion criteria to identify relevant literature. Publications were filtered through systematic screening of titles, abstracts, and full texts to ensure alignment with PI-related concepts and readiness dimensions. In the subsequent phases, extracted data were synthesized thematically to identify critical aspects of readiness, which were then formulated into measurable indicators and categorized across the five ALICE roadmap dimensions. The final output is a set of actionable indicators integrated into a multidimensional evaluation framework.

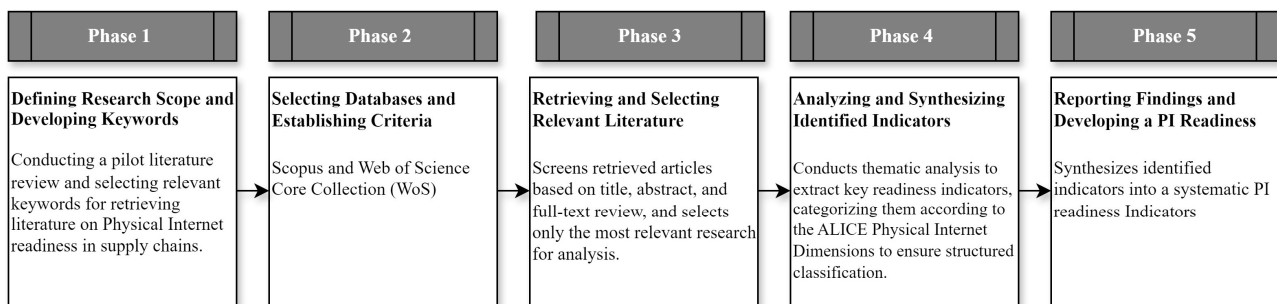


Figure 1: Research Methodology

3.1 Defining Research Scope and Developing Keywords

The final Boolean search string used in this study was: (“Physical Internet” AND “Readiness” AND (“Supply Chain” OR “Logistics”)) AND (“Smart Logistics Hubs” OR “Autonomous Logistics” OR “Blockchain in Logistics” OR “Regulatory Framework” OR “Green Logistics”). The selection of these keywords was directly informed by the ALICE 2024 roadmap and its five development areas. “Physical Internet” and “Readiness” were chosen as core terms to ensure the retrieval of literature

explicitly discussing the PI paradigm and the preparedness of logistics systems to adopt it. The inclusion of “Supply Chain” and “Logistics” ensured coverage of both broad and specific domains in which PI implementation is relevant.

The additional keywords were selected to reflect key enablers across the roadmap’s dimensions. “Smart Logistics Hubs” and “Autonomous Logistics” represent advancements in digital and automated infrastructure that are central to the transition from conventional logistics nodes to PI Nodes. “Blockchain in Logistics” was used to capture secure and interoperable data-sharing mechanisms, essential for building connected logistics networks. “Regulatory Framework” aligns with the governance area of the roadmap, which emphasizes the need for harmonized policy and legal structures to enable cross-network collaboration. Finally, “Green Logistics” addresses the embedded sustainability focus across all development areas, recognizing that PI systems are expected to support environmental efficiency through resource optimization and emissions reduction. These carefully selected keywords enabled a targeted yet comprehensive retrieval of literature that aligns with both the conceptual and practical dimensions of PI readiness.

3.2 Selecting Databases and Establishing Inclusion/Exclusion Criteria

The systematic literature search was executed in two major scholarly databases: Scopus and Web of Science. The search focused exclusively on peer-reviewed journal articles and conference papers published within the last 15 years. Inclusion criteria required that studies explicitly address PI readiness, digital transformation in logistics, or organizational adaptation within logistics contexts. Conversely, non-peer-reviewed articles, editorials, and studies unrelated to PI readiness were excluded.

3.3 Retrieving and Selecting Relevant Literature

A systematic search using predefined keywords and Boolean operators was conducted across Scopus and Web of Science databases. The selection process followed a multi-stage protocol: initial retrieval, title and abstract screening, full-text review, and final selection. Each step was guided by predefined inclusion and exclusion criteria to ensure methodological soundness and the academic relevance of selected publications.

3.4 Analyzing and Synthesizing Identified Aspects and Indicators

The selected literature was analyzed using a thematic approach to extract and classify PI readiness indicators. Recurring concepts were coded and organized in alignment with the five development areas outlined in the updated 2024 ALICE roadmap. These include the transformation of logistics nodes into standardized and digitally connected PI nodes; the integration of logistics networks into flexible, multimodal PI networks; the development of a federated system of interoperable logistics networks; the organizational capacity required for access and adoption; and the governance mechanisms needed to ensure regulatory alignment and trust across stakeholders. This analytical structure enabled the identification of key enabling factors, systemic interdependencies, and implementation challenges, resulting in a structured and holistic classification of PI readiness indicators grounded in the roadmap’s systems-based approach.

3.5 Development of Readiness Indicator Framework

In the final phase, findings were synthesized into a structured set of PI readiness indicators, reflecting critical organizational, technological, and governance capacities required for PI adoption. These indicators offer a practical framework for evaluating readiness, diagnosing implementation gaps, and formulating targeted strategies for transitioning toward PI-aligned logistics systems. The framework contributes both theoretically and practically, serving as a foundation for further research and application in real-world supply chain contexts.

4. Result

4.1 Selection and Evaluation of Literature for PI Readiness in Supply Chains

A structured literature selection process was conducted, as illustrated in the PRISMA diagram (Figure 2). An initial search in Scopus and Web of Science yielded 436 records. After removing 26 duplicates, 410 records were screened by title and abstract, resulting in 139 articles for full-text review. Of these, 104 were excluded for lacking a direct focus on PI readiness. The final sample comprised 35 studies, which form the empirical foundation for the development of the proposed readiness assessment framework.

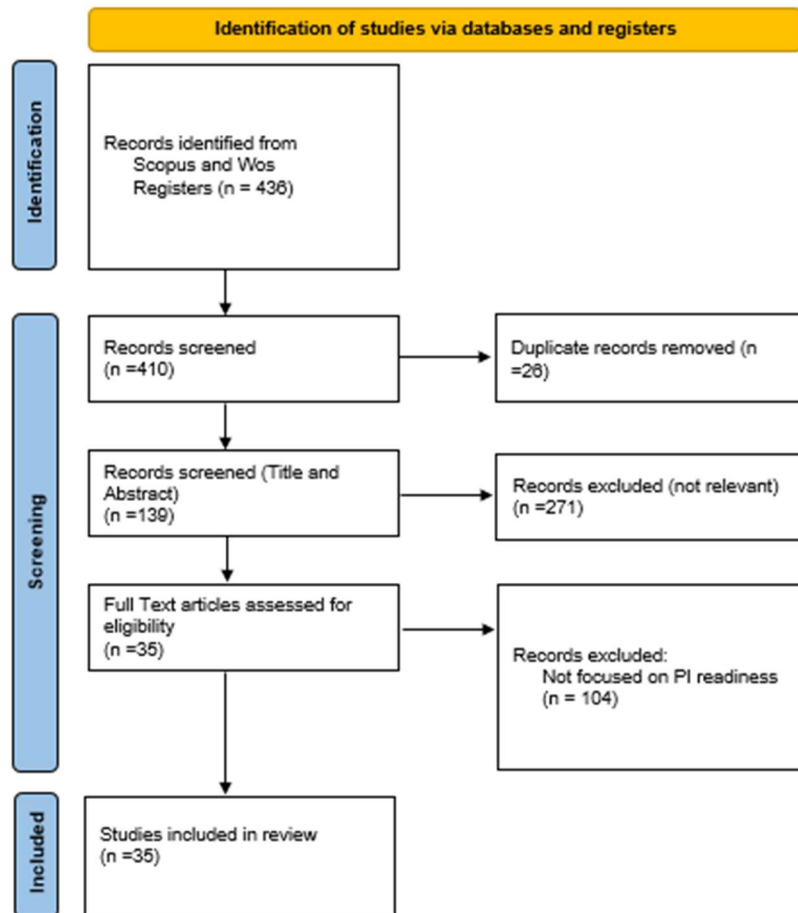


Figure 2: PI Readiness Literature Selection Process

Subsequent title, abstract, and full-text reviews ensured methodological rigor and thematic relevance, resulting in a final selection of 35 high-impact studies. These publications form the empirical basis for the development of the PI readiness indicators presented in this study.

This iterative refinement process produced a focused and credible dataset, providing a robust foundation for constructing a comprehensive readiness assessment framework consistent with the ALICE vision of an open, interconnected, and sustainable logistics ecosystem.

Table 1: Analysis and Clustering Category Papers

Thematic Category	No. of Papers	Key Research Topics
PI Readiness & Adoption	10	Readiness assessment models, adoption challenges, organizational transformation strategies
Smart Logistics Hubs	5	Digital logistics centers, automation in supply chains, IoT-enabled warehousing

Table 1: Analysis and Clustering Category Papers (Cont.)

Thematic Category	No. of Papers	Key Research Topics
Blockchain in Logistics	4	Secure data sharing, supply chain transparency, decentralized logistics networks
Supply Chain Digitalization	6	AI-driven decision-making, real-time tracking, digital platforms for logistics
Modular & Autonomous Systems	5	Standardized π -containers, multimodal transport optimization, AI in logistics automation
Sustainability & Green Logistics	5	CO ₂ emissions reduction, circular economy logistics, sustainable freight networks

Based on Table 1, the 35 studies identified from the systematic review are categorized into six thematic areas aligned with key dimensions of PI adoption. The most represented theme, PI Readiness & Adoption (10 studies), explores organizational preparedness, strategic alignment, policy enablers, and implementation challenges. Smart Logistics Hubs (5 studies) emphasize infrastructure digitalization through automation, IoT, and AI. Blockchain in Logistics (4 studies) highlights secure data exchange, transparency, and decentralized logistics for enhanced cross-border efficiency. Supply Chain Digitalization (6 studies) focuses on real-time tracking, AI-supported decision-making, and integrated logistics platforms. Modular & Autonomous Systems (5 studies) address π -container standardization, robotics, and multimodal optimization to promote interoperability. Lastly, Sustainability & Green Logistics (5 studies) examine low-carbon strategies, circular models, and environmentally sustainable freight operations, reinforcing the ecological relevance of PI.

This thematic classification offers a structured lens for analyzing PI readiness by synthesizing key research contributions and revealing underexplored areas. It facilitates a holistic understanding of how technological, strategic, and sustainability dimensions shape the transition toward a digitally integrated PI ecosystem. Nonetheless, potential biases must be acknowledged, particularly those arising from the exclusive use of Scopus and Web of Science, which may omit relevant studies indexed elsewhere. Additionally, the specificity of keywords and inclusion criteria may unintentionally exclude pertinent literature not explicitly aligned with predefined terms. Recognizing these methodological limitations enhances the transparency and contextual validity of the review findings.

4.2 Identified Physical Internet Readiness Aspects and Indicators

The readiness for adopting the PI is crucial for transforming logistics systems, aligning with the five development areas outlined in the 2024 ALICE roadmap. Key aspects include the evolution of logistics nodes into digitally connected hubs, which leverage modular containers and IoT-enabled automation to enhance operational efficiency and sustainability [14] [15]. The integration of PI networks emphasizes multimodal transport, shipment bundling, and dynamic management systems, which collectively improve routing efficiency and reduce environmental impacts [16] [17]. Furthermore, developing a system of logistics networks necessitates interoperability among various stakeholders through federated digital platforms and standardized protocols, such as blockchain, to facilitate seamless information exchange and shared infrastructure access [17]. This comprehensive approach not only fosters collaboration but also aligns with lean principles to minimize waste and optimize resource utilization across the supply chain.

The Access and Adoption area of organizational transformation emphasizes the necessity for internal roadmaps that align with performance indicators (PIs), workforce training, and the adoption of flexible business models like pay-per-use and logistics-as-a-service. These models enable broader participation in logistics networks without necessitating full ownership of assets, as highlighted by the evolution of business models driven by digital platforms and connected technologies [18]. Furthermore, the Governance area underscores the importance of institutional readiness, which is facilitated through cross-border regulatory harmonization and public-private partnerships (PPPs) that

foster trust among stakeholders [19]. Collectively, these frameworks support a transition towards sustainable and efficient logistics systems by addressing technological, organizational, and policy dimensions, ultimately enhancing collaboration and operational resilience in supply chain management [20].

These indicators, summarized in Table 2, serve as a robust foundation for developing a readiness assessment model. The framework enables both researchers and practitioners to diagnose current capabilities, identify strategic gaps, and support decision-making for the phased implementation of the PI vision.

Table 2: PI Development Areas (Refer ALICE) and aspects.

Dimension	Physical Internet Contribution	Aspects	Publication
From Logistics Nodes to PI Nodes	Standardized, digitally accessible, and automated logistics hubs	<ul style="list-style-type: none"> Real-time tracking and visibility Modular and interoperable handling infrastructure IOT enabled warehouse automation Digital service interfaces (booking, planning) 	Furtado P,2015 [21] Sternberg H,2017[22] Deepu T.S.,2021 [23] Mahor V, 2022[24] Mangina E,2020 [25]
From Logistics Networks to PI Networks	Seamless, flexible, multimodal logistics networks managed through open platforms	<ul style="list-style-type: none"> Intermodal routing coordination Dynamic transport planning Shipment bundling and synchronization Network-wide optimization 	Fahim P.B.M.,2021[26] Chadha S.S.,2022 [27] Mahor V, 2022[24] Meyer T,2019 [28] Treiblmaier H,2020 [29]
Developing the System of Logistics Networks towards PI	Federated platforms, cross-network data exchange, and shared access to logistics services and resources	<ul style="list-style-type: none"> Secure data interoperability Participation in federated digital ecosystems API and blockchain integration Multi-party platform access 	Zheng L,2019 [30] Chen S,2022 [31] Tran-Dang H,2025 [32] Grest M,2020 [33]
Access and Adoption	Organizational readiness and willingness to transition to PI models	<ul style="list-style-type: none"> Self-assessment tools Strategic leadership for PI adoption Pay-per-use and flexible service models Capacity-building initiatives 	Michelotto&Joia,2024 [34] Gülmez and G. Denktas,2024 [35] Tran-Dang H,2021[36]
Governance	Cross-sector regulation, trust-building mechanisms, and policy innovation supporting system-wide PI implementation	<ul style="list-style-type: none"> Regulatory harmonization Public-private partnerships (PPPs) Certification and standardization Institutional coordination and trust 	Grover N,2021 [38] Nouiri M,2020 [39] Nouiri , 2020 [40] Hofman W,2015 [37]

The thematic dimensions and key aspects synthesized from the literature in Table 2 provide the conceptual foundation for constructing measurable readiness indicators. Each dimension reflects critical enabling PI adoption. These aspects, drawn from empirical studies and theoretical models, highlight recurring challenges and capabilities that must be addressed across diverse logistics systems. Building upon these insights, Table 3 translates the conceptual elements into practical indicators that organizations can use to assess their current readiness. By aligning each aspect with a corresponding metric and assessment approach, Table 3 operationalizes the framework outlined in Table 2, bridging academic theory and real-world application to support strategic decision-making in PI implementation.

4.3 Developing Physical Internet Readiness Indicators

The development of PI indicators provides organizations with practical criteria for assessing their preparedness for PI adoption. Structured around the ALICE development areas, these indicators encompass five development areas as table 3.

Table 3 PI Readiness Indicators

Development areas	Aspects	Readiness Approach	Indicators
Logistics Nodes to PI Nodes	Real-time tracking and visibility [21],[22],[26]	Implementing IoT sensors and dashboards in logistics nodes	% of logistics hubs with real-time operational visibility
	Modular and interoperable logistics infrastructure [24] , [40]	Adopting standardized π -containers and modular handling systems	% of containers and load units conforming to PI modularity standards
	Automation capability [25] , [28]	Integrating robotics and smart systems into warehouses	% automation of node operations % energy savings from automation
	Digital service accessibility [21],[28]	Enabling API-based interfaces for booking and planning	Availability of API-accessible digital services
Logistics Networks to PI Networks	Intermodal routing and coordination [24] , [40]	Deploying AI-driven TMS for dynamic route optimization and coordination	% of multimodal flows managed through collaborative routing platforms
	Shipment bundling and network optimization [30] , [40]	Implementing shipment consolidation and adaptive scheduling algorithms	Average shipment consolidation ratio
Developing the System of Logistics Networks towards PI	Cross-network interoperability [41] , [31]	Joining federated logistics platforms with shared access to services/resources	% of logistics partners integrated into cross-network platforms
	Secure data exchange [29] , [42]	Implementing blockchain or standardized APIs for trusted data interoperability	% of transactions conducted through secure, interoperable digital channels
Access and Adoption	Organizational transformation [43] , [44]	Establishing readiness self-assessment and transition roadmaps	Existence of PI roadmap Internal PI maturity score
	Business model innovation [45] , [33]	Offering pay-per-use, shared logistics or on-demand services	% of services aligned with PI-enabled business models
	Capacity building [33] , [42]	Training programs for digital logistics and modular system operations	% of logistics staff trained on PI-related technologies
Governance	Regulatory alignment [38] , [39]	Conforming to national/international PI-relevant legal frameworks	# of PI-aligned environmental policy frameworks
	Stakeholder collaboration [36] , [46]	Participation in standardization bodies and logistics public-private partnerships (PPP)	# of stakeholder forums addressing green logistics
	Trust and certification, [46]	Adopting certification schemes for PI readiness, data security, and modular operations	Existence of green logistics/PI certification schemes

Table 3 presents a structured set of readiness indicators categorized according to the core development areas defined in the 2024 ALICE roadmap. The transformation of logistics nodes into PI Nodes is captured through indicators that assess real-time visibility, predictive capabilities, and partner interoperability. These include the percentage of shipments tracked using Transport Management Systems (TMS) and GPS, the forecasting accuracy of digital twin simulations used in infrastructure planning, and the degree of digital integration across logistics partners. In the evolution from traditional

networks to PI Networks, readiness is reflected in the system's modularity, standardization, and automation. Readiness within the System of Logistics Networks is determined by the capacity to securely and transparently share data across actors. Relevant indicators include the implementation rate of standardized APIs or Electronic Data Interchange (EDI), the performance of AI-based predictive models, and the organization's openness to collaborative data-sharing practices. Access and Adoption are gauged through metrics that capture business model innovation and institutional flexibility, such as the share of services delivered through pay-per-use or shared models, compliance with PI-aligned regulations, and engagement in public-private partnerships (PPPs). Lastly, indicators reflecting the Governance area address sustainability and circular economy alignment, including the proportion of fleets powered by clean energy, the reduction in CO₂ emissions per shipment, and organizational initiatives supporting reverse logistics, material reuse, and waste minimization. Collectively, these indicators offer a multidimensional tool for assessing how prepared logistics systems and organizations are to transition toward the PI paradigm.

4.4 Discussion

The proposed readiness assessment framework translates the conceptual vision of the PI, as articulated by the ALICE roadmap, into a set of practical, measurable indicators. As illustrated in Figure 3, the framework is structured across five interrelated dimensions each representing a critical domain of organizational capability necessary for successful PI adoption.

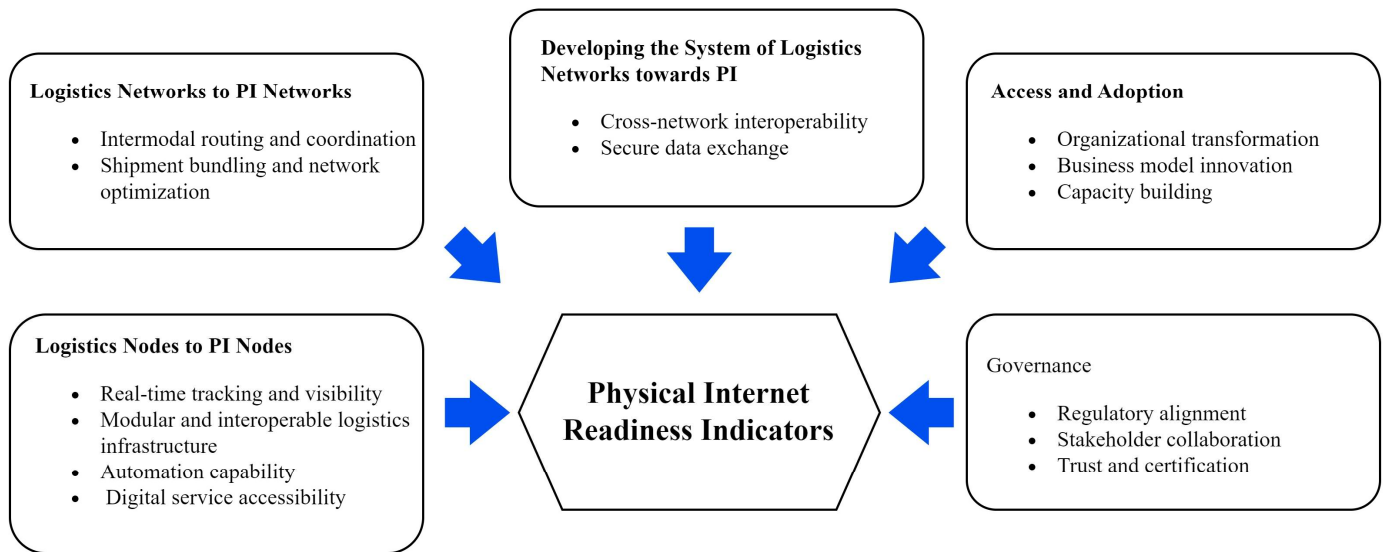


Figure 3: PI Readiness Evaluation Framework

To enhance the analytical precision and contextual relevance of the framework, future research may incorporate structured multi-criteria decision-making techniques such as the Analytic Hierarchy Process (AHP) or Delphi method. These approaches can facilitate the weighting of indicators based on expert judgment and contextual priorities, especially in sector-specific or region-specific applications. Although these techniques are not employed in the present study, their integration represents a logical extension for tailoring the indicator set to practical decision-making needs. By enabling prioritization of readiness aspects, such methods would strengthen the diagnostic value of the framework and increase its adaptability across diverse logistics settings. Table 4 outlines the distinction between the proposed PI-specific indicators and previous maturity models, underscoring the contribution of this study to advancing readiness assessment for PI transformation.

Table 4: Comparative Overview of Existing Readiness Frameworks and the Proposed PI Model

Dimension	Conventional Readiness Frameworks	Proposed PI Readiness Framework
Scope	Focused on isolated elements (e.g., ICT, digitalization)	Integrates five ALICE-aligned PI Development Areas
PI Specificity	Generic logistics or Industry 4.0 orientation	Explicitly designed for PI systems
Measurability	Primarily qualitative or abstract	Quantifiable and operational KPIs
Sustainability	Often excluded or treated superficially	Embedded as a core dimension (e.g., CO ₂ reduction, circularity)
Governance & Policy	Rarely addressed	Includes legal alignment, business model innovation, and PPP readiness
Applicability	Centered on developed economies	Adaptable to emerging and infrastructure-constrained contexts

By linking theoretical constructs to measurable operational indicators, the proposed set of PI readiness indicators provides a practical tool for both strategic planning and operational decision-making. Its integrative structure is well-suited to environments where digital infrastructure, governance mechanisms, and sustainability goals evolve concurrently. This contribution addresses a critical gap in literature and enhances the utility of readiness assessments in diverse logistics contexts. While broadly applicable, the indicator set must be adapted to sector-specific conditions. Variations in technological maturity, process standardization, and supply chain complexity may influence the relevance and applicability of specific indicators.

Therefore, future applications of the framework should incorporate sector-specific adaptation mechanisms, ensuring that readiness assessments are contextualized to industry practices and technological capabilities. This could involve the selective application or weighting of indicators, or the development of tailored sub-frameworks for sectors where PI principles intersect differently with operational realities. Recognizing these differences is essential to enhance the framework's validity and practical utility across diverse industrial contexts.

5. Conclusion

This study presents a structured set of readiness indicators to support the strategic transition toward PI adoption, grounded in the five development areas outlined in the 2024 ALICE roadmap. Synthesized from key technological, organizational, and institutional enablers, the indicators are translated into measurable KPIs that enable comprehensive assessment of readiness across logistics systems.

Designed for adaptability, the indicator set supports organizations in identifying capability gaps, prioritizing investments, and aligning transformation efforts with broader goals of digital integration, modularity, and sustainability. Although weighting techniques such as the Analytic Hierarchy Process (AHP) or Delphi method are not applied in this study, the findings offer a foundation for future refinement and contextual prioritization.

To ensure practical relevance, future research should focus on validating and calibrating the indicators within specific industry or regional contexts. Such application would enhance the framework's diagnostic accuracy and its utility for guiding strategic planning in diverse logistics environments undergoing PI-oriented transformation.

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Network Design and Capacity Management in Hyperconnected Urban Logistic Networks

Xiaoyue Liu^{1,2}, Praveen Muthukrishnan^{1,2} and Benoit Montreuil^{1,2,3}

¹ H.Milton Stewart School for Industrial & Systems Engineering, Georgia Institute of Technology, Atlanta, United States

² Physical Internet Center, Supply Chain & Logistics Institute, Atlanta, United States

³ Coco-Cola Material Handling & Distribution Chair

Corresponding author: xliu800@gatech.edu

Abstract: *In response to the growing need for eco-friendly urban deliveries, this paper presents a methodology for the network design and capacity management of hyperconnected urban logistic networks. Following a Physical Internet (PI) concept, we first design three-level service regions using a demand-balanced spectral clustering algorithm that partitions city regions into urban areas, local cells, and unit zones. We then introduce a large-scale network design optimization model to generate a three-tier hyperconnected urban logistic network composed of gateway, local, and access hubs to integrate and support freight movements. To evaluate the logistics performance of the proposed network, we develop a dynamic capacity management model for containerized urban deliveries, leveraging modular containers for swift load transfers. This model also incorporates dynamic vehicle sharing and repositioning to support flexible scheduling of electric trucks and delivery vans. In the case study, we use the Metro Atlanta area as a testbed to compare our hyperconnected network with a traditional end-to-end network. The experimental results demonstrate that the hyperconnected network enhances resource utilization, reduces operational costs, improves service quality, and achieves greater environmental sustainability, providing new insights for agile and sustainable urban logistics.*

Keywords: *Urban Logistics; Hyperconnected Urban Logistic Network Design; Dynamic Capacity Deployment; Multi-period Vehicle Routing & Repositioning; Net-Zero Emission; Physical Internet.*

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

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

1 Introduction

According to the report by Carey and Baertlein (2023), many start-up companies in Europe and the United States are rapidly positioning themselves to capture the growing market for zero-emission, electric last-mile urban deliveries to retailers and consumers. In addition, major logistics companies have set long-term targets for fleet electrification. FedEx aims to achieve a fully zero-emission delivery fleet by 2040 (FedEx, 2022), while Deutsche Post DHL Group plans for 60% of its delivery fleet to be electric by 2030 (DHL, 2023). This growing emphasis on zero-emission urban transport underscores the need for innovative logistics solutions that not only deliver operational efficiencies but also reduce environmental impact.

To address these global logistics challenges, Montreuil (2011) introduced the concept of the Physical Internet (PI), which aims to revolutionize supply chain operations through modularity, containerization, open asset sharing, and hyperconnectivity to ultimately enhance efficiency and sustainability. Building upon this foundation, Crainic and Montreuil (2016) proposed the concept of hyperconnected city logistics, introducing nine key principles that together offer a conceptual framework for designing efficient and sustainable urban logistic systems. Moreover, Crainic et al. (2020) developed an optimization model for tactical planning within a two-tier hyperconnected network, allowing for the evaluation of the proposed framework's benefits.

Inspired by the core principles of hyperconnected city logistics, this study introduces a methodology for the network design and capacity management of PI-enabled hyperconnected urban logistic networks, aiming to achieve both environmental sustainability and operational efficiency. Specifically, we employ a demand-balanced spectral clustering approach to define three-tier service regions, followed by a large-scale network design optimization model to select hub locations. This facilitates the construction of a three-tier hyperconnected hub network. To evaluate the logistics performance of the proposed network, we develop a multi-period capacity management model to optimize freight and vehicle routing across the network, ensuring demand fulfillment while minimizing total delivery costs. In our case study, we use the Atlanta metropolitan area as a test bed to compare the proposed hyperconnected network with a conventional end-to-end network. We evaluate performance along four key dimensions (i.e., network & service configuration, operational efficiency, environmental impact, and cost effectiveness) to provide a comprehensive comparison. Overall, this research contributes to the practical implementation of the PI concept within urban logistics and highlights its potential to reshape traditional paradigms into more adaptive, efficient, and eco-friendly systems.

The rest of this paper is structured as follows. Section 2 provides a literature review of related work. Section 3 outlines the problem setting. Section 4 details the proposed methodology for network design and capacity management. Section 5 presents the case study and numerical results. Finally, Section 6 concludes with a summary and discusses future research directions.

2 Literature Review

The network design problem has received extensive research attention in both industry and academia for decades. One of the earliest network configurations involved direct shipments from origin to destination. While straightforward, this end-to-end approach lacks scalability and leads to high costs due to fragmented routing. To address this inefficiency, the hub-and-spoke model was proposed by O'Kelly and Miller (1994), enabling the consolidation of freight through central hubs to benefit from economies of scale. However, the inherent centralization in hub-and-spoke networks often results in extended travel paths and vulnerability to disruptions. These structural limitations prompted the introduction of hyperconnected logistic networks under the PI initiative. Unlike hub-and-spoke structures, hyperconnected networks feature densely interlinked hubs operating across multiple layers, enabling efficient consolidation, dynamic routing, increased resilience, and more robust system performance (Muthukrishnan et al., 2021; Li et al., 2023; Liu et al., 2023; Xu et al., 2024). Moreover, Kim et al. (2021) evaluated a PI-enabled hyperconnected network in urban last-mile delivery settings, demonstrating its potential to provide an efficient and cost-saving urban delivery solution.

Several studies have contributed to the development of capacity planning models within the field of PI. Oger et al. (2021) proposed a decision support system aimed at making strategic capacity planning more flexible and responsive in the face of uncertainties inherent in hyperconnected logistics. Faugère et al. (2022) explored the application of a hyperconnected urban parcel logistic network, where modular smart lockers are strategically deployed at PI

access hubs for first-mile pickup and last-mile delivery. Liu et al. (2024) focused on strategic capacity and resource planning in hyperconnected modular distributed construction supply chains. By deploying mobile production containers dynamically across the facility network, their approach helps regulate production rates and mitigate risks arising from fluctuating demand and unforeseen disruptions. Moreover, Liu et al. (2025) investigated dynamic logistic hub capacity planning within a hyperconnected relay-based transportation network, which accounts for uncertainties in both demand and geographic disruptions.

3 Problem Description

This work introduces a structured approach to design and manage the capacity of PI-enable hyperconnected urban logistic networks, with the goal of enhancing environmental performance while optimizing logistical operations. It is important to emphasize that this study aims to provide a methodology to support the implementation of the PI, serving as a tool for stakeholders rather than prescribing specific investments or decisions. In practice, these decisions are typically made collaboratively by multiple parties involved in urban logistics.

Under the concept of PI, the urban territory is divided into unit zones, which are grouped into local cells and further clustered into urban areas, forming a multi-level urban service region as demonstrated in Figure 1 (a). Among these, unit zones represent the smallest service regions. Their scale and form vary based on local context, which could range from an industrial site, residential block, or airport to designated areas within a multi-story building (Montreuil et al., 2018). In most cases, these zones can be visualized as compact, adjacent polygons on a geographic map.

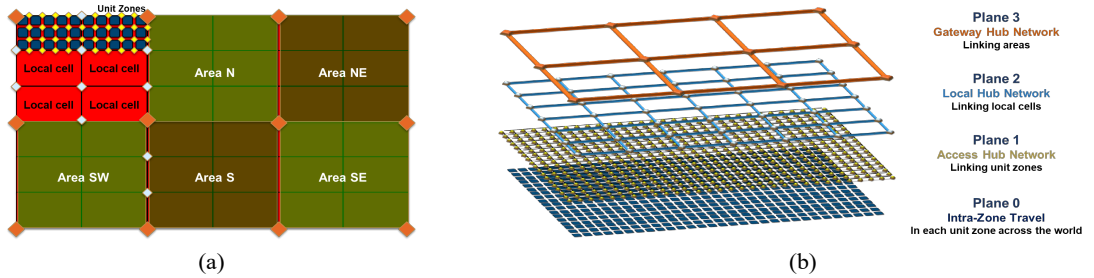


Figure 1: Hyperconnected urban logistic network in generic urban region (Montreuil et al., 2018)

Building upon this, multi-tier hyperconnected urban logistic networks can be defined. As illustrated in Figure 1 (b), there are four planes of interconnected meshed hub networks: gateway hub network, local hub network, access hub network, and intra-zone network. Each tier is designed to facilitate efficient freight movement, ensuring seamless consolidation and transfer between its corresponding service regions. In this paper, we focus on the delivery operations associated with network layers 1, 2, and 3, assuming that these deliveries are containerized. Instead of handling freight directly, modular, and standardized containers are consolidated at hubs, in line with the PI-container concept, which aims to streamline logistics operations and reduce handling times. Once containers reach the access hubs, couriers unload the packages and carry out final deliveries to customer-specified locations using intra-zone travel within plane 0; however, this last layer of operations is out of the scope of this work.

To assess the performance of hyperconnected urban logistic networks, we further propose a dynamic capacity management model to operate containerized deliveries within the network. Inspired by the open resource sharing concept from PI, this study considers dynamic vehicle sharing and repositioning, which collectively utilizes various sizes of vehicles among the same-level logistic hubs for urban containerized deliveries. Unlike traditional vehicle routing problems that require vehicles to return to their original hubs, our model provides scheduled

service routes that enable vehicles to be dynamically repositioned based on fluctuating demand patterns. To achieve environmental sustainability, our routing strategy involves the coordinated use of two primary types of electric vehicles: 1) high-capacity electric semi-trailer trucks for longer-distance transfers between gateway and local hubs, and 2) smaller delivery vans for agile, localized distribution between local and access hubs. We note that the capacity in our context is related to number of scheduled service routes and delivery vehicles in the network.

4 Methodology

To build a multi-tier hyperconnected hub network, we first design PI-enabled multi-level service regions, consisting of unit zones, local cells, and urban areas. In this work, unit zones are defined using the boundaries of census tracts, which are relatively homogeneous units in terms of population characteristics and economic status, identified by the U.S. Census Bureau.

4.1 Designing Multi-Level Service Regions

To cluster unit zones into local cells, we propose a demand-balanced spectral clustering algorithm, detailed in Algorithm 1. By using spectral type clustering, this ensures geographical connectivity (Ma'arif, 2016) while balancing logistics demand across multiple service regions.

Algorithm 1: Demand-Balanced Spectral Clustering

Input: graph, target number of regions, minimal number of neighbors,
number of iterations.
Build spatial adjacency graph;
Apply spectral clustering to assign initial regions;
for $i \leftarrow 1$ **to** number of iterations **do**
 foreach region **do**
 if region is overpopulated **then**
 foreach tract in the region **do**
 if moving the tract to a neighboring region improves balance
 and meets connectivity & compactness constraints **then**
 Accept the move;
 break;
 if region is underpopulated **then**
 foreach tract in a neighboring region **do**
 if importing the tract improves balance and meets connectivity
 & compactness constraints **then**
 Accept the import;
 break;
return region clustering results;

Specifically, the algorithm begins by constructing an adjacency graph from geographic data and applying spectral clustering to generate an initial set of local cells. It then iteratively balances demand by removing unit zones from overpopulated local cells and assigning them to underpopulated ones. Each move is validated to satisfy two constraints: (1) graph connectivity and (2) compactness of the resulting local cells. To measure compactness, we count the number of neighboring unit zones within each local cell. A minimum-neighbor constraint is enforced during each adjustment to maintain compact cell shapes. Correspondingly, this same algorithm is then applied to cluster local cells into urban areas.

4.2 Designing Multi-Tier Hyperconnected Hub Networks

After defining the multi-level service regions, we construct the multi-tier hyperconnected hub network. We begin by identifying a broad set of potential hub locations for each tier. These

candidates are then refined through specialized algorithms that assess their suitability based on specific criteria for each hub type and its intended function.

Access hubs, which are smaller and more adaptable, can be situated in a range of locations as long as there is sufficient space to accommodate mobile hubs. In contrast, local hubs, which serve as secondary consolidation points, and gateway hubs, which handle large volumes and longer-distance transfers, require more specific facilities to ensure practical feasibility, operational efficiency and seamless integration into the broader logistics system. To identify suitable locations for local and gateway hubs, we leverage CoStar, the leading platform for verified commercial real estate information, analytics, and data-driven news. CoStar enables us to filter potential sites based on criteria such as listing type (sale or lease), available space, and specific amenities. For gateway hubs, which need to accommodate large vehicles like trucks, we prioritize locations with essential features like docking stations, sortation areas, secure parking, and rest stops. This data-driven approach ensures that the selected hubs meet both functional and operational requirements, enhancing overall efficiency of the logistics network.

4.2.1 Gateway Hub Networks

The gateway hub network forms the backbone of the multi-tier urban logistics system, designed to handle the largest volumes and facilitate long-distance transfers between urban areas. To establish this critical layer, we begin by identifying candidate gateway hub locations within each urban area using CoStar. Then, we identify the clusters of these facilities and refine this using a k-medoids clustering approach, which selects the most representative cluster based on spatial distribution and expected throughput, ensuring efficient coverage of each urban area. In contrast, defining the local and access hub networks involves far more candidate locations and more complex decisions regarding their service regions and precise placements, making simple clustering approaches insufficient. Therefore, for these two layers, we employ large-scale network design optimization models to ensure that the overall system achieves high levels of efficiency, scalability, and robustness under varying demand conditions.

4.2.2 Access Hub Networks

Access hubs serve as first-tier consolidation points for shipments from unit zones, typically located within or near these zones. When strategically positioned at the intersections of multiple zones, they enhance network resiliency by supporting several zones simultaneously. However, the dense and complex nature of urban infrastructure often results in a large number of candidate locations around each unit zone, making the identification of viable access hubs challenging. To address this, we apply the set-cover based optimization framework from Muthukrishnan et al. (2021). This approach begins by generating initial set of candidates from all intersection points of unit zone polygons and determining which zones each candidate can feasibly serve by defining a geo-specific threshold that adapts to the local density of unit zones. Then, two critical parameters guide the selection of process of potential hubs

- α_u : the minimum number of hubs that should be accessible to each unit zone, ensuring operational resilience
- β_h : maximum number of zones each hub can support, controlling load distribution across the network

The model assumes modular capacity at access hubs, aligning with Physical Internet principles, and aims to minimize the combined costs of daily courier operations, hub establishment, and modular capacity deployment. This approach significantly reduces the candidate pool, identifying potential locations that are several orders of magnitude smaller than the initial set.

4.2.3 Local Hub Networks

Once potential access hub locations are identified, the next step is to select local hub locations, which serve as intermediate consolidation points between access hubs and gateway hubs. This requires considering physical distances and directional flow patterns to minimize operational costs. However, to keep the initial selection tractable, we focus on key capacity and connectivity criteria to other tiers at this stage, leaving detailed routing and vehicle assignment decisions for later, when precise inter-hub flow modeling is performed.

Similar to the gateway hub design, we start by identifying initial candidate facilities for local hubs using CoStar, applying filters based on specific operational requirements like available space and handling capacity. We then determine which local cells each hub can potentially serve, excluding intra-cell flows, which are assumed to be handled by access hubs. Next, we classify the freight flows handled by local hubs into two main categories:

- **Intra-Area Flows** - Shipments moving between local cells within the same area - *typically between access hubs in each local cell with local hub as intermediate points*
- **Inter-Area Flows** - Shipments moving between local cells across different areas - *typically between local hubs with gateway hub as intermediate point*

We then apply the modified set-cover-based network flow model (Muthukrishnan et al., 2021), defining two critical parameters similar to the access hub model, to minimize the combined costs of hub establishment, capacity deployment, and inter-hub operations between local hubs and access/gateway hubs, while meeting both intra and inter-area flow requirements.

4.3 Evaluation of Proposed Network

To evaluate the performance of the proposed network, we formulate a two-echelon, multi-period vehicle routing and capacity management model that determines both vehicle assignments and freight routing across the urban logistic network. As noted in Section 3, all freight is transported within standardized containers. At each logistic hub, full and empty containers are directly swapped between vehicles. Based on network tiers, we predefine first- and second-echelon scheduled service routes connecting gateway, local, and access hubs. The model synchronizes container movements across the three-tier networks by enforcing flow conservation at each hub and ensuring vehicle availability for every scheduled service route. More specifically, vehicle routing decisions are coupled with container assignment, subject to echelon-specific vehicle capacity limits. The objective of this model is to minimize total delivery expenses, including transportation and handling costs, hub capacity costs, and penalties for outsourced deliveries. Overall, this optimization model enables operational planning for vehicle-to-service assignment and container routing in urban delivery settings.

5 Case study

5.1 Experimental settings

5.1.1 Estimating Freight Flows

In this study, we use the Atlanta metropolitan area as our testbed. We begin by estimating freight flows at the tract level to identify clusters of local cells and urban areas, which form the basis for selecting the three tiers of hubs: gateway, local, and access. To achieve this, we leverage the Freight Analysis Framework (FAF), which provides comprehensive estimates of the weight shipments across the United States, categorized by commodity types and transportation modes, using a system of 132 aggregated FAF regions.

To increase geographic granularity, we adopt a methodology similar to the experimental county-to-county commodity flow product recently developed by the Bureau of Transportation

Statistics (BTS). This approach uses population and labor force as production and attraction factors to disaggregate FAF region-level flows into county-level flows. For our urban logistics focus, we extend this further, converting county-level flows to tract-level flows using the same methodology. Finally, we aggregate these tract-level flows to form clusters representing local cells and urban areas, identifying potential candidates for each layer of hubs based on the methods detailed in the previous section.

5.1.2 Mapping Commodity Flows from Tract to Hub Level

To provide the origin-destination demand data for the capacity management model, we aggregate flows from region-to-region level into hub-to-hub flows. Prior to this mapping, the FAF flows are classified into the following categories: External FAF regions to Metro Atlanta Tracts, Metro Atlanta Tracts to External FAF regions, Between Metro Atlanta Tracts. Given the high spatial granularity of the urban area and the complex nature of hub assignment based on directionality and flow volumes, we adopt a structured mapping strategy that reflects one possible logistics routing behavior in this study context:

- **External FAF Regions to Metro Atlanta Tracts:** These flows are modeled as originating from the nearest gateway hub to the external FAF region and are distributed among access hubs that can feasibly serve the receiving tracts.
- **Metro Atlanta Tracts to External FAF Regions:** These flows are modeled as departing from access hubs associated with the sourcing tracts and are destined to the nearest gateway hub that connects to the External FAF region.
- **Between Metro Atlanta Tracts:** These flows are categorized into high and low volume origin-destination pairs based on a predefined threshold:
 - **Higher Volume Flows:** Mapped between local hubs assigned to serve the tracts, prioritizing the local hubs that are aligned with the flow direction to avoid detours.
 - **Lower Volume Flows:** Mapped among multiple access hubs assigned to the tracts.

We remark that when multiple hubs are feasible for either origin or destination, individual flow volumes can be split and assigned across these hubs. Ideally, such assignments could be guided by probability distributions based on empirical data (e.g., service frequency, hub available capacity, or observed routing patterns). However, since the lack of detailed information at this stage, we currently use uniform random allocation among the feasible hubs.

For the network logistics performance experiments, we consider a 3-day planning horizon. We assume that each first-echelon electric truck can carry up to 10 containers, and each second-echelon electric delivery van can carry up to 4 containers. Moreover, each container is designed to carry a maximum of 1.5 tons of freight. In this paper, due to computational tractability, we focus on freight flow from gateway to access hubs within a region instance with 3 urban areas.

5.2 Results

Figures 2 and 3 present the service region clustering and three-tier hub selection results for Metro Atlanta area. The result includes 1,248 unit areas, which are clustered into 100 local units and 10 urban areas according to empirical testing. These parameters can be adjusted to reflect the scale and characteristics of specific regions under consideration. It can be seen from Figure 2 that the proposed Algorithm 1 yields clusters with strong graph connectivity and spatial compactness, while the freight flows across regions are well balanced. In addition, we observe that service regions near city boundaries tend to be larger, whereas those in downtown areas are smaller. This variation in service area sizes is reasonable from a logistics management perspective, as densely populated urban cores typically experience higher demand and greater traffic congestion, necessitating finer regional divisions. In Figure 3, a total of 10 gateway hubs

are identified, all strategically located near major highways. The optimization model then selects 109 local hubs and 1,122 access hubs, situated at the intersections of local cell and unit zone boundaries, respectively.

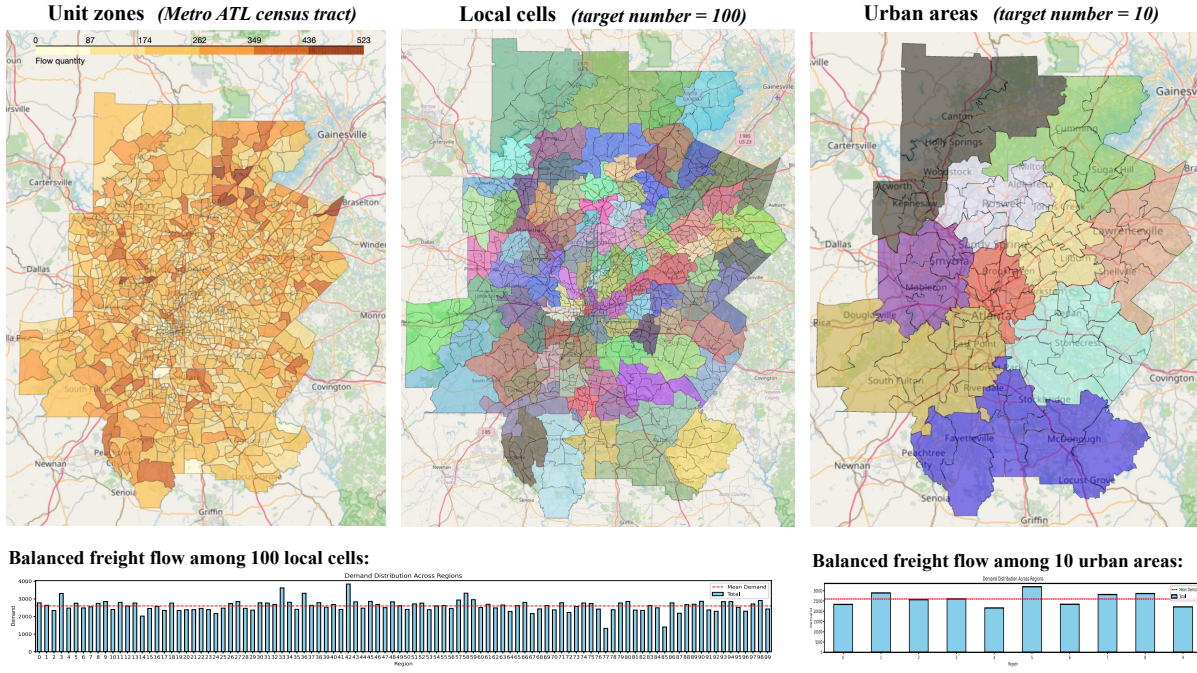


Figure 2: Hyperconnected service region division results

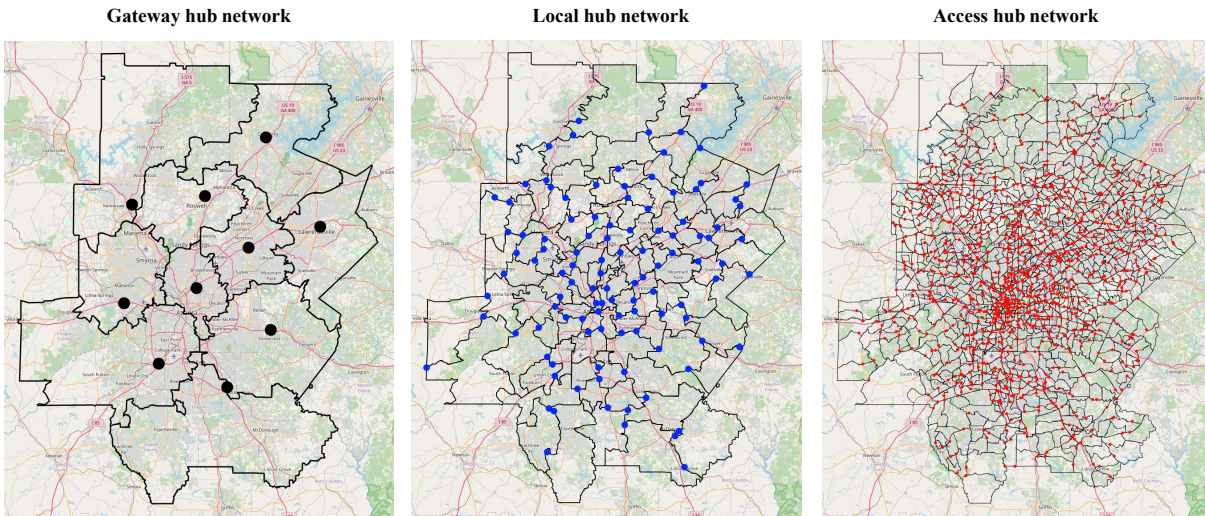


Figure 3: Hub selection results for gateway, local, and access hub network

In the case study, we compare two transportation approaches: 1) direct transportation using a classical end-to-end network, where freight is transported directly from sources to destinations without intermediate handling or consolidation, and 2) hyperconnected transportation, where freight is routed through the proposed three-tier hyperconnected hub network to enable consolidation and relay operations. As shown in the multi-layer visualization of Figure 4, the hyperconnected network features both vertical and horizontal connectivity, structured according to service region assignments and distance-based thresholds. Then, comparing the two network configurations shown on the left side of Figure 4 reveals that arcs in the hyperconnected network are significantly shorter than those in the end-to-end network, indicating more consolidated and efficiently organized freight flows.

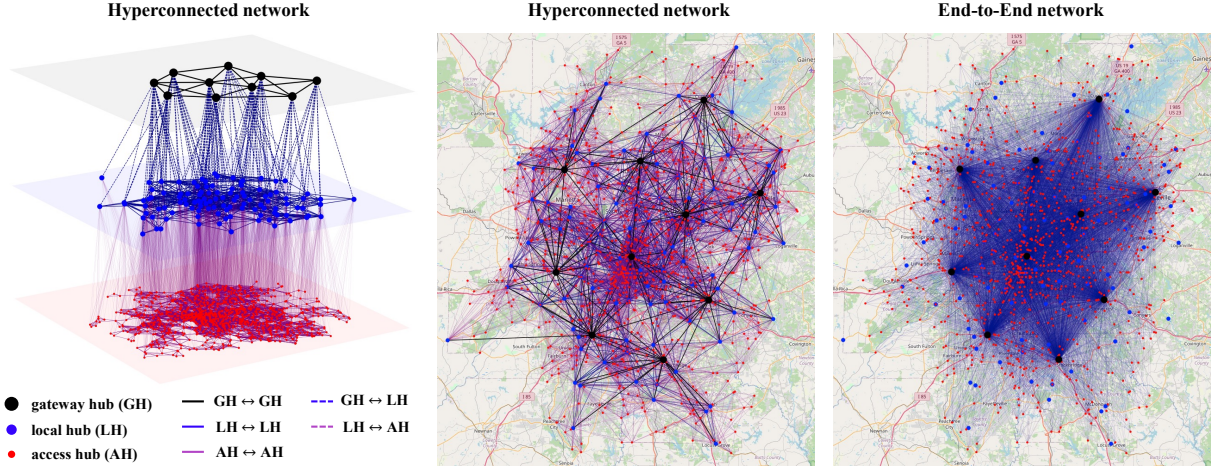


Figure 4: The resulting three-tier hyperconnected network and the corresponding end-to-end network

To quantitatively evaluate the logistics performance of the hyperconnected urban logistic network against the end-to-end network, we solve the proposed capacity management model to test freight operations in two networks. Table 1 summarizes the comparative results of detailed performance metrics across four key dimensions.

Field	Performance metrics	End-to-End network	Hyperconnected network
Network & Service	# of scheduled service routes per day	1,208	1,782
	Average # of service routes per hub per day	402.67	46.89
	Travel time per day (hours)	1,043	515
	Travel distances per day (miles)	37,512	16,818
Operation Efficiency	Service route delivery efficiency	3.24	22.76
	Service route overall truck fill rate (%)	34.92	53.18
Environmental Impact	Fuel consumption per day (tons)	23.47	11.60
	CO ₂ emissions per day (metric tons)	65.14	32.21
Cost Metrics	Total cost per day (\$)	42,230	38,791
	Transportation cost per day (\$) (percentage (%))	41,717 (98.79)	32,475 (83.72)
	Hub cost per day (\$) (percentage (%))	512 (1.21)	5,822 (15.01)

Table 1: Network performance comparison - hyperconnected network vs end-to-end network

As shown in Table 1, while the hyperconnected design involves more scheduled service routes, it achieves a 50.62% reduction in daily travel time and a 55.17% decrease in travel distance, due to the introduction of local hubs for consolidation and transshipment. In terms of operational efficiency, the hyperconnected network delivers over seven times the delivery efficiency (i.e., total number of delivered containers divided by total travel time) and improves the overall truck fill rate by 18.26%, reflecting efficient freight consolidation. Environmentally, the hyperconnected network reduces daily fuel usage and CO₂ emissions by more than half, highlighting significant sustainability gains. Finally, the total daily cost is reduced by 8.14%, primarily driven by lower transportation expenses. Overall, these results demonstrate that the hyperconnected network provides both economic and environmental benefits in urban logistics.

6 Conclusion

In summary, this study presents a methodology for designing and capacity-managing PI-enabled hyperconnected urban logistic networks, combining a three-tier hyperconnected hub

network, containerized urban deliveries, and dynamic vehicle sharing to provide a more sustainable and efficient solution for urban freight operations. Our case study demonstrates that by shifting from end-to-end transportation to a hyperconnected configuration, cities can more effectively accommodate growing freight volumes while reducing their carbon footprint.

For future work, we will generalize the capacity management model to capture multi-directional freight flows across all network tiers, providing a more realistic representation of urban logistics. Moreover, we will explore advanced solution approaches, such as column generation, to improve the scalability and computational efficiency of the proposed model. Finally, we plan to develop a simulation tool, potentially using agent-based modeling, to emulate detailed freight flows within the Metro Atlanta area, incorporating road network constraints, vehicle routing with hub processing dynamics, and time-dependent traffic conditions.

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The Physical Internet: Research Trend Analysis Through Natural Language Processing

Muhammad Ilham Fahreza¹ and Enna Hirata¹

Graduate School of Maritime Sciences, Kobe University, Kobe, Japan

Corresponding author: rezananda2009@gmail.com

Abstract: *The Physical Internet (PI) is a revolutionary concept in the logistics sector that has emerged over the past decade. It aims to develop an integrated network that emphasizes sustainability and efficiency to achieve interoperability and a collaborative global logistics system. To achieve this, numerous studies have been conducted addressing various aspects of the PI. However, understanding how PI research is currently developing and which directions it focuses on remains limited. Thus, a comprehensive analysis of past PI research is needed. This study aims to analyze the research trend of the PI by identifying the current state of research and under-researched aspects using natural language processing techniques. Relevant PI-related papers were obtained throughout the years from numerous journals and served as the dataset for this research. The data were reconstructed and filtered through natural language processing (NLP) to retain only relevant information. It is further analyzed using BERTopic, a machine learning technique based on Bidirectional Encoder Representations from Transformers (BERT). The analysis produced several topics that represent focus points in PI research. These topics highlight research trends and indicate areas that can be evaluated, offering better insights for future research related to the Physical Internet.*

Keywords: *Physical internet, machine learning, natural language processing, bertopic.*

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

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

1 Introduction

The logistics sector plays a vital role in society as it ensures the movement of goods and services to maintain economic stability, both locally and globally. One of the most important aspects of this sector is the logistics network. True to its name, a logistics network acts as a distribution system that delivers products from manufacturers to customers. However, the current system faces multifaceted challenges, including greenhouse gas emissions, traffic congestion, and poor working conditions in the labor force (Sternberg and Norrman, 2017). These challenges make the current system increasingly unsustainable.

This unsustainability calls for transformation. One such alternative is the Physical Internet (PI), a system built through the utilization of the concept and architecture of the Digital Internet to create an open, standardized, and interconnected network (Montreuil, Meller and Ballot, 2012). Similar to the Digital Internet, PI delivers goods using standardized means to create

interconnected networks operated in a modular and collaborative fashion (Ballot, 2019). PI standardization encompasses protocols, modular containers, and interfaces to push for an increase in efficiency and sustainability (Sternberg and Norrman, 2017).

PI aims to create a global logistics system through the integration of assets and operations. It includes distribution, collaborative warehousing, and dynamic routing through open-access networks and modular packaging (Ballot, Montreuil and Zacharia, 2021). Despite this, PI as a concept is still in its infancy. Although numerous studies have been conducted, several aspects remain under-researched, including business models, implementation roadmaps, and the effects of implementation itself (Sternberg and Norrman, 2017).

Due to these deficiencies, conducting a systematic review and analysis of PI's current state becomes a necessity. The analysis will give a better insight into PI's research trends. One of the recently popular techniques for large-scale data analysis is Natural Language Processing (NLP), a machine learning method that implements algorithms on data to uncover information not previously identified (Lauriola, Lavelli and Aioli, 2022). One of the NLP-based models is BERTopic, a machine learning technique developed by Grootendorst (2022) to generate representative topics from text data to uncover new insights.

This study applies NLP through the BERTopic model to analyze current research trends of the PI. Findings from the analysis will be used to evaluate the current research focus and uncover potential areas for future research. The remainder of this study is organized into several sections: Section 2 reviews past studies on PI and NLP. Section 3 details the data and methodology. Section 4 presents the findings and identifies key themes and gaps. Section 5 concludes the study and offers recommendations for future research.

2 Literature review and research gaps

Several relevant past studies have been reviewed in this paper. This includes several studies related to the physical internet, in particular, past studies regarding the literature review of the physical internet and studies related to the utilization of natural language processing.

2.1 Studies related to Physical Internet

Studies about PI have become a growing interest due to its potential to change the existing condition of the logistics network. This interest produced numerous studies that have led to several studies with the main priority of conducting a literature review and an analysis to know the current state of PI and the potential future development of PI research itself.

Numerous studies utilize various methods to come to their conclusions. Sternberg and Norrman (2017) reviewed 46 papers through expert judgment and literature review to provide a future research outline for the PI. They found that while PI has potential as a concept, there is a deficiency in defining its potential under practical application and uncertainty in its contribution to logistics sustainability. Another study by Treiblmaier et al. (2020) found through a systematic literature review of 148 publications that the most pressing issue for PI is the development of a structured framework for future guidance of PI research.

Chen, Su and Cheng (2022) analyzed 88 publications to identify key themes and existing gaps in PI research. Although the study shows seven research clusters and five methodologies that have been used, it also states the lack of studies that bridge the theoretical and practical approaches. Nguyen et al. (2022) conducted a study through a large-scale bibliometric mapping of 518 papers on PI and Digital Twin in supply chain management. They concluded that PI research still lacks cohesiveness due to the high dispersion across numerous research fields, with few bridging aspects for the research. Meanwhile, Aron and Sgarbossa (2023) focused on

the aspect of PI's resilience by conducting a review analysis of 27 papers. They concluded that the study on PI's resilience is still in its infancy, hinting at the potential for PI research.

Even though these studies gave an insight regarding the state of PI research in its current condition, one limitation consistently appears: the limited scope of the reviewed studies. This potentially creates a condition where some important key aspects of PI research have not been discovered yet. Thus, a large-scale analysis is needed to gain a thorough knowledge of the current state of PI research and what can be improved or focused on in the future.

2.2 Studies related to natural language processing

Natural Language Processing (NLP) is one of the novel methods that focuses on analyzing large text-based datasets. The ability of NLP to process the data and extract useful information has made it highly useful for exploring previously under-researched or less understood topics, such as the Physical Internet (PI). Among the many models under the NLP umbrella, BERTopic stands out for its effectiveness in uncovering key topics from large textual datasets.

BERTopic was utilized by Saidi, Trabelsi and Thangaraj (2022) to identify and classify Twitter (now X) profiles associated with terrorism. Meanwhile, Hirata and Matsuda (2023) utilized BERT to analyze the sentiment of the public on logistics-related tweets during the COVID-19 pandemic, highlighting NLP's ability to provide an outlook in logistics. A similar study by Karabacak and Margetis (2023) used BERTopic to find prevalent research topics in spine studies. Meanwhile, Ma et al. (2024) utilized BERTopic to analyze user reviews from online food delivery services, revealing overlooked topics such as corporate responsibility. Raman et al. (2024) conducted a scientometric review of artificial intelligence using BERTopic in the academic field, while Verbytska (2024) applied it to media reporting style, revealing narrative biases in Western and Eastern coverage of the Russia-Ukraine war.

These studies highlight the strength of BERTopic in revealing hidden or uncovered topics that can provide deep insight into various research fields. Given these advantages, the application of BERTopic to PI research potentially reveals uncovered areas and provides a comprehensive, data-driven understanding of the field.

2.3 Research gaps

As mentioned before, NLP, in particular, BERTopic, have proven to be one of the leading methods in analyzing large datasets to extract important information, including key topics from PI studies. Past studies, including Sternberg and Norrman (2017), Treiblmaier et al. (2020), and Aron and Sgarbossa (2023) may have revealed several insights regarding PI. However, those studies still rely on conventional methodologies, such as systematic review or bibliometric analysis, which depend on smaller data. Therefore, it limits their capability of analyzing PI. Meanwhile, NLP methods have been successfully utilized in other research fields, including logistics-related social media (Hirata and Matsuda, 2023), AI in the academic field (Raman *et al.*, 2024), and a bias analysis on the media (Verbytska, 2024). In those studies, BERTopic showed its strength by consistently revealing topics from large data. Given its clear advantage to handle large-scale data and its effectiveness in uncovering topics, BERTopic has great potential to be utilized to uncover numerous PI-related topics that might exist.

3 Methods

This methodological approach for this study consists of four steps: (1) data collection, (2) data preprocessing, (3) topic modelling and clustering, and (4) visualization. Data collection involves the compiling process of a large dataset that consists of past research and academic

publications that revolve around the PI concept using selected queries to capture all related research.

The second step is preprocessing. This step involves NLP techniques that include tokenization, the removal of non-essential elements, and lemmatization. This ensures that the content in the dataset will consist only of relevant texts and will not generate any potential noise or disruption to the next step of the analysis. Topic modelling is the next step that is performed using BERTopic, a derivative of BERT, which in itself is one of the NLP models. After topics are generated through BERTopic, the final step will be visualization. This step involves Uniform Approximation Manifold and Projection (UMAP) for reducing the dimension of all the generated topics so that they can be projected into a two-dimensional space. Another part is Hierarchical Density-Based Spatial Clustering of Applications with Noise (HDBSCAN) for clustering all the topics. These steps can be further examined in Figure 1.

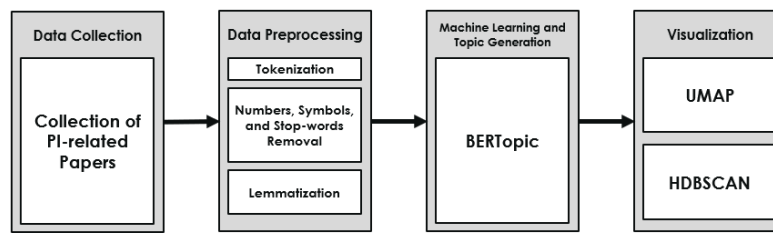


Figure 1: Methodologies of The Research

3.1 Data collection

The data collected in this research consists of PI-related research and publications. Through the compiling process, 5,151 papers were obtained and became the basis of the dataset. The dataset was obtained through a Python-based metadata retrieval method using the ScienceDirect Application Programming Interface (API). To obtain relevant publications, certain search queries were applied. Keywords such as "Physical Internet", "Cyber-Physical Internet", "logistics networks", "synchromodality" were used. After initially obtaining 4,755 papers, those that do not have accessible content and a full text version were filtered, bringing down the number to 3,043. This dataset was then combined with another existing dataset of 2,626 papers. These combined datasets were further refined to remove any redundant paper that exists in both datasets, resulting in a final number of papers in the dataset of 5,151.

The dataset will be used as the basis of the next step in the NLP-based analysis, providing bigger data to be analyzed so that a more comprehensive analysis can be performed. This dataset forms the foundation for the subsequent NLP-based topic modelling analysis, offering a comprehensive and chronologically appropriate representation of scholarly work on the Physical Internet.

3.2 Data preprocessing

The dataset was then analyzed using NLP techniques to filter out irrelevant information and provide a clean dataset for further analysis using BERTopic. This step can be considered paramount since failure to do preprocessing would result in the model of the BERTopic being trained using irrelevant words that have no connection to PI research. This may result in topics that have little or no relevance to the PI's research. Figure 2 explains the full workflow of the preprocessing that was applied to the research. This includes tokenization, removal of

unnecessary elements, and lemmatization. The data preprocessing consists of several sub-steps as outlined below:

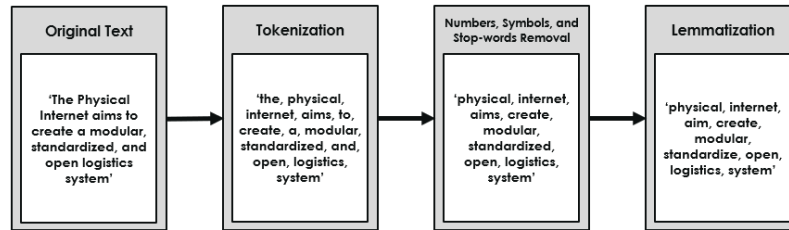


Figure 2: Steps of Data Preprocessing

3.2.1 Tokenization

The first step of data preprocessing is tokenization. It splits a sentence into individual words that will be known later as tokens, enabling the BERTopic to process each token and allocate them into separate, unique units. For example, a sentence such as: "The Physical Internet aims to create a modular, standardized, and open logistics system." would be tokenized into: "the, physical, internet, aims, to, create, a, modular, standardized, and, open, logistics, system". The tokenization process was done using the Natural Language Toolkit (NLTK) library in Python to tokenize all of the papers in the dataset.

3.2.2 Removal of non-essential elements

Once the tokens have been generated through the process of tokenization, non-essential elements such as numbers, special characters, and stop words are removed. This is very important because those elements might generate noise in the process that would reduce the accuracy of the machine learning process. Applying this filtering to the previous tokenized example results in: "physical, internet, aims, create, modular, standardized, open, logistics, system".

3.2.3 Lemmatization

The final step of data preprocessing will be the lemmatization process. It turns each token into its base form, also known as the lemma, to streamline every word that shares the same root form but may come in a different form due to certain grammatical rules. For example, words like 'eat', 'ate', 'eating', and 'eaten' would be streamlined into one root form, 'eat'. Taking the previous example as the sample, a final set of purified tokens will be: "physical, internet, aim, create, modular, standardize, open, logistics, system". After this process, the dataset will then be ready to be utilized and analyzed using BERTopic to produce a meaningful outcome.

3.3 Machine learning and topic generation

The next step in this research will be machine learning and topic generation. The dataset that has been transformed into lemmatized tokens in the preprocessing stage will be used to train the BERTopic to generate relevant topics. BERTopic, as a direct derivative of BERT, further improve this capability by integrating BERT-based document embeddings with Class-Based Term Frequency-Inverse Document Frequency (c-TF-IDF), a method used to produce interpretable topic representations from a dataset (Grootendorst, 2022). The basic operation of BERTopic can be divided into three steps. First, the dataset will be changed into a series of vectors with numerical values assigned to them that will be called embeddings using a language model. Next, the dimension of all the vectors will be reduced into low-dimensional embeddings using UMAP to enable an easy clustering process. Third, HDBSCAN will be applied to identify

each cluster from similar vectors. The last step will be the topic generation process using a c-TF-IDF algorithm to produce unique topics that will serve as the result.

BERTopic is essential in uncovering the important topics that might represent the current research trend in PI, and it might also indicate the under-researched theme through the lack of appearance of the said theme in the result. The large dataset analysis also ensures a comprehensive analysis and gives an even bigger picture to PI research itself. Figure 3 will give a complete illustration of how the machine learning process through BERTopic will be conducted.

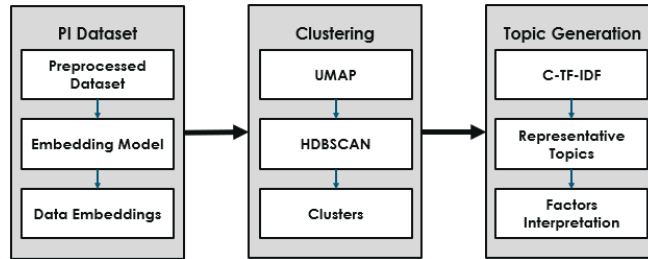


Figure 3: Steps of BERTopic Analysis

3.4 Visualization

The final step in the analysis is the visualization of the results obtained from the BERTopic analysis. This enables the complex output from the analysis to be visualized in an interpretable form, thus allowing for easier analysis and identification of the result of research trend analysis of PI studies. This step can be done by utilizing UMAP and HDBSCAN from BERTopic as mentioned before. UMAP is utilized due to its ability to preserve local and global structures of high-dimensional data. This enables the high-dimensional data to be represented with a high degree of accuracy in two-dimensional form. The key advantage of HDBSCAN is its ability to treat any noise that might appear as outliers and prevent it from being clustered with other groupings, thus increasing the accuracy of the clusters themselves and leading to more meaningful topic representations (Grootendorst, 2022). The final output of this step is the topic and cluster map from the analysis that can be further interpreted for the PI research trend and reveal other relevant information that might help with the research development of PI in the future.

4 Results and Discussions

4.1 Topic generation

Through the BERTopic analysis, 36 topics were identified. These topics contain important keywords that can be further interpreted to fully understand the current state of PI research and also to provide an overview of the current research landscape on PI itself.

4.2 Topic coherence and topic diversity score

To validate the accuracy of the generated results from BERTopic, topic coherence and topic diversity score need to be calculated. Topic coherence mainly revolves around how meaningful the words are within specific topics, whereas topic diversity is the proportion of unique words across all topics (Grootendorst, 2022). The topic coherence score ranges from 0 to 1, with values closer to 1 indicating a high degree of similarity among each topic, which makes it easier to

interpret. Meanwhile, the topic diversity score also ranges between 0 and 1, with higher values indicating a good composition of unique words.

From the analysis, the score for topic coherence is 0.6543, and the score for topic diversity is 0.6189. Both of these values indicate that the result generated by BERTopic has a good balance in terms of topic interpretability and also how unique the words that represent each topic are. This enables a meaningful interpretability and analysis later on the topics and clusters that were produced from the analysis.

4.3 Visualization result

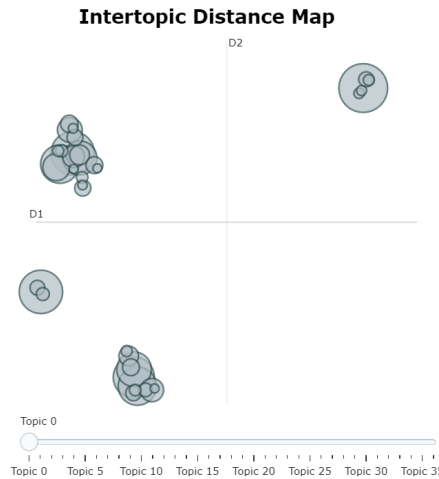


Figure 4: Clusters Generated from BERTopic Analysis

The topics generated are visualized using UMAP and HDBSCAN. As shown in Figure 4, the visualization grouped all 36 topics into four distinct clusters. These clusters represent the current research focus of the PI's research. The clusters are outlined as follows:

Table 1: Clusters formed from the BERTopic analysis

Cluster	Topics	Cluster's Focus
Cluster 1	0, 20, 27, 30, 31	This cluster mainly revolves around automation from a cyber-physical aspect, manufacturing, and industrial integration with PI technologies.
Cluster 2	2, 21, 23	This cluster mainly focused on transport, multimodal logistics, and the element of infrastructure within the PI-based networks.
Cluster 3	3, 5, 6, 10, 13, 16, 19, 22, 26, 28, 36	This cluster focused on innovation, sustainability, resilience, and traceability in the PI-based environment.
Cluster 4	1, 4, 7, 8, 9, 11, 12, 14, 15, 17, 18, 24, 25, 29, 32, 33, 34, 35	The broadest cluster in terms of scope. It represents other PI-related research aspects such as cybersecurity, IoT systems, microgrid integration, and smart governance.

4.4 Cluster interpretation

Table 2: Clusters formed from the BERTopic analysis

Cluster	Interpretation
Cluster 1 (PI node automation and industry integration)	Represented by Topic 0, this cluster highlights the role of industrial and cyber-physical systems in evolving logistics nodes into fully interoperable PI nodes. As outlined in the ALICE roadmap, this reflects Generation 3–4 of logistics node development, which involves automated node service requests and interconnectivity across networks
Cluster 2 (Freight movement and network configuration)	Mainly centered around the topic of freight optimization, multimodal logistics, and transportation flows. This represents the alignment of the research with the PI network vision, explained by ALICE (2020). This cluster represents the focus of the research on the synchromodal operations and intermodal flexibility.
Cluster 3 (Resilience, sustainability, and flow Innovation)	This cluster contains the research focus on PI-related aspects such as disruptions, perishable logistics, and recycling processes. According to ALICE (2020), those aspects focus mainly related to the system of logistics networks, which puts an emphasis on secure and efficient protocols to ensure and support the flows of goods.
Cluster 4 (Enabling technologies and frameworks)	The cluster contains topics mainly discussing PI-related technologies such as IoT, cybersecurity, and microgrids. Those topics support the development of access and adoption aspects, and also governance aspects.

4.5 Topics discussion

From the analysis, several results regarding the research trend can be analyzed, and it can provide evaluations and additional insight as to the current research focus of PI-related research. These results can be grouped into 5 main groups:

Table 3: Clusters formed from the BERTopic analysis

Key Dimensions	Interpretation
Logistics nodes (Upstream focus)	Currently, the main focus for the logistics nodes has always been on the upstream part. Most of the research only explores the transformations from a technological aspect within the industrial environment and the cyber-physical system. Leaving other studies, such as node interconnectivity or downstream-focused aspects, to be under-researched.
Logistics networks (Fragmented approach)	Logistics networks have been one of the most widely researched topics throughout the years. This, however, is not without problems since all the past research mainly focused on individual logistics networks. Thus, leaving interconnected logistics networks-related research under-researched.
System of logistics networks (Security aspect)	There is a gap in terms of research regarding the system-wide integration of logistics networks. Current research mainly discusses network security and challenges in

	interoperability. This resulted in under-researched aspects such as the interconnectivity of the networks and seamless operation within the PI-based logistics network itself.
Access and adoption	Aspects such as organizational readiness, trust-building mechanisms, or stakeholder education are rarely discussed, and this has resulted in the lack of research on those aspects, which can be deemed as important to the adoption of PI itself in the real world.
Governance of the Physical Internet	Based on the analysis of all the available PI-related publications, the governance aspect remains under-researched. Aspects such as standard-setting bodies, policy coordination, or regulatory frameworks have not yet been researched at an adequate level. This aspect is important in regulating and formalizing PI-related aspects in real-life implementation.

4.6 Research trend analysis

Based on the BERTopic analysis, a chronological analysis is also performed to reveal the research trends from 2011 to 2025. The analysis reveals that the nature of PI-related research keeps evolving. Early pioneer research from 2011 to 2014 mainly focused on network connectivity and cyberinfrastructure. Research from 2015 to 2019 shifted towards cybersecurity, sustainability and traceability. Between 2020 and 2024, the main focus was resilience and innovation, which indicates an increased interest in sustainable PI design and implementation.

5 Conclusion

This research utilizes BERTopic as part of the NLP methods as a way to analyze the trend of PI studies. Comprehensive methods such as data collection, data preprocessing, the BERTopic analysis, and visualization were applied, and 36 topics were obtained and clustered into four main clusters. These clusters were further interpreted to provide insights into the current research trend of PI and which area can be developed based on the key dimensions of the roadmap of PI. Based on further interpretation and analysis, it can be inferred that although considerable progress has been made in the research of PI, particularly in its technological aspects, several areas remain under-researched.

Research in the logistics nodes dimension mainly revolves around the upstream aspects, such as automation and digital transformation, leaving the downstream side underexplored. Meanwhile, the analysis from the logistics networks dimension found that current studies mostly focused on individual nodes such as transport or freight, while other aspects, such as integrated and interconnected networks, remain under-researched. From the access and adoption side, aspects such as organizational readiness, trust-building mechanisms, and stakeholder education are not fully researched. The least explored dimension will be from the governance side, in which little to no research has been conducted in aspects such as policy coordination, standard-setting bodies, and regulatory frameworks. The analysis from the research trend also found that aspects such as resilience and sustainability have grown; others, such as governance, interoperability, and adoption strategies, remain underexplored. These gaps can be utilized to provide a new focus to future PI-related research. Therefore, future development can be directed to provide robust academic findings that will support the implementation of PI in real-world situations in the future.

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Advancing the Physical Internet with GraphRAG: A New Way to Review and Integrate Existing Research

Hisatoshi Naganawa¹, Enna Hirata², Russell G. Thompson³, and Akira Yamada⁴

1. Faculty of Ocean Science and Technology, Kobe University, Kobe 658-0022, Japan
2. Graduate School of Maritime Sciences, Kobe University, Kobe 658-0022, Japan
3. Department of Infrastructure Engineering, the University of Melbourne, Australia.
4. Center for Mathematical and Data Sciences, Kobe University, Kobe 657-8501, Japan.

Corresponding author: enna.hirata@platinum.kobe-u.ac.jp

Abstract: *Physical Internet (PI) is an emerging concept that applies the digital internet as a design metaphor for the development of sustainable, interoperable, and collaborative freight transportation. It is considered a way to bring logistics into the next generation of transformation. Effective tools for organizing and integrating knowledge are essential for navigating the emerging research in this area. In this study, we explore the application of Graph Retrieval Augmented Generation (GraphRAG) in the context of PI, using GPT-4o mini and Neo4j to construct a knowledge graph and systematically analyze existing PI-related literature. Our approach synthesizes scattered research findings, highlights emerging trends, and identifies knowledge gaps. Furthermore, we demonstrate that GraphRAG improves accessibility by structuring complex information into interconnected graphs and provides a deeper understanding of underlying research dynamics. This research will contribute to future research and innovation by providing a new method of information analysis in the PI domain.*

Keywords: *Physical Internet, Natural Language Processing, Graph Retrieval Augmented Generation, Large Language Models, Graph database*

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

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

1 Introduction

Physical Internet (PI) refers to the concept of creating a sustainable global logistics network by incorporating the concept of the digital internet into the transportation and distribution of physical goods. It aims to improve efficiency, flexibility, and sustainability by redesigning existing logistics networks and utilizing information and communication technologies (ICT) alongside standardized logistics infrastructures. Almost fifteen years have passed since Montreuil et al. (2010) first introduced the PI concept, which has since progressed from a theoretical framework to active empirical research. Efforts to make PI a reality have gained momentum through international conferences (IPIC) and the development of roadmaps by national governments, including EU and Japan.

In this study, we apply a graph retrieval-augmented generation (GraphRAG) approach to gain deeper insights from the existing literature. GraphRAG is an innovative method that combines

information retrieval and generation technologies. It helps clarify relationships between data, efficiently retrieves the most relevant information in response to a query, and then generates new contents based on these results. This approach delivers powerful performance, especially for solving problems with complex data structures.

We aim to assess the potential contributions of existing structured research and theoretical frameworks by leveraging GraphRAG to analyze them. Specifically, we demonstrate how GraphRAG can support policy development and the formulation of research agendas to realize PI. This is the first application of GraphRAG in the context of PI-related studies. It offers a novel perspective and contributes to advancing this research domain.

The remainder of this paper is organized as follows: Section 2 presents a literature review. Section 3 describes the data used and the proposed methodology. Section 4 presents several results and compares them. Section 5 concludes and identifies areas of research.

2 Literature Review

2.1 Brief overview on Physical Internet

The concept of PI was introduced by Montreuil in 2010 (Montreuil et al., 2010). PI is an innovative concept that uses the digital internet as a design metaphor to foster the development of sustainable, interoperable and coordinated freight transportation (Sternberg and Norrman, 2017). The key concept behind the PI logistics system is to route highly modular containers to transit centers, known as PI hubs, to achieve a highly efficient transportation network that takes advantage of consolidation opportunities (Venkatadri et al., 2016). The concept of PI has attracted many stakeholders to support the development of logistics networks in the last few years; the literature on PI has increased dramatically over the past decade. Although summaries of past and future PI research are sporadically reported in recent studies (Aron and Sgarbossa, 2023; Ballot et al., 2021), now fifteen years after the introduction of PI, there is a growing need for an integrated method to efficiently organize the current research and address future research challenges.

2.2 Brief overview on generative AI

Artificial intelligence (AI) has attracted great attention in a variety of fields and industries (Hyder et al., 2019). Beginning with Alan Turing's basic concepts in the 1950s, AI has long gone through several stages of development and a period of stagnation, known as the AI winters (Turing, 2009). However, the global prominence of AI surged after OpenAI released its chat generation pre-trained transformer (ChatGPT) in late 2022. The GPT family uses huge data sets and large language models (LLMs) trained with deep learning techniques to generate human-like text (Cascella et al., 2024). GPTs excel at understanding context and processing diverse queries, but their main limitation is knowledge rigidity. It relies on existing training data and cannot incorporate real-time updates. Furthermore, when faced with unknown information, they struggle to provide factually accurate responses, often misleading or deriving incorrect content through inference. These limitations pose challenges for applications that require high reliability (McIntosh et al., 2024; Oviedo-Trespalacios et al., 2023; Rawte et al., 2023).

2.3 GraphRAG

One potential solution to this challenge is the use of GraphRAG, which has attracted considerable interest. GraphRAG is a technology that improves the accuracy of responses by adding the ability to search external databases to a LLM (Figure 1). Developed by Microsoft

researchers, GraphRAG was introduced in February 2024, and a reference implementation was made available on Github in July 2024 (Microsoft, 2025).

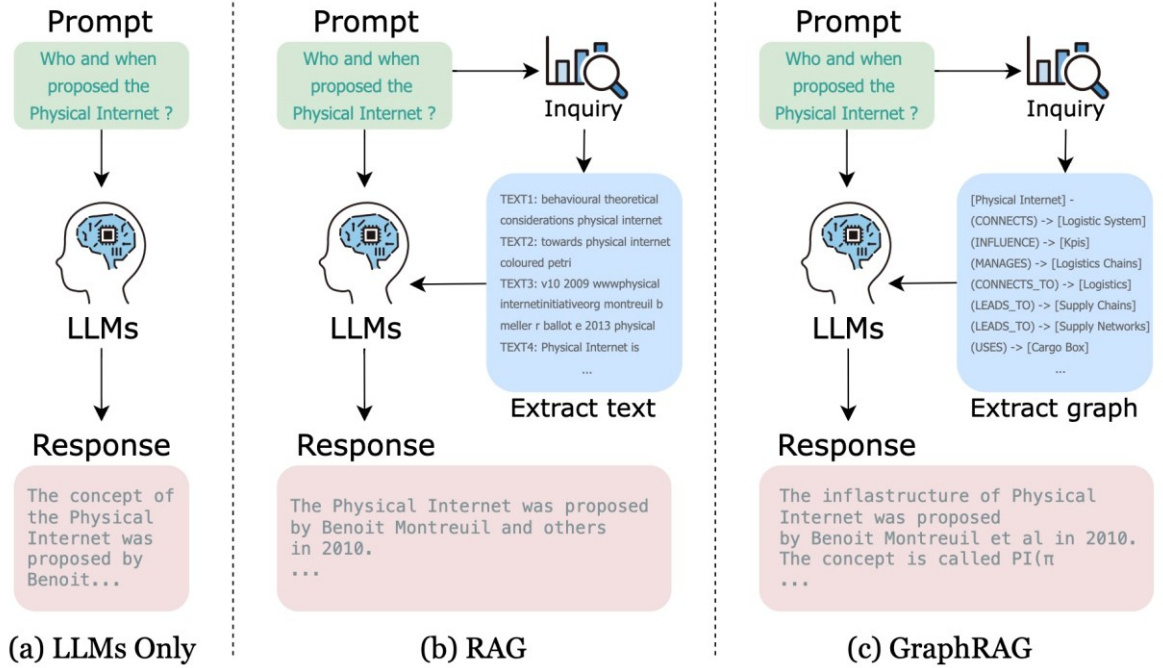


Figure 1: Different methods using LLMs

GraphRAG is an advanced form of retrieval-augmented generation (RAG) that enhances large language models by structuring retrieved information as a graph. In this graph, nodes represent concepts, and edges denote their relationships. This graph-based approach allows the model to better understand context, identify meaningful connections, and reason more effectively across multiple documents. It is particularly useful for complex tasks such as research synthesis and policy development. GraphRAG is relevantly new technology with a limited number of studies exploring its application. Li et al. (2025) propose to use GraphRAG to convert vast amounts of unstructured supplier capability data into a knowledge graph, thereby improving supplier discovery and making manufacturing suppliers more accessible and searchable. Ojima et al. (2024) present a knowledge management system for automotive failure analysis using GraphRAG.

3 Data

In this study, we create a knowledge graph (KG) specific to PI by integrating three data sets (Table 1). The first set consists of the proceedings of the international physical internet conference (IPIC) held from 2016 to 2024. The second set is the PI roadmap developed by ALICE (ALICE, 2020), and the third set is the PI roadmap for Japan prepared by the Ministry of Economy, Trade and Industry (METI, 2022). The IPIC proceedings were downloaded from the conference website since its inception; the ALICE PI roadmap was obtained from the ALICE website; and the Japan PI roadmap was obtained from the METI website. A Python script is used to convert PDF documents into text data for subsequent analysis.

Table 1: List of Contents

Contents	Year	Source and collection method
Proceedings of IPIC	2016 ~ 2024	Download from IPIC repository (IPIC, 2025)
PI Roadmap (ALICE)	2020	Download from ALICE website (ALICE, 2020)
PI Roadmap (Japan)	2022	Download from METI website (METI, 2022)

4 Methodology

The overall research flow is shown in Figure 2. It consists of data collection, preprocessing, response generation, and performance measurement.

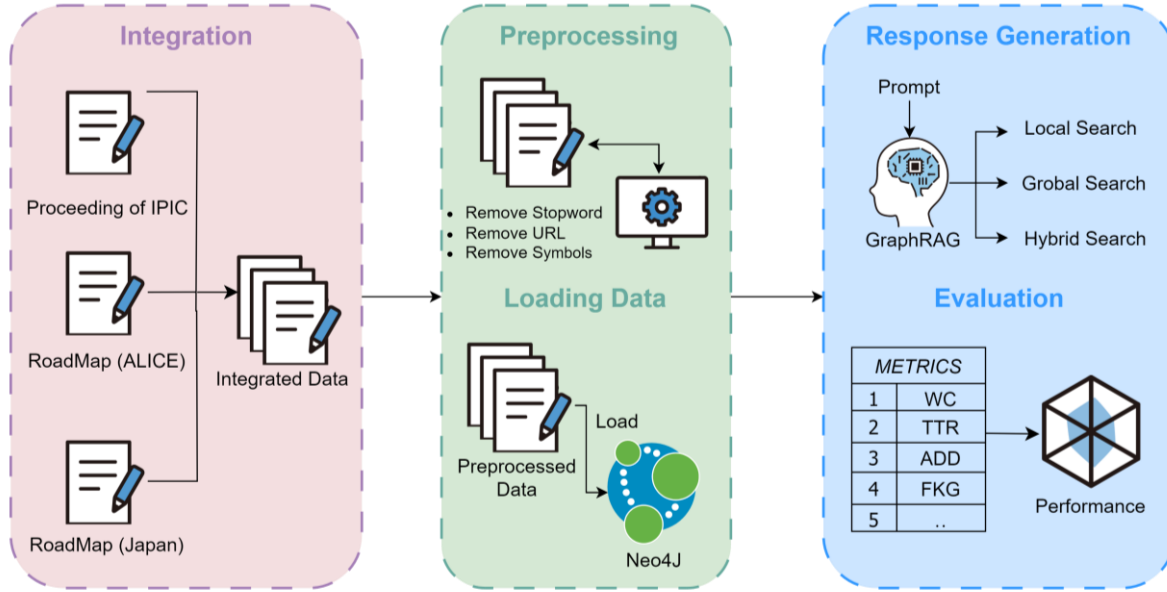


Figure 2: Different methods using LLM

4.1 Preprocessing

For preprocessing, we first integrate IPIC proceedings data and data from ALICE and Japan's PI roadmaps. The NLTK library is then applied to remove stop words, which include standard stop words and content specific stop words such as URLs, symbols, and other extraneous characters (*NLTK*). The resulting refined text data is then loaded into GraphRAG.

4.2 Response generation based on GraphRAG

GraphRAG is used to generate responses to the two prompts in four models: GPT-Only (I), Local Search (II), Global Search (III), and Hybrid Search (IV). Local Search (LS) model searches for nodes and edges in the graph that are semantically close to the query and retrieves directly related items from the graph database. Global Search (GS) model identifies clusters within the graph and provides a summarized view of the entire community relevant to the query. Hybrid Search (HS) model combines LS and GS to generate comprehensive responses with both specific examples and broader contextual information.

GraphRAG was created using neo4j desktop as the database and GPT 4o-mini as the LLM; the two prompts were created from two perspectives: promoting innovation and research, and practical implementation and social impact (Table 2).

Table 2: Prompt

No.	Prompt
1	Comparing to the ALICE and Japan roadmaps, what are the areas lacking in research focusing on Physical Internet?
2	Please provide concrete proposals for promoting the social implementation of the Physical Internet in Japan.

4.3 Performance metrics

The performance of each model is evaluated using five metrics (Table 3). Paraphrase-MiniLM-L6-v2 was applied to embed sentences, for the calculation of cosine similarity.

Table 3: Performance Evaluation Metrics

Metrics	Abbreviation	Description
Word Count	WC	Total number of words in a sentence.
Type Token Ratios	TTR	Measures vocabulary diversity.
Average Dependency Distance	ADD	Measures the distance of dependencies between words in a sentence.
Flesch-Kincaid Grade Level	FKG	Indicator for evaluating the readability.
Cosine Similarity	CS	An index that quantifies the degree of textual similarity. In this study, it is calculated based on responses generated by Model I (GPT-only).

5 Results and Discussion

5.1 Prompts and Responses

Following the definition explained in Section 4.2, the prompts are run in each of the four models, namely (I) GPT-Only, (II) Local Search, (III) Global Search, and (IV) Hybrid Search, and the results are shown in Table 4, 5.

Table 4: Response to prompt 1- Comparing to the ALICE and Japan roadmaps, what are the areas lacking in research focusing on physical internet?

Model	Output
I	While the ALICE and Japan roadmaps lay a solid foundation for the Physical Internet (PI), several research gaps remain. Key areas include the development of universal standards for interoperability, secure data-sharing mechanisms, and more robust sustainability metrics. There is also limited research on decentralized logistics models, which could improve resilience. Emerging technologies like IoT, AI, and blockchain need further exploration for integration into the PI framework. Additionally, workforce impacts, including job displacement and retraining, are insufficiently addressed. Lastly, economic models and funding mechanisms for PI adoption require more in-depth study.
II	The areas lacking in research focusing on the Physical Internet, when comparing the ALICE and Japan roadmaps, include a more comprehensive exploration of reinforcement learning applications, integration of logistics providers, and strategies for achieving emission targets. Additionally, there is a need for enhanced collaboration between stakeholders and a clearer definition of research innovation paths specific to the Physical Internet.
III	The areas lacking in research focusing on the physical internet, compared to the ALICE and Japan roadmaps, include insufficient exploration of protocols and methods for implementing digital internet functionalities within the physical internet framework. Additionally, there is a need for deeper analysis of resilience and efficiency in the transport of physical goods, as well as a focus on integrating IoT technologies for improved risk management in construction and logistics. Overall, there is a gap in addressing the complexities of logistics networks and the development of commercial data platforms that ensure seamless and transparent operations.
IV	The areas lacking in research focusing on the physical internet, compared to the ALICE and Japan roadmaps, include insufficient exploration of container development, hub inventory management, and the integration of Internet of Things (IoT) technologies in risk management within prefabricated construction. Additionally, there is a need for deeper analysis of protocols and methods for resilience and efficiency in transport concepts, as well as a more comprehensive understanding of the functionalities and attributes of road-based physical internet systems.

Table 5: Response to prompt 2 - please provide concrete proposals for promoting the social implementation of the Physical Internet in Japan.

Model	Output
I	To promote the social implementation of the Physical Internet in Japan, it is essential to foster collaboration between government, industry, and academia to create a unified vision. Developing pilot projects in urban areas can demonstrate the benefits of interconnected logistics systems. Encouraging

	public-private partnerships will facilitate investment in necessary infrastructure and technology. Raising awareness through educational campaigns can help inform stakeholders about the advantages of the Physical Internet. Additionally, establishing regulatory frameworks that support innovation while ensuring safety and security is crucial. Finally, leveraging Japan's advanced technology landscape, such as IoT and AI, can enhance the efficiency and effectiveness of the Physical Internet.
II	To promote the social implementation of the Physical Internet in Japan, it is essential to foster collaboration among stakeholders, including government, industry, and academia. Encouraging public awareness campaigns can help educate citizens about the benefits of the Physical Internet. Additionally, investing in infrastructure that supports seamless logistics and data sharing will be crucial. Implementing pilot projects can demonstrate the effectiveness of the Physical Internet in real-world scenarios, while providing incentives for businesses to adopt these practices can drive participation. Finally, establishing regulatory frameworks that facilitate innovation and ensure data security will support sustainable growth in this area.
III	To promote the social implementation of the Physical Internet in Japan, it is essential to enhance coordination and collaboration among stakeholders to build social capital. Encouraging transparency and clear communication about the tangible benefits of the Physical Internet will help engage businesses and researchers alike. Highlighting successful case studies can demonstrate the effectiveness and value of the Physical Internet, fostering trust and cooperation. Additionally, addressing potential barriers through education and awareness initiatives will be crucial in attracting new participants to the network. Finally, focusing on the financial aspects and quality outcomes will ensure that stakeholders recognize the importance of collaboration for future success.
IV	To promote the social implementation of the Physical Internet in Japan, it is essential to enhance stakeholder engagement by showcasing successful case studies that demonstrate tangible benefits and quality outcomes. Encouraging collaboration among researchers, businesses, and logistics providers can foster a shared understanding of the value of the Physical Internet. Emphasizing the importance of clear communication and education about costs and operational decisions will help address potential barriers. Additionally, building trust and reciprocity within logistical networks can strengthen social capital, facilitating the transition to open supply networks. Finally, leveraging innovative technologies, such as reinforcement learning for logistics optimization, can improve efficiency and sustainability in urban logistics.

The intuitive impression is that the GPT model (I) generate more broader, general proposals, while RAG-based models (II, III, IV) provide more specific and targeted suggestions. Quantitative performance evaluation is discussed in Section 5.2.

5.2 Performance Metrics

The performance of each model, evaluated using the metrics described in Section 4.3, is shown in Table 6. The results show that the GraphRAG models (Models II – IV) outperformed the standard GPT model (Model I) on all metrics except WC. In particular, Model IV (HS) achieved highest scores of all models. This is likely because the standard GPT model is superior at understanding broader, context-rich scenarios and generating responses in relatively plain language, whereas GraphRAG incorporates specialized terminology and complex vocabulary from external knowledge sources, resulting in more detailed and domain-specific responses. In other words, GraphRAG can be particularly valuable when factual accuracy and transparent source traceability are critical. To advance research and real-world implementation of PI, the optimal model should combine a search-based system like GraphRAG for factual grounding with the GPT’s ability to synthesize information and foster creative system design.

Table 6: Performance Metrics (bold indicates best performance)

Prompt	1				2			
Model	I	II	III	IV	I	II	III	IV
WC	108	66	102	87	117	109	112	119
TTR	0.72	0.73	0.64	0.68	0.68	0.70	0.67	0.71
ADD	3.19	2.94	3.16	3.41	2.99	3.09	2.99	2.91
FKG	15.00	21.90	20.20	24.20	18.30	19.10	18.40	19.80
CS	-	0.67	0.71	0.67	-	0.95	0.86	0.87

6 Conclusion

This study provides a new perspective on the research challenges and social implementation of PI by analyzing large amounts of textual data related to the PI using GraphRAG. Going beyond traditional statistical analysis, this study provides a new approach to understanding the challenges of implementing the PI. Four models were used to generate responses to two prompts representing the innovation and research promotion, and the practical application and social impact perspectives. In both cases, GraphRAG outperformed the GPT model, demonstrating higher lexical density, readability, and similarity of responses.

This study makes several important contributions. First, it presents the first application of GraphRAG to PI, pioneering its use in reviewing and synthesizing existing research. The results demonstrate the potential of AI-driven methods in providing new insights from existing literature. Second, by applying a large-scale natural language processing approach, this study provides a solution for capturing diverse datasets, including not only academic literature but also real time internet data sources reflecting public opinion and industry perspectives. Third, by comparing various search strategies (local, global, and hybrid) within GraphRAG, this study provides valuable insights into the optimization of search augmentation generation models for PI.

There are several limitations to this study. First, the dataset consists primarily of data from IPIC proceedings. While the proceedings provide relevant insights into PI, they lack the technical depth and detailed information associated with the topic. Second, the use of GraphRAG, especially hybrid search, increases computational costs, potentially limiting its scalability for real-time search augmentation. Third, the study does not compare its results to official logistics data or expert opinion, which limits the validation of its conclusions.

Future research should combine GraphRAG with broader range of academic papers, official industry reports, and other sources to generate more comprehensive insights. In addition, the development of improved methods for validating and interpreting AI-generated insights would be valuable in advancing the adoption and implementation of PI. Finally, further research should explore how AI-driven analytics can influence government regulations and industry standards for sustainable logistics.

7 Conflicts of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Improving the Gains Through Consolidation of Orders from Multiple Shippers at the Cross-Dock Facility in the Philippines

Rovie Manansala¹ and Varsolo Sunio¹

University of Asia and the Pacific, Pasig City, Philippines

Corresponding author: varsolo.sunio@uap.asia

Abstract: This study investigates how shipment consolidation can enhance truck utilization in a cross-docking facility operated by a logistics service provider (LSP) in the Philippines. Using actual dispatch data from December 2024 to February 2025, the research identifies inefficiencies, including frequent underutilized truck dispatches and limited multi-order consolidation. Three optimization models were built in Python to simulate and improve load planning: 1) the Load Plan Model (LPM), which consolidates orders and requested delivery dates using greedy heuristics and linear optimization; 2) the Dynamic Lower Bound Load Plan Model (DLB-LPM), which introduces a dynamic lower bound to improve truck assignment efficiency; and 3) the DLB+Temporal Relaxation Model (DLB+TR), which incorporates soft constraints for temporal flexibility. These models treat truck loading as a multi-knapsack optimization problem, accounting for real-world operational constraints like weight, volume and delivery scheduling. Compared to actual dispatch performance, the models significantly reduced truck underutilization from 30-40% range to as low as 14.6% and improved consolidation frequency. All three models executed in under 7 minutes, demonstrating scalability and computational feasibility. These findings show that tailored optimization strategies can enhance day-to-day logistics operations and support a shift toward Physical Internet principles for more sustainable and efficient transport systems.

Keywords: Consolidation, Cross-docking, Logistics Service Provider, Physical Internet

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

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

1 Introduction

The global pandemic significantly disrupted business operations, including logistics in the Philippines. Fortunately, the sector has since rebounded and is on a growth trajectory. In 2023, the Philippine logistics industry reached ₱768 billion in Gross Value Added (GVA), contributing 3.6% to the country's Gross Domestic Product (GDP). It's projected to grow at 8.2% annually, reaching ₱1.16 trillion by 2027 (Moral, 2023). This growth indicates increasing shipment activity but also highlights persistent infrastructure challenges, particularly limited storage capacity. As a result, logistics collaboration has become essential to address inefficiencies and resource constraints.

Globally, collaboration is a proven strategy for improving logistics. Ferrell et al. (2019) examined how freight consolidation enhances truck utilization. In the US, truck capacity averages only 43%, contributing to higher costs, emissions and congestion. Consolidation can

reduce these inefficiencies, with studies showing 7-15% cost savings through better load sharing and route optimization.

Shipment consolidation (SCL) aligns with the broader shift towards the Physical Internet (PI), as described by Venkatadri et al. (2016). PI models logistics on the Digital Internet, using modular containers and interconnected hubs to streamline goods movement. The goal is a cost-efficient, sustainable, and socially responsible logistics network. For third-party logistics providers (3PLs), better truck utilization through SCL is particularly advantageous, given their reliance on warehouse networks and multimodal transport.

2 Related Studies

Logistics and supply chain are a complex system with varying components that need integration. This necessitates the formulation of strategies that can solve logistics inefficiency, such as shipment consolidation. This section aims to explore some computational methods in solving a shipment consolidation problem and how it aligns with Physical Internet (PI) concepts to achieve a cost-effective and sustainable logistics network.

Table 1. Review of Shipment Consolidation Studies

Author (s) / Year	Title	Problem Addressed	Methodology	Key Findings / Contribution
Venkatadri et al. (2016)	On Physical Internet Logistics: Modeling the Impact of Consolidation on Transportation and Inventory Costs	Comparing PI vs traditional logistics in terms of cost savings	MILP P2P optimization with Monte Carlo	PI logistics outperforms traditional logistics through the reduction of inventory and total system costs despite longer delivery times
Aringhieri et al. (2018)	Simple but Effective Heuristics for the 2-Constraint Bin Packing Problem	Theoretical problem of minimizing bins to pack items subject to weight and volume constraints	Heuristic-based algorithms (greedy and neighborhood search)	Strategy of introducing a dynamic lower bound and infeasibility recovery to effectively solve the bin packing problem
Memon et al. (2021)	Time and Quantity-Based Hybrid Consolidation Algorithms for Reduced Cost Product Delivery	Cost optimization on delivery, combining time and quantity rules	Rule-based hybrid heuristic	Showcased the consolidation improvement with rule-based implementation
Büyükdvecia et al. (2024)	Multi-objective shipment consolidation and dispatching problem	Consolidation based on cost and distance, considering transshipment and routing	Multi-objective MILP + Metaheuristic	Jointly optimized cost and distance and modeled based on real-world constraints and factors
Goodarzi et al. (2024)	Evaluating the sustainability and resilience of an intermodal transport network leveraging consolidation strategies	Minimize the cost of intermodal network design subject to delivery time, disruption and single recovery per link	MILP + Langrarian Relaxation	34x cost savings after consolidation
Mercurio et al. (2024)	Freight consolidation through carrier collaboration -A cooperative game	LTL inefficiency due to underutilization and lack of trust in collaboration	MILP + Cooperative Game Theory	Conditions such as no or symmetric transfer costs are conditions favorable for stable collaboration

3 Case Study

3.1 Use-Case Operational Inefficiency in a Philippine Cross-Docking Facility

Earlier studies lacked real-world applications to address logistical inefficiencies (Ferrell et al., 2019). This research, however, leverages a partnership with a top Philippine logistics firm referred to here as “**Organization A**” to protect confidentiality. Organization A is a leading logistics operator in the Philippines, with a nationwide presence as an integrated, end-to-end logistics provider. The study focuses on one of Organization A’s cross-docking facilities, where inbound shipments from multiple firms are sorted and loaded onto outbound trucks for B2B deliveries. Due to the transactional nature and shipment volumes, the facility presents a real-world opportunity for logistics collaboration and consolidation.

Data from the Transport Management System (Dispatch) was analyzed, covering three months (Dec 2024-Feb 2025). Initial findings revealed consolidation inefficiencies. Trucks were categorized by utilization: ‘Underutilized’ ($\leq 50\%$), ‘Moderately Utilized’ (51–75%), ‘Utilized’ (76–90%), and ‘Severely Utilized’ (91–100%). Nearly half of the trips were underutilized (Figure 1) and many shipments carried only one order (Figure 2a), which limits consolidation. While some shipments were double or triple consolidated, they were still outnumbered by single-order trips. Roughly one-third of high-capacity trips showed latent inefficiencies (Figure 2b), indicating consolidation opportunity even in high-utilization cases.

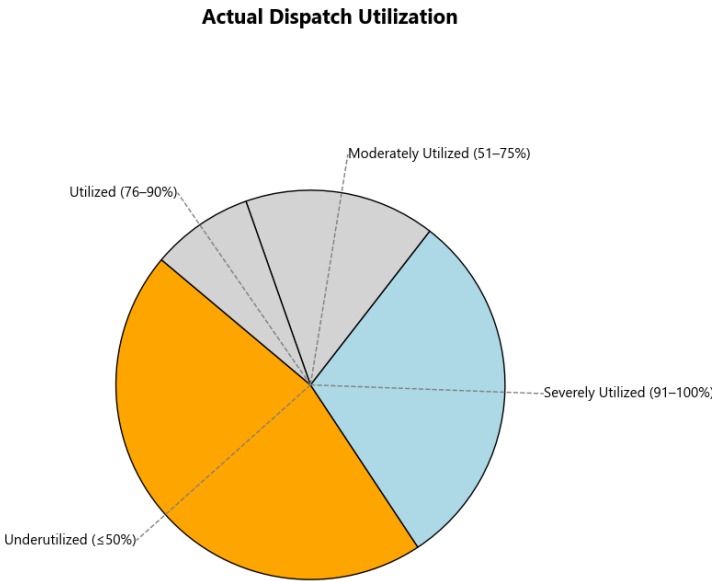


Figure 1: Distribution of actual truck dispatch volume utilization levels based on 3-month internal logistics data. Utilization is categorized into: Underutilized ($\leq 50\%$), Moderately Utilized (51–75%), Utilized (76–90%), and Severely Utilized (91–100%). Actual proportions of trucks in each category are not disclosed to protect industry confidentiality; only approximate distribution is illustrated.

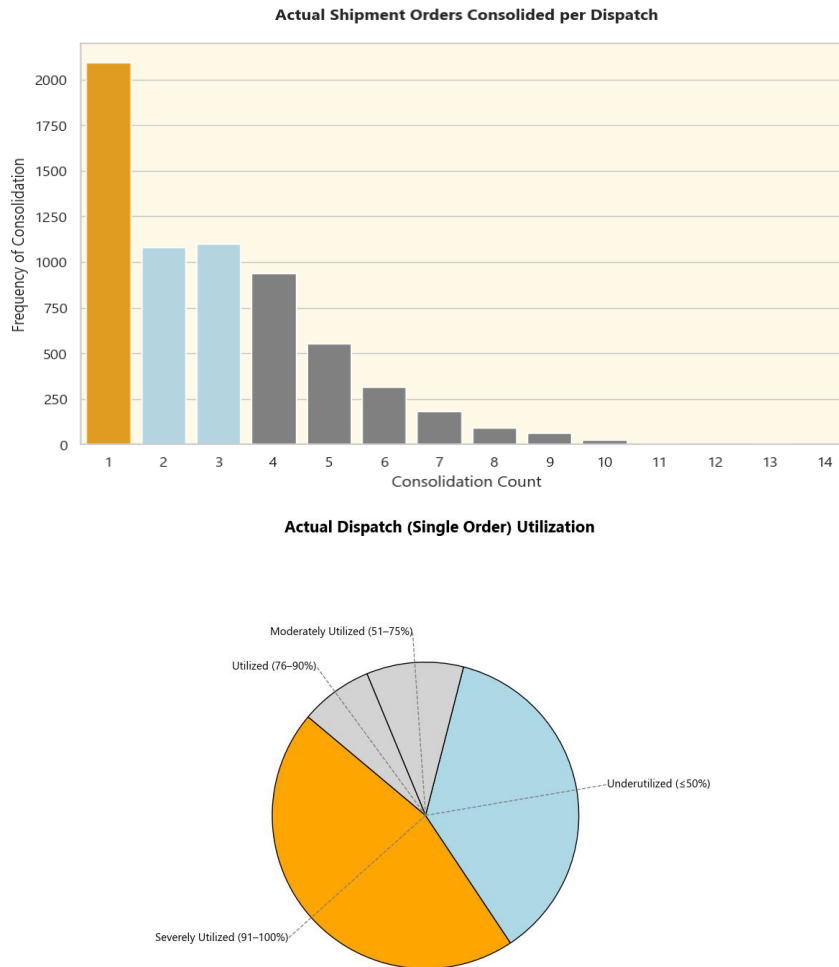


Figure 2a (top) Frequent Number of Consolidated Orders per Dispatch; 2b (bottom): Single-Order Utilization Category Composition (Note: actual proportions are not disclosed to protect industry confidentiality; only approximate distribution is illustrated.)

Overall, these findings support the case for optimizing consolidation strategies at Organization A’s cross-docking center, aligning with Physical Internet (PI) principles for efficient freight movement.

3.2 Objectives

The primary goal of this study is to provide actionable insights into improving truck utilization at Organization A’s cross-docking facility, while aligning operations with Physical Internet (PI) principles.

Key Objectives:

- **Develop an Optimization-Based Consolidation Framework:** Create a solution to maximize truck utilization and minimize inefficiencies by determining the optimal way to consolidate shipments, considering operational constraints and controllable decisions.
- **Increase Multi-Order Consolidation:** Encourage the presence of multiple-order shipments, reducing the number of trucks carrying single orders. This aims to improve load density and enhance overall operational efficiency.

Success Metrics:

- **Reduction in Underutilized Trucks:** Fewer trucks should be classified as underutilized ($\leq 50\%$ capacity), reflecting better truck load planning and fewer empty transport miles.
- **Scalable, Adaptive Assignment Model:** The framework should be computationally feasible and scalable across Organization A's logistics network, enabling adaptive shipment assignments in real-world conditions.

4 Data and Methods

The data used for modeling was extracted from Organization A's Transport Management System (TMS) in CSV format. Two datasets were referenced: the **TMS load planning file**, containing 19,576 order-level records with 34 attributes and the **actual dispatch file** with 6,453 records representing consolidated shipments over a three-month period (December 2024 to February 2025). To protect the identification of the logistics firm, all information pertaining to the company, facilities and internal data (identifiers, truck IDs, shipment dates) was anonymized. Identifying characteristics are withheld in accordance with confidentiality agreements.

During preprocessing, columns used solely for documentation, those with excessive missing values, and those with only one unique entry were removed from the dispatch dataset, reducing the attribute count from 34 to 20. Supplementary data on truck availability and capacity (in terms of weight and volume) were also integrated.

The objective is to develop a shipment consolidation framework that improves truck utilization and minimizes dispatches, which supports both operational efficiency and broader Physical Internet (PI) logistics principles.

The optimization models were developed in Python and designed to simulate an enhanced dispatch plan. Conceptually, the problem resembles a multiple-knapsack scenario, where trucks represent knapsacks with volume and weight constraints and shipments represent items to be optimally assigned to maximize total utilization. To address this, three models were created and evaluated based on their optimization quality and computational feasibility:

1. **Load Plan Model (LPM):** Baseline model using deterministic rules and heuristics.
2. **Dynamic Lower Bound Load Plan Model (DLB-LPM):** Enhances LPM by incorporating a dynamic lower bound to improve solution space efficiency.
3. **DLB + Temporal Relaxation (DLB+TR):** Extends DLB-LPM by allowing soft violations of temporal constraints, with penalties.

Model evaluation criteria included:

- **Optimization Performance:** Ability to improve daily truck utilization.
- **Solution Quality:** Reduction in single-order dispatches and increase in consolidation.
- **Computational Efficiency:** Execution time under 15 minutes for daily planning.

A comparative summary of these models and their components is presented in Tables 2a and 2b. These models aim not to replace the current system but to provide a robust, automated alternative to improve decision-making in cross-docking operations.

Table 2a. LPM, DLB-LPM, DLB+TR – Model Equation

Elements	Load Plan Model (LPM)		Dynamic Lower Bound (DLB) LPM	DLB + Temporal Relaxation
Objective Function Goal of the model	Maximize Total CBM Utilization: $Maximize\ Z = \sum_{(s,t) \in P} x_{st} \cdot Vs$		Maximize Net Efficient Utilization: Maximize CBM while penalizing truck usage and underutilization $Max \left(\sum_{(s,t) \in P} x_{st} \cdot Vs - \gamma \sum_{t \in T} y_t - \omega_{under} \sum_{t \in T} u_t - \omega_{over} \sum_{t \in T} o_t \right)$	Maximize Net Efficient Utilization: Maximize CBM while penalizing truck usage, underutilization and temporally infeasible assignments $max \sum_{(s,t) \in P} x_{st} \cdot Vs + \sum_{(s,t) \in P_{inf}} x_{st}^{inf} \cdot Vs - 0.1 \sum_{t \in T} y_t - 5 \sum_{t \in T} \left(y_t - \frac{Vs\ assigned\ to\ t}{V_t^{max}} \right) - 10 \sum_{(s,t) \in P_{inf}} x_{st}^{inf}$
Sets and Indices Groups and identifiers used in the model	S – Set of remaining shipments T – Set of available trucks (s, t) ∈ P – Valid shipment-truck pairs based on compatibility and delivery schedule			
			P ⊆ S × T : Valid (feasible) shipment-truck pairs P_{inf} ⊆ S × T : Temporally infeasible shipment-truck pairs	
Parameters Fixed inputs describing shipment, truck, rules, penalties and heuristics	Vs – Volume (CBM) of shipment s Ws – Weight (KG) of shipment s V_t^{max} – Maximum CBM capacity of truck t W_t^{max} – Maximum weight capacity of truck t			
	ε – Small positive number (e.g., 0.0001) to activate truck usage	α = 0.76 Lower bound utilization ratio β = 0.90 Upper bound utilization ratio ω_{under} = 5 Penalty per truck for underutilization ω_{over} = 10 Penalty per truck for overutilization γ = 0.1 Penalty per truck used		
		Food_s : Indicator whether shipment s is food (1 if food, 0 otherwise) Z₀ : Heuristic (greedy) objective value used as a lower bound		
Decision Variables Choices the model makes	x_{st} ∈ { 0, 1 } – 1 if shipment s is assigned to truck t , 0 otherwise y_t ∈ { 0, 1 } – 1 if truck t is used, 0 otherwise f_t ∈ { 0, 1 } – 1 if truck t is assigned food shipments, 0 otherwise			
		u_t ≥ 0 Underutilization slack variable for truck t o_t ≥ 0 Overutilization slack variable for truck t	x_{st}^{inf} ∈ { 0, 1 } – 1 if shipment s is assigned to truck t (infeasible)	
Constraints Rules that the model must satisfy	1. Single Assignment Constraint Each shipment can be assigned to at most one truck: $\sum_{(s,t) \in P} x_{st} \leq \forall s \in S$		1. Single Assignment Constraint Each shipment can be assigned to at most one truck: $\sum_{t: (s,t) \in P} x_{st} + \sum_{t: (s,t) \in P_{inf}} x_{st}^{inf} \leq 1 \forall s \in S$	

	2. Truck Capacity Constraints For every truck $t \in T$: $0.76 \cdot V_t^{\max} \leq \sum_{(s,t) \in P} x_{st} \cdot V_s \leq 0.90 \cdot V_t^{\max}$ $0.76 \cdot W_t^{\max} \leq \sum_{(s,t) \in P} x_{st} \cdot W_s \leq 0.90 \cdot W_t^{\max}$	2. Truck Capacity Constraints with Slack For every truck $t \in T$: $\sum_{(s,t) \in P} x_{st} \cdot V_s + u_t \geq \alpha \cdot V_t^{\max}$ $\sum_{(s,t) \in P} x_{st} \cdot V_s - o_t \leq \beta \cdot V_t^{\max}$ $\sum_{(s,t) \in P} x_{st} \cdot W_s \leq \beta \cdot W_t^{\max}$	2. Truck Capacity Constraints For every truck $t \in T$: $\sum_{s: (s,t) \in P} x_{st} \cdot V_s + \sum_{s: (s,t) \in P_{inf}} x_{st}^{inf} \cdot V_s \leq 0.9 \cdot V_t^{\max}$ $\sum_{s: (s,t) \in P} x_{st} \cdot V_s + \sum_{s: (s,t) \in P_{inf}} x_{st}^{inf} \cdot V_s \geq 0.76 \cdot V_t^{\max}$
	3. Truck Usage Activation If any shipment is assigned to a truck, mark it as used: $\sum_{(s,t) \in P} x_{st} \cdot V_s \geq \epsilon \cdot Y_t \quad \forall t \in T$	3. Truck Usage Activation If any shipment is assigned to a truck, mark it as used: $\sum_{(s,t) \in P} x_{st} \cdot V_s \geq 0.0001 \cdot Y_t \quad \forall t \in T$	3. Truck Usage Activation If any shipment is assigned to a truck, mark it as used: $\sum_{s: (s,t) \in P \cup P_{inf}} x_{st} \cdot V_s + x_{st}^{inf} \cdot V_s \geq 0.0001 \cdot y_t$
	4. Food and Non-Food Incompatibility Ensure food and non-food are not mixed on the same truck: <ul style="list-style-type: none"> If shipment s is Food: $x_{st} \leq f_t$ If shipment s is Non-Food: $x_{st} \leq 1 - f_t$ for all $(s,t) \in P$ 		4. Food and Non-Food Incompatibility Ensure food and non-food are not mixed on the same truck: <ul style="list-style-type: none"> If shipment s is Food: $(x_{st} + x_{st}^{inf}) \leq f_t$ If shipment s is Non-Food: $(x_{st} + x_{st}^{inf}) \leq 1 - f_t$ for all $(s,t) \in P$
	4. Dynamic Lower Bound Constraint Objective value must perform at least as well as greedy heuristic baseline: $Objective\ value \geq Z_0$		

Table 2b. LPM, DLB-LPM, DLB+TR – Model Comparison

Feature	LPM	DLB-LPM	DLB + TR	Feature	LPM	DLB-LPM	DLB + TR
Heuristic Phase	✓	✓	✓	Food/Non-Food Split	✓	✓	✓
Truck Type Compatibility	✓	✓	✓	Max 3 RDD Constraint	X	✓	X
Delivery Day Constraint	✓ (strict)	✓ (strict)	X (relaxed via penalty)	Dynamic Lower Bound	X	✓	✓
Underutilization Penalty	✓	✓	✓	Infeasibility Allowed	X	X	✓ (with penalty)

5 Results and Discussion

To evaluate the performance of the proposed models, a five-day window in the month of February 2025 operations from Organization A’s Transport Management System (TMS) was selected. Model outputs were compared against the actual dispatch data to assess improvements in truck utilization. To maintain confidentiality, numbers were reported mostly in an aggregated form to preserve insights while ensuring the protection of Organization A’s proprietary data.

5.1 Sample Model Output

Table 3 represents the first five dispatches generated by the DLB+TR (Dynamic Lower Bound + Temporal Relaxation) model, showing consolidated shipments with requested delivery dates (RDDs), weights, volumes and utilization rates. These dispatches complied with constraints on truck capacity, available fleet and operational rules.

Table 3. Sample Aggregated Model Output (DLB + TR Results)

Truck Used	# Shipment Nos Consolidated	# Delivery Dates Consolidated	Total Weight	Total Volume	Utilization %
A_1	5	3	1761.75	4.37	76.60%
A_2	9	4	2162.44	5.62	94.02%
A_3	7	3	1969.7	5.03	85.64%
A_4	2	2	1453.47	3.73	63.19%
A_5	5	2	1779.88	4.54	77.39%
A_6	6	2	1384.81	3.47	60.21%

5.2 Comparative Performance

Table 4 summarizes the performance of the three optimization models: 1) LPM (Load Plan Model), 2) DLB-LPM (with Dynamic Lower Bound) and 3) DLB+TR (DLB with Temporal Relaxation).

Utilization Gains: All models improved truck utilization compared to actual dispatch data. DLB+TR achieved the lowest underutilization (14.6 %), while DLB-LPM had the highest percentage of fully utilized trucks (30.8%).

Consolidation Effectiveness: Frequent consolidation (orders grouped into the same truck) increased across all models, reducing single-order dispatches. DLB-LPM model in particular, reduced single-order dispatches by over 85%.

Execution Time and Scalability: All models completed within 7 minutes, well under the 15-minute benchmark, confirming feasibility for real-time application.

Strategic Insights: The models validated the impact of combining consolidation by quantity and delivery date. Introducing constraints like capacity bounds and infeasibility penalties significantly improved output quality.

These findings confirm that optimization models not only reduce underutilized trips but also increase the presence of multiple-order consolidations, which are essential for reducing operational inefficiencies.

Table 4. Results of the three models – LPM, DLB-LPM, DLB+TR

Rubrics	Ideal Outcome	Actual Dispatch	Load Plan Model (LPM)	Dynamic Lower Bound (DLB) LPM	DLB + Temporal Relaxation
Optimization Performance	↓ Underutilized	35-40 %	29.1 %	15.4 %	14.6 %
	↓ Severely Utilized	35-40 %	7.0 %	16.7 %	18.3
	↑ Utilized	5-10 %	14.0 %	30.8 %	29.3 %
	↑ Moderately Utilized	15-20 %	50.0 %	37.2 %	37.8 %
Execution Time	≤15 minutes (900 seconds)	---	403.77 seconds	285.31 seconds	301.49 seconds
Quality of Solutions	↓ Single Order Dispatch	100-120	21	15	18
	↑ Frequent Consolidation Count	1	3	4	4

*Note: Actual Dispatch values were transformed into ranges where the actual value falls

6 Conclusion

This study explored how optimization-based models can enhance truck utilization in cross-docking operations, using data from a leading logistics firm in the Philippines. By applying three algorithmic approaches, namely LPM, DLB-LPM and DLB+TR, the study showcased significant improvements in shipment consolidation.

Key takeaways:

- All models successfully decreased underutilized and single-order dispatches.
- Consolidation strategies led to better load distribution, aligning with PI logistics principles of modularity and efficiency.
- Execution times met operational feasibility, supporting real-world scalability.
- Each model demonstrated specific strengths:
LPM minimized severely utilized trips and had the most moderately utilized trucks.
DLB-LPM produced the highest number of fully utilized trucks in the least amount of time.
DLB+TR reduced underutilized trucks the most and maintained strong consolidation rates.

Ultimately, this research provides actionable insights into practical optimization strategies for improving cross-docking operations, making a strong case for scalable, algorithm-driven consolidation frameworks in modern logistics planning.

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Comments for reviewers

Response to Review 3:

We thank you for the constructive and valuable feedback. We have revised the abstract to better reflect the practical implications of our governance framework and added concrete examples to clarify the relevance of governance for real-world PI challenges.

We fully acknowledge the importance of points 3 and 4. However, due to the strict 10-page limit of the IPIC conference and the fact that our paper already reaches this maximum, we are unfortunately unable to further elaborate on the limitations of the DI-PI analogy or include a discussion on implementation barriers at this stage. That said, we consider both points highly relevant and will integrate them into an extended version of the paper for submission to a journal.

Response to Review 4:

Thank you very much for your thoughtful and encouraging feedback. We appreciate your recognition of the paper's conceptual contribution.

Governing the Physical Internet: Insights from Internet Governance and Future Research Directions

Malte Spanuth¹, Rod Franklin¹, André Ludwig^{1,2}, Gero Niemann¹

1. Kühne Logistics University, Hamburg, Germany

2. Leipzig University, Leipzig, Germany

Corresponding author: malte.spanuth@klu.org

Abstract: *Despite growing technical maturity, implementation of the Physical Internet remains limited. A key reason is that while operational mechanisms such as routing protocols and modular containers are well-researched, governance remains insufficiently addressed. This study explores how governance structures for the Physical Internet can be conceptualized, drawing on lessons from Physical Internet, horizontal logistics collaboration, and the evolution of governance in the Digital Internet. We conduct a systematic literature review and identify a gap in the consideration of collective-choice and constitutional governance, including rulemaking, stakeholder participation, and conflict resolution. To address this, we propose a conceptual framework grounded in Ostrom's Institutional Analysis and Development framework and inspired by the decentralized governance trajectory of the Digital Internet. The governance framework distinguishes between operational, collective-choice, and constitutional rule levels, offering a structure for coordinating logistics actors without centralized control supporting aligned operations for service providers and adaptive rulemaking for policymakers.*

Keywords: Governance; Horizontal Logistics Collaboration; Physical Internet; Institutional Analysis and Development

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

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

1 Introduction

The Physical Internet (PI) presents a transformative vision for the future of logistics, promising to enhance efficiency, interoperability, and sustainability by enabling logistics systems to function as an open, interconnected network of networks (Montreuil, 2011). Drawing inspiration from the Digital Internet (DI), the PI aims to move goods with modularity, flexibility, and scalability similar to how data packets travers digital networks. Rather than relying on a single provider for end-to-end delivery, the PI envisions shipments being dynamically routed, consolidated, and processed by a distributed network of independent logistics service providers (LSPs).

While technical innovations such as modular containers and routing protocols have received considerable academic attention (Achamrah et al., 2024; Briand et al., 2022; Sarraj, Ballot, Pan,

Hakimi, et al., 2014), the governance dimension of the PI remains significantly underexplored. Yet, governance is crucial if the PI is to enable collaboration among autonomous logistics actors, integrate across regulatory regimes, and operate in competitive markets where data sharing and coordination amongst others pose major challenges, for example, resolving liability in multi-actor shipment delays, or managing data ownership across international hubs.

Existing work on Horizontal Logistics Collaboration (HLC) and the PI often assumes the need for a neutral governing entity to enforce collaboration and manage conflicts (Cruijssen, 2012; Frisk et al., 2010). However, empirical studies such as Sternberg et al. (2022) challenge this assumption, showing that external facilitation can undermine trust and deter participation. Drawing a parallel to the DI, which was initially governed by government and academic institutions under the DARPA umbrella, it gradually evolved into a decentralized system shaped by voluntary stakeholder-based standards-setting bodies such as the Internet Engineering Task Force (IETF). This trajectory suggests that PI governance may also evolve from initial coordination toward distributed, adaptive forms.

Understanding how such an evolution might unfold in the PI requires moving beyond individual coordination tools to consider how they are embedded within a broader governance architecture. While previous studies have analyzed how routing, auction mechanisms, and optimization tools can enhance operational efficiency, they often overlook the broader governance structures needed to support such mechanisms in a decentralized system. The analogy with the DI underscores the importance of layered, flexible governance rather than fixed top-down structures. At the same time, key differences between digital and physical networks, such as the high cost of shipment loss or redirection, the high variability in costs and schedules, and capacity constraints, require governance models that are specifically tailored to the logistical, environmental, and institutional complexities of physical distribution systems.

To address these gaps, we first analyze the governance mechanisms and approaches in existing PI and HLC literature. Building on this foundation, we outline a conceptual governance framework for the PI, informed by lessons from HLC, the evolution of the DI, and the Institutional Analysis and Development (IAD) framework. The remainder of the paper is structured as follows: Section 2 introduces the theoretical background. Section 3 reviews governance-related literature in PI and HLC and maps findings using the IAD framework. Section 4 outlines a conceptual framework and discusses implications for future research.

2 Theoretical and Conceptual Background

2.1 Development of the Digital Internet

The PI draws on the architecture and principles of the DI, making it essential to briefly revisit how the DI evolved and where the analogy meets its limits. The origins of the DI date back to the 1960s, when DARPA initiated research into decentralized communication systems, leading to the creation of ARPANET, the first packet-switching network that connected selected research institutions (Kahn et al., 1997; Leiner et al., 2009). The successful transmission of data in 1969 laid the foundation for what would become the global Internet. A major development followed in 1974, when Cerf and Kahn introduced the Transmission Control Protocol (TCP), which was later split into TCP and IP to support scalable communication across heterogeneous networks (Cerf & Kahn, 1974). The formal adoption of the TCP/IP protocol in 1983 is widely considered the start of the modern Internet (Cerf, 1993; Leiner et al., 2009).

Initially, governance was managed by academic and governmental institutions such as DARPA and the National Science Foundation. Over time, this shifted toward a more decentralized model, with the Internet Engineering Task Force (IETF), established in 1986, becoming central

to defining technical standards and ensuring interoperability (Kurose & Ross, 2017). This shift from centralized control to stakeholder-driven governance provides relevant insights for the PI, where coordination will similarly involve distributed actors.

Nevertheless, important differences must be acknowledged. In the DI, data packets are transmitted within seconds and can be retransmitted at negligible cost if lost. In contrast, physical shipments may take days or weeks to arrive, cannot be duplicated easily, and involve significant costs and constraints in case of rerouting, delay, or disruption (Dong & Franklin, 2021). These differences call for governance mechanisms that are adapted specifically to the realities of physical logistics networks.

2.2 Mapping the PI Landscape: Themes and Gaps

The conceptual development of the PI has been strongly shaped by the Alliance for Logistics Innovation through Collaboration in Europe (ALICE). They have led the coordination of industry, policy, and research, positioning the PI as a pillar of sustainable freight transport and introduced a PI roadmap in 2020 (ALICE, 2020). Projects like MODULUSHCA, SENSE, ICONET, and NEXTRUST have advanced this vision by piloting modular containers, data-sharing platforms, and digital infrastructures (ICONET, 2018; Nexttrust, 2020; Wu et al., 2025). The ALICE Roadmap outlines governance as a critical enabler for the PI, focusing on the development of rules, trust mechanisms, and coordination structures across logistics nodes, networks, and networks of networks. Building on Montreuil's foundational vision, academic research has developed in several directions. Münch et al. (2023) identify eight major communities, which we group into three themes: 1. *strategic foundations and actor roles*, 2. *technological enablers and infrastructure*, and 3. *application contexts and operational control*.¹

Strategic foundations and actor roles: Our first theme includes three of Münch's communities. The first community addresses the benefits of the PI over conventional logistics and the challenges of its operationalization. Simulation studies highlight gains in cost, lead time, and distance (Ambra et al., 2021; Zheng et al., 2019), while others explore managerial incentives (Plasch et al., 2021) and the modularity of container as a success factor for operationalization (H. S. Sternberg & Denizel, 2021). The second community, dealing with research on actor roles, examines open hub structures, pricing, and behavioral aspects (Pan et al., 2015; Qiao et al., 2019), while the third community focusing on foundational work, defines PI principles and Internet analogies (Montreuil et al., 2013; Sarraj, Ballot, Pan, Hakimi, et al., 2014).

Technological enablers and infrastructure: This theme also includes three of Münch's communities. The fourth community explores product-service systems and emerging business models, including the use of PI principles in smart manufacturing with IoT and big data (Pan et al., 2019; Y. Zhang et al., 2016). The sixth focuses on ICT foundations such as IoT-based frameworks and smart containers for real-time data exchange (Sallez et al., 2016; Tran-Dang & Kim, 2018), for enabling PI operations. The seventh community centers on modular containers as enablers of interoperability, covering design and volume optimization models (Landschützer et al., 2015; Lin et al., 2014; Meller et al., 2012).

Application contexts and operational control: Our third theme includes the final two communities identified by Münch. The fifth community connects the PI to city logistics concepts, introducing hyperconnected city logistics (Crainic & Montreuil, 2016), collaborative planning and resource sharing (Crainic et al., 2020), and urban system architectures (Kim et al.,

¹ Note that we maintain Münch's numbering scheme for the communities identified to ensure easy cross-referencing.

2021). The eighth community focuses on PI hub control, including disruption-resilient scheduling (Chargui et al., 2020), intermodal control architectures (Vo et al., 2018), and port integration requirements (Fahim et al., 2021).

A recently emerging area of research is the Cyber-Physical Internet, which adds a cyber layer to the PI for real-time sensing, analytics, and autonomous coordination (Wu et al., 2025). Closer to the architecture of the digital Internet, the CPI adopts layered protocols and decentralized control. Recent studies highlight simulation-based planning (Wu et al., 2025), digital twin coordination frameworks (Wu et al., 2024), routing protocols (Qu et al., 2024), and pricing mechanisms (He et al., 2024), showcasing Cyber-Physical Internet's potential for scalable and intelligent logistics networks.

While the research discussed demonstrates the PI's emphasis on openness, interoperability, and collaboration, there is limited research into how such systems are governed, how rules are set, enforced, and adapted in open, decentralized environments. Wu et al. (2025) and Münch et al. (2023) both note that current contributions pay little attention to institutional mechanisms, decision rights, compliance frameworks, or platform-level coordination. This persistent omission points to the need for a dedicated research stream on PI governance.

2.3 Structuring Governance: Theories and Frameworks

Governance plays a central role in inter-organizational collaboration by structuring interactions, enabling coordination, and mitigating opportunism in the absence of hierarchical control. It comprises the structures, rules, and processes through which partners jointly manage responsibilities and resolve conflicts across organizational boundaries (Bryson et al., 2006; Emerson et al., 2012).

A common distinction in the literature is between contractual and relational governance (Poppo & Zenger, 2002; Prakash et al., 2021). In HLC, these are sometimes referred to as formal and informal governance (Lotfi & Larmour, 2021; Sheffi et al., 2019). For consistency, we use the terms contractual and relational governance. Contractual governance relies on formal agreements to specify roles, rights, and enforcement mechanisms, grounded in transaction cost economics (Poppo & Zenger, 2002; Williamson, 1979). Relational governance emphasizes trust, shared norms, and mutual commitment, drawing on relational and social exchange theories (Cao & Lumineau, 2015; Dyer & Singh, 1998; Raue & Wieland, 2015). The relevance of each logic varies by collaboration context, though they often complement one another.

Originally developed within the field of institutional economics and political science, Ostrom's IAD framework offers a valuable theoretical foundation for analyzing governance systems in decentralized and multi-actor contexts. It conceptualizes institutions as formal and informal rules, norms, and shared strategies that structure decision-making and interaction among multiple actors (Ostrom, 2009). Although originally developed to examine how communities self-organize around common-pool resources, the framework is well suited for inter-organizational collaboration, as both settings involve distributed authority, collective rulemaking, and the coordination of shared activities.

A foundational element of the IAD framework is its distinction between three institutional rule levels: operational, collective-choice, and constitutional. Operational rules govern day-to-day activities, e.g., routing protocols or scheduling tools in PI networks. Collective-choice rules define how operational rules are set and revised, through, for instance, stakeholder platforms or collaborative planning bodies. Constitutional rules determine who sets collective-choice arrangements, addressing foundational questions like actor eligibility, alliance formation, or

standard-setting authority. Examples include membership rules in logistics alliances or federated platform charters.

By distinguishing these three levels, the IAD framework provides a structured lens for analyzing governance in collaborative logistics. It moves beyond technical coordination and draws attention to questions of authority, legitimacy, and participation. It also offers a conceptual basis for assessing gaps in existing research and designing governance structures tailored to the complexity of systems such as the PI.

3 Governance Research Landscape in PI and HLC

3.1 Uncovering Governance Mechanisms in PI and HLC: A Systematic Literature Review

To ensure methodological rigor and transparency, we followed the guidelines proposed by vom Brocke et al. (2009), who emphasize the importance of systematically documenting the literature search process. A structured and replicable search strategy not only enables the identification of relevant studies but also strengthens the credibility and cumulative value of a review. The summary of our literature search and selection process is presented in Figure 1.

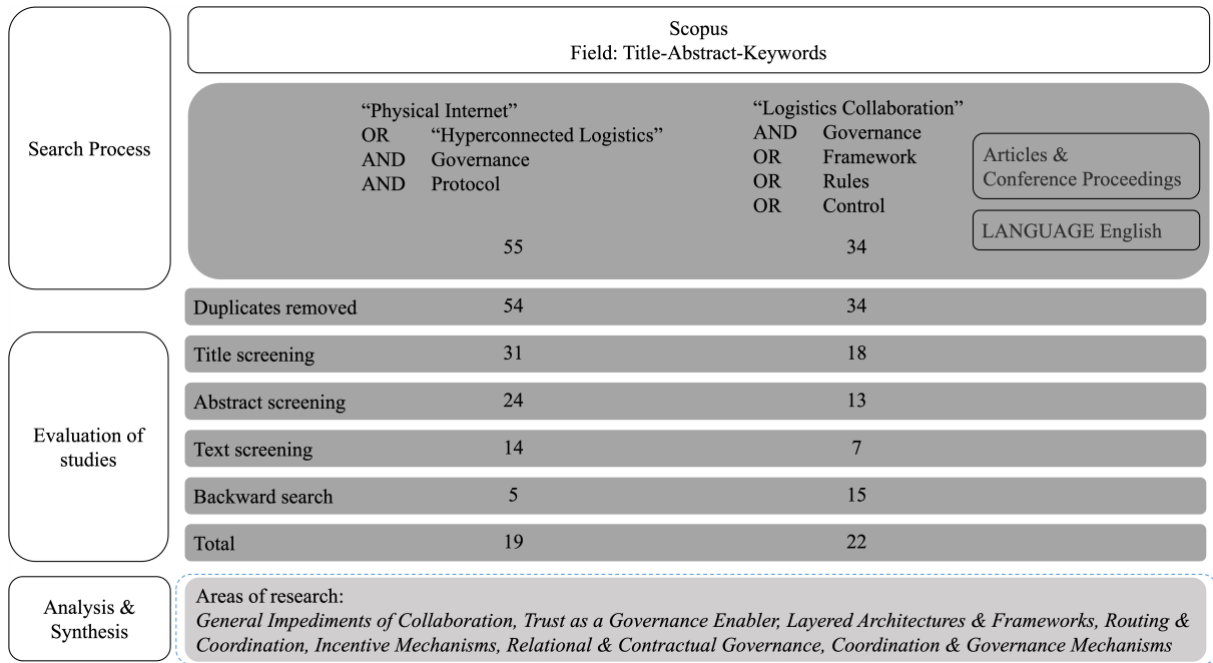


Figure 1: Literature Review Search Process

While governance is rarely addressed explicitly in the PI literature, many contributions propose coordination mechanisms, such as routing protocols, auction mechanisms, and layered architectures, that serve governance functions implicitly. These mechanisms structure behavior in distributed networks and address trust, interoperability, and authority distribution. In parallel, HLC research provides valuable insights into incentive alignment, facilitation, and trust dynamics. Together, these bodies of work form a fragmented but increasingly relevant basis for governance design in the PI.

General Impediments of Collaboration: To understand the foundations of governance design in logistics collaboration, it is essential to first consider the barriers that inhibit cooperation. Cruijssen et al. (2007) identify benefit allocation, cross-boundary coordination, and strategic autonomy concerns as central obstacles to HLC. These concerns are echoed in Fawcett et al.

(2015), who emphasize the role of structural misalignment and low trust as root causes of underperformance. Larsson et al. (2024) add a digital perspective, pointing to platform neutrality, legal safeguards, and data governance as prerequisites for collaboration. These findings underscore that effective collaboration requires not just technical solutions, but governance mechanisms that address actor incentives, trust, and coordination roles.

Trust as a Governance Enabler: Building on these challenges, a growing body of work investigates the role of trust in enabling logistics collaboration. Prakash et al. (2021) show its mitigating effect on conflict, especially under uncertainty. Daudi et al. (2017b) and Sitadewi et al. (2020) demonstrate how trust evolves over time and is shaped by transparency, data accuracy, and benefit-sharing mechanisms. While not a governance tool in itself, trust supports both contractual and relational control systems.

Layered Architectures and Frameworks: A key stream of research explores how collaboration in the PI can be structured through layered architectures and formal frameworks. Montreuil et al. (2013) introduce eight core principles like modularity and interconnectivity, while the OLI and NOLI models (Colin et al., 2016; Montreuil et al., 2012) define layered architectures for logistics networks based on the seven layer OSI model. Later work aligns more closely with the TCP/IP model, emphasizing protocol layering as a basis for decentralized operations (Dong & Franklin, 2021; Wu et al., 2025). Studies by Kaup et al. (2021) and Qu et al. (2024) translate Internet-inspired logic into routing and coordination models. Hofman (2015) proposes a federated platform for logistics coordination, while Fahim et al. (2021) develop a layered framework for PI port integration that includes governance at the node level. While not always framed as governance research, these works offer key building blocks for structuring decentralized logistics systems.

While earlier contributions focus on coordination through protocol architectures and system-level design, the HLC literature shifts attention to the relational foundations of collaboration. Audy et al. (2012) develop a model for multi-party collaboration focusing on leadership and fairness. Daudi et al. (2017) map trust dynamics across strategic and operational levels, while Pomponi et al. (2015) link governance maturity to collaboration evolution. Sheffi et al. (2019) offer a layered framework combining contractual, relational, and informational governance in logistics clusters. Collectively, these studies illustrate how governance design spans both system-level architecture and relational coordination structures.

Routing and Coordination: Routing protocols represent one of the most developed operational governance areas. Sarraj, Ballot, Pan, and Montreuil (2014), Sarraj, Ballot, Pan, Hakimi, et al. (2014), and Gontara et al. (2018) demonstrate modular routing models inspired by the DI. Boysen et al. (2025) formalize this into optimization procedures grounded in PI logic. Achamrah et al. (2024), W. Zhang et al. (2020), and Q. Zhang et al. (2022) explore real-time decentralized coordination, while Sun et al. (2024) address trust and privacy concerns in protocol design. These studies exemplify how routing can embed governance by defining rules, authority, and coordination processes.

Incentive Mechanisms: Incentive alignment is another core governance function explored through profit-sharing and auction mechanisms. Yea et al. (2022) develop a cooperative game-theoretic profit-sharing model, while Briand et al. (2022) introduce auction-based routing with integrated payments. Van Duin et al. (2021) and van Heeswijk (2020) show how bidding systems and smart containers can self-organize last-mile delivery, though overarching governance is needed to ensure fairness and system coherence. These models provide technical solutions for coordination but also reveal the importance of meta-governance to ensure compliance, fairness, and stability in open systems.

Relational and Contractual Governance: Several studies explicitly compare governance mechanisms. Wallenburg and Raue (2011) argue that relational governance supports conflict resolution more effectively than contracts, while Schmoltzi and Wallenburg (2012) and Raue and Wieland (2015) emphasize their complementarity in dynamic settings. Lotfi et al. (2021) and Ramjaun et al. (2023) show how governance must evolve over time, from informal trust-based structures to more formalized hybrid models. These findings reinforce the view that governance must balance structure with flexibility and adapt to the life cycle of collaboration.

Coordination and Governance Mechanisms: Finally, a cluster of studies examines facilitation and coordination structures as implicit governance mechanisms. Ciprés and de la Cruz (2019) and Schultz et al. (2021) emphasize the role of neutral facilitation and transparent rules, while practice-oriented research by Ramjaun et al. (2024) and Hingley et al. (2011) show how coordination models vary based on actor maturity and perceived legitimacy. In contrast, Sternberg et al. (2022) caution that systematic facilitation can erode trust and autonomy. These studies reveal that facilitation is not one-size-fits-all but must align with actor preferences, power dynamics, and governance needs.

3.2 Mapping Governance Research through the IAD Lens

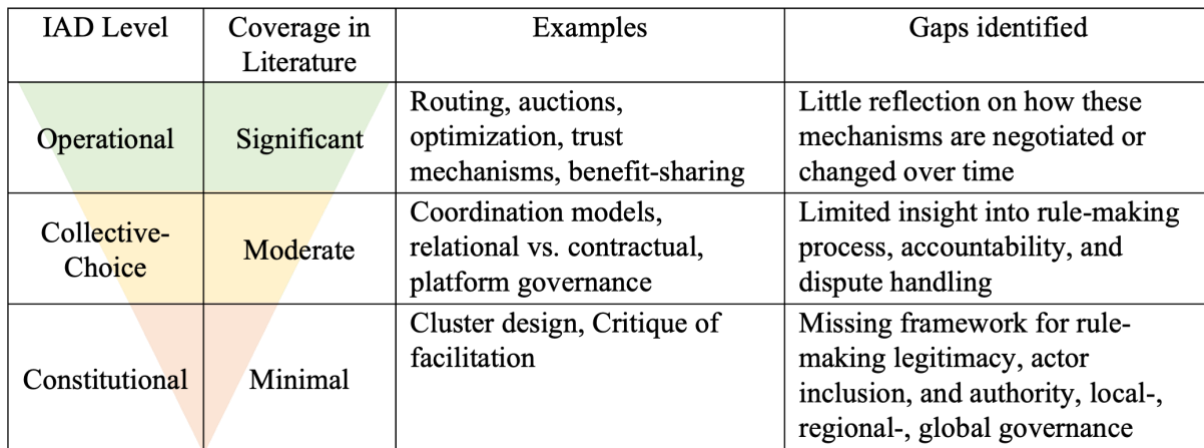
To assess the depth and orientation of governance research in the PI and HLC, we mapped the reviewed literature against the previously introduced three institutional levels defined in Ostrom's IAD framework: operational, collective-choice, and constitutional rules (Figure 2). This framework helps differentiate between the mechanisms used to execute coordination, the processes through which those mechanisms are negotiated and maintained, and the foundational structures that define governance itself.

Most of the studies concentrate on governance at the operational level. Studies in this category primarily focus on coordination mechanisms such as routing protocols, auction-based assignment systems, and trust-building practices. These include research on DI-inspired logistics protocols (Boysen et al., 2025; Gontara et al., 2018; Sarraj, Ballot, Pan, Hakimi, et al., 2014), decentralized optimization models (Achamrah et al., 2024; Q. Zhang et al., 2022; W. Zhang et al., 2020), and incentive-compatible auction schemes (Briand et al., 2022; van Duin et al., 2021). While these contributions do not always frame their findings in governance terms, they directly shape how decisions are made and responsibilities are allocated in decentralized networks, aligning closely with operational rule design.

The literature also addresses governance at the collective-choice level, particularly in the HLC domain. Studies in this area consider how collaborative arrangements are negotiated, sustained, and institutionalized. For example, Ramjaun et al. (2024) and Hingley et al. (2011) investigate facilitation models such as lead firms or third-party coordinators; Raue and Wieland (2015) and Schmoltzi and Wallenburg (2012) explore the interplay between relational and contractual mechanisms; and Sheffi et al. (2019) propose a layered governance framework for logistics clusters. These works highlight the importance of shared rule-setting, mutual adjustment, and platform governance, but often stop short of explicitly theorizing how such rules evolve or who participates in their development.

In contrast, constitutional-level governance remains largely underexplored. Only a few studies engage with questions of rulemaking legitimacy, actor inclusion, and meta-level authority. Fahim et al. (2021) introduce a governance layer within their PI port framework but limit their analysis to node-level concerns. Sheffi et al. (2019) also briefly touch on foundational design choices in logistics clusters. Sternberg et al. (2022), while critical of systematic facilitation, highlight the need for governance models that safeguard self-determination and reflect participant expectations. Their critique shifts attention from how collaboration is managed to

how it is initially framed and who holds authority to define its structure. This reveals a gap in understanding how governance in collaborative logistics is constituted and legitimated.



IAD Level	Coverage in Literature	Examples	Gaps identified
Operational	Significant	Routing, auctions, optimization, trust mechanisms, benefit-sharing	Little reflection on how these mechanisms are negotiated or changed over time
Collective-Choice	Moderate	Coordination models, relational vs. contractual, platform governance	Limited insight into rule-making process, accountability, and dispute handling
Constitutional	Minimal	Cluster design, Critique of facilitation	Missing framework for rule-making legitimacy, actor inclusion, and authority, local-, regional-, global governance

Figure 2: IAD Analysis

Taken together, this mapping shows that research in PI and HLC is heavily concentrated at the operational level, with some attention to coordination and facilitation at the collective-choice level. However, little is known about how governance structures are established and legitimized at the constitutional level. The IAD framework thus highlights not only the areas where governance thinking has been most developed but also where further conceptual and empirical work is needed.

4 Bridging Gaps: Governance and Future Research for the PI

Although individual aspects of governance in the context of HLC and PI such as routing, coordination mechanisms, or incentive structures have been studied in detail an integrated approach that systematically links these elements is still lacking. A comprehensive governance framework for the PI that brings together these dimensions and considers their interdependencies has yet to be developed.

In the beginning we emphasized that the evolution of the DI offers important lessons for the governance of the PI, while also highlighting the need to adapt these lessons to the distinct realities of physical logistics networks. The DI did not begin as a decentralized system. Early stages of development were coordinated by government and academic institutions, such as DARPA and the National Science Foundation, which provided the structural foundation for protocol development, interoperability, and stakeholder experimentation. Over time, as the system matured, governance transitioned toward stakeholder-driven models such as the IETF, which enabled decentralized rule-setting and consensus-building without centralized control.

This trajectory suggests that governance systems in large-scale, open networks like the PI do not need to be fully decentralized from the outset. Instead, they can evolve iteratively. Early governance structures may initially require coordination, oversight, and strong technical guidance to build interoperability and trust. Over time, these structures can give way to more decentralized, actor-driven models as participants gain experience and mechanisms for distributed coordination are institutionalized.

At the same time, significant differences between digital and physical infrastructures must be considered. Unlike digital data, physical goods cannot be re-sent at negligible cost, are subject to greater temporal and spatial constraints, and operate under more intense competitive pressures. These characteristics create governance requirements that go beyond protocol design

and technical coordination: they demand attention to trust-building, liability, incentive compatibility, and multi-level decision-making.

The literature review confirms these needs and identifies several important research gaps. First, most existing studies focus on operational mechanisms such as routing protocols, optimization models, and auction systems, while governance structures at higher institutional levels, such as rule-setting processes, stakeholder representation, and meta-level authority, remain underexplored. Second, current contributions rarely consider multi-level governance. There is little discussion on how governance should be structured across local, regional, and global levels, or how rulemaking authority should be distributed and coordinated across scales. Third, many studies frame governance primarily as a technical optimization problem. Yet the DI demonstrates that governance systems do not evolve through optimization alone, but through pragmatic solutions, stakeholder negotiation, and institutional layering over time. The PI will similarly need adaptive, inclusive, and legitimacy-focused governance structures that can operate effectively under real-world constraints.

To address these needs, we propose a governance framework for the PI that integrates insights from the IAD framework, DI governance, and the literature on HLC (Figure 3). The framework is structured along two dimensions: institutional layers (operational, collective-choice, and constitutional) and spatial scales (local, regional, and global). This structure allows us to address both the content of governance (what rules are needed and how they are made) and the scope of governance (where and at what scale governance takes place).

In addition to distinguishing governance levels, it is important to differentiate the underlying governance logic at each level. Drawing on the distinction between contractual and relational governance, we argue that different layers may rely on different mechanisms. At the operational level, governance tends to follow a contractual logic, emphasizing protocols, agreements, and performance control. At the collective-choice level, relational mechanisms such as trust, mutual adjustment, and consensus gain importance for resolving disputes and adapting rules to evolving needs. At the constitutional level, legitimacy and inclusion are central, and both contractual structures (e.g., formal eligibility criteria) and relational processes (e.g., long-term partnerships or shared values) play a role. The table below summarizes these elements:

	Local Level	Regional Level	Global Level
Operational Rules	Definition of local coordination practices and service standards; alignment of actor responsibilities; data exchange within nodes.	Harmonization of processes across nodes; development of shared infrastructure use protocols; oversight of corridor-level operations.	Establishment of global interoperability principles; creation of universally accepted technical standards and compliance mechanisms.
Collective-Choice Rules	Design of inclusive decision-making structures for local actors; local mechanisms for adapting operational rules and resolving disputes.	Regional coordination and planning forums; negotiation structures for cross-node rule adaptation and benefit allocation.	Institutions for cross-regional representation, rule convergence, and adaptive standard governance.
Constitutional Rules	Criteria for actor inclusion and participation; assignment of rights and responsibilities; local rulemaking legitimacy.	Definition of authority structures within regional alliances; frameworks for stakeholder representation and institutional alignment.	Foundational principles for the governance of the global system, including openness, neutrality, and institutional legitimacy.

Figure 3: Conceptual Governance Framework Elements

To operationalize this framework as a research agenda, we propose a set of guiding questions for each level of governance across spatial scales. These questions are intended to direct future research.

Operational Governance

Local: How can routing protocols be standardized within PI nodes while preserving local autonomy? What safeguards are needed for last-mile data sharing?

Regional: How should interoperability standards be developed across jurisdictions? What monitoring systems are feasible at the regional level?

Global: What minimum technical standards are required for interoperability? How can cross-border routing protocols integrate with regional constraints?

Collective-Choice Governance

Local: What voting rights and accountability structures are effective at the node level? How can stakeholders revise local rules fairly?

Regional: What coordination bodies are needed for regional planning? How should disputes and benefits be negotiated among actors?

Global: What federated decision-making models preserve local flexibility while enabling global alignment? How can diverse actors be represented equitably?

Constitutional Governance

Local: What inclusion rules and access rights define node-level governance? How is data ownership governed among local actors?

Regional: What legitimacy frameworks support regional rulemaking? How should authority be distributed in regional networks?

Global: What institutional design supports global meta-governance? How can openness and neutrality be ensured across regions?

These research questions emphasize the importance of systematically addressing how governance at different institutional levels, operational, collective-choice, and constitutional, can be effectively designed, negotiated, and legitimated across spatial scales. Together, they highlight that governance in the PI is not a monolithic construct but a layered and evolving system that must be tailored to the complexities of real-world logistics networks.

Building on this foundation, future research should pursue three interconnected directions. First, it should translate these guiding questions into concrete governance mechanisms, with particular emphasis on the currently underdeveloped collective-choice and constitutional levels. Second, empirical investigations are needed to evaluate governance models in early PI pilots, examining how coordination unfolds under practical constraints and which design choices promote legitimacy, adaptability, and adoption. Third, theoretical work should refine principles of modularity, subsidiarity, and meta-governance that support dynamic scaling across local, regional, and global layers.

By moving beyond technical coordination and engaging with the deeper institutional structures that enable trust, inclusion, and accountability, governance research can play a central role in making the PI vision operational. Rather than being defined by a static blueprint, governance must be approached as a flexible architecture, capable of evolving with the network it is meant to sustain.

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Collaborative Optimization in Open Logistics Networks

Qian Huang¹, Kohei Mishio², Shunichi Ohmori³ and Kazuho Yoshimoto⁴
^{1,2,3,4} Waseda University, Tokyo, Japan

Corresponding author: huangqian@akane.waseda.jp

Abstract: *The development of open logistics networks has advanced rapidly in Europe and has recently gained significant attention in Asia. A major challenge is enabling effective collaboration among a large number of diverse participants. This includes collaboration between different roles, such as manufacturers, warehouse operators, and transportation providers, as well as among companies with similar logistics functions.*

Previous research has primarily focused on conceptual analyses of network frameworks and key components. However, studies on practical model implementation and algorithm development remain limited. This study not only considers the multiple transportation modes but also addresses the challenges posed by different logistics players with varying priorities in network operations. To enhance overall efficiency, we propose a multi-objective optimization model that optimizes the whole logistics network simultaneously. Additionally, we analyze how factors such as participant homogeneity, heterogeneity, and fluctuations in transportation capacity impact network performance.

Keywords: *Open Logistics Networks; Multi-objective Optimization Model; Decision-making Processes; Physical Internet*

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

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

1 Introduction

In recent years, the development of Open Logistics Networks has been gaining momentum in certain advanced countries and regions. For example, China's JD Group has proposed the "Three-Network Integration" strategy, which simultaneously advances a Global Warehouse Network, Parcel Delivery Network, and Air Cargo Network. In Europe, the European Logistics Innovation Cooperation Alliance (ALICE) has introduced the concept of the Physical Internet (PI). This concept aims to transform traditional logistics hubs into Physical Internet nodes by leveraging standardized, intermodal, modular loading units. The goal is to realize a seamless, highly flexible, and resilient logistics network. These initiatives indicate that in domains related to open logistics networks, innovation and collaboration are progressing toward building more interconnected sustainable and efficient logistics systems.

However, in the process of collaboration within open logistics networks, two distinct types of coordination can be observed depending on the relationships among participants: vertical and horizontal collaboration. Vertical collaboration refers to collaboration among entities with

different roles, such as manufacturers, warehouse operators, and transportation providers. In contrast, horizontal collaboration involves coordination among companies that share similar functions (e.g., logistics providers). The latter is particularly challenging, as each company operates independently and competes for logistics resources and customers, making the establishment of cooperative relationships more complex.

This study focuses on horizontal collaboration and develops an optimized logistics network model that takes into account the goals and characteristics of participants with similar functions. By comparing locally optimized strategies—where each participant seeks to optimize independently—with strategies based on global optimization, we examine the effectiveness and necessity of cooperative behavior.

2 Related Work

Benoit Montreuil first defined the concept of the Physical Internet (PI) in 2011. While different countries and regions may use varying terms, they commonly refer to the construction and utilization of what is essentially an Open Logistics Network.

Previous research has predominantly focused on conceptual analyses and theoretical frameworks for developing PI, including its foundational components and architecture (Kubek and Więcek). Some studies have proposed mathematical models and algorithms—for example, the design and allocation of π -containers (Dang et al.), coordination among inventory hubs (Yang et al.), and integrated strategies through vertical collaboration (Ji et al.). However, these studies primarily target specific functional aspects of logistics networks and lack comprehensive quantitative analysis on the strategic collaboration among players within the network.

Moreover, a key distinction between the PI and the traditional Internet lies in its emphasis on the physical flow of goods and the diversity of transportation modes. Since the movement of cargo involves various transport methods such as trucking, railways, and maritime shipping, optimization must consider the specific characteristics and constraints of each mode and route. In particular, under conditions of limited transportation resources, competition among homogeneous players tends to intensify—making the facilitation of collaboration within such contexts a critical challenge.

Therefore, this study targets open logistics networks that include multiple transport modes and diverse players. We develop a multi-objective optimization model from both individual (local) and system-wide (global) optimization perspectives. Furthermore, we investigate how differences in homogeneity and heterogeneity among players affect the overall efficiency of the network and the effectiveness of collaboration.

3 Proposed Model

3.1 Problem description

This section presents the characteristics of the Open Logistics Network as defined in this study, along with the proposed multi-objective optimization models. Two types of decision-making processes are introduced: the individual optimization model (Local-opt) and the system-wide optimization model (Global-opt).

The individual optimization model refers to a sequential decision-making process in which each player independently formulates their transportation plan based on their own objectives. In

contrast, the system-wide optimization model seeks to determine the transportation plans for all players simultaneously, with the objective of minimizing the overall cost of the entire network.

In this study, we assume that each player typically belongs to a different company and independently aims to transport their cargo from its origin to its destination using preferred methods. However, since the logistics network has capacity constraints, competition can arise when multiple players prefer the same transport modes or routes. Under such conditions, players who are not prioritized may choose alternative modes or routes for transportation.

To avoid this kind of competition—or what may be termed a “race for resources”—a simultaneous optimization approach through the system-wide model can be introduced. By optimizing collectively, the allocation of transport resources can be better coordinated, potentially leading to more efficient and equitable outcomes across the network.

3.2 Mathematical formulation

This section defines the mathematical formulation of the proposed model. We begin by introducing the relevant sets, parameters, and decision variables used. These notations provide the foundation for constructing both the individual and system-wide optimization models in the following.

Sets

- N Set of nodes in the logistics network.
- E Set of edges representing transportation links.
- P Set of players (logistics participants).
- $M_{(i,j)}$ Set of available transportation modes on edge (i, j) .

Parameters

- d_p The demand quantity of player p .
- (s_p, t_p) The start and end nodes for player p .
- C_{ij}^m The cost per unit transported via mode m on edge (i, j) .
- R_{ij}^m The transportation rigidity per unit via mode m on edge (i, j) .
- $CO2_{ij}^m$ The CO2 emission tax per unit via mode m on edge (i, j) .
- Cap_{ij}^m The maximum transportation capacity for mode m on edge (i, j) .
- $\omega_p^{cost}, \omega_p^{rigid}, \omega_p^{co2}$ The weight coefficients for cost, rigidity, and CO2 emissions for player p .

Decision Variables

- $x_{p,(i,j)}^m$ The amount of goods transported by player p via mode m on edge (i, j) .

Objective Function

Model I : Individual Optimization Model (Local – opt)

$$\begin{aligned} \text{Min} \sum_{p \in P} \left(\omega_p^{cost} \sum_{(i,j) \in E} \sum_{m \in M_{(i,j)}} C_{ij}^m x_{p,(i,j)}^m + \omega_p^{rigid} \sum_{(i,j) \in E} \sum_{m \in M_{(i,j)}} R_{ij}^m x_{p,(i,j)}^m \right. \\ \left. + \omega_p^{co2} \sum_{(i,j) \in E} \sum_{m \in M_{(i,j)}} CO2_{ij}^m x_{p,(i,j)}^m \right) \end{aligned} \quad (1)$$

Model II : System – wide Optimization Model (Global – opt)

$$\begin{aligned} \text{Min} \quad & \sum_{p \in P} \omega_p^{\text{cost}} \sum_{m \in M(i,j)} C_{ij}^m x_{p,(i,j)}^m + \sum_{p \in P} \omega_p^{\text{rigid}} \sum_{(i,j) \in E} \sum_{m \in M(i,j)} R_{ij}^m x_{p,(i,j)}^m \\ & + \sum_{p \in P} \omega_p^{\text{co2}} \sum_{(i,j) \in E} \sum_{m \in M(i,j)} CO2_{ij}^m x_{p,(i,j)}^m \end{aligned} \quad (2)$$

Constraints

Demand Satisfaction Constraint

Each player p must transport exactly their required demand from start node s_p to end node t_p :

$$\sum_{j \in N} \sum_{m \in M(s_p,j)} x_{p,(s_p,j)}^m = d_p, \quad \forall p \in P \quad (3)$$

$$\sum_{i \in N} \sum_{m \in M(i,t_p)} x_{p,(i,t_p)}^m = d_p, \quad \forall p \in P \quad (4)$$

Flow Conservation Constraint

For any intermediate node n (excluding source and destination), the total incoming flow must equal the total outgoing flow for each player:

$$\sum_{i \in N} \sum_{m \in M(i,n)} x_{p,(i,n)}^m = \sum_{j \in N} \sum_{m \in M(n,j)} x_{p,(n,j)}^m, \quad \forall p \in P, \forall n \in N \setminus \{s_p, t_p\} \quad (5)$$

Capacity Constraint

The total amount of transported goods using a specific mode on an edge cannot exceed its capacity. The capacity constraint plays a central role in differentiating the outcomes of the Local-opt and Global-opt approaches. In the Local-opt approach, inefficient resource allocation and increased competition among players are likely to occur due to sequential decision-making. In contrast, the Global-opt model enables all players to make decisions simultaneously, reducing conflict and leading to a more efficient overall outcome:

$$\sum_{p \in P} x_{p,(i,j)}^m \leq \text{Cap}_{ij}^m, \quad \forall (i,j) \in E, \forall m \in M(i,j) \quad (6)$$

Non-Negativity Constraint

The transported amount must be non-negative:

$$x_{p,(i,j)}^m \geq 0, \quad \forall p \in P, \quad \forall (i,j) \in E, \forall m \in M(i,j) \quad (7)$$

4 Numerical Experiments

This section presents the results of computational experiments using the proposed model in scenarios involving multiple players and multiple transportation modes and routes with capacity. We applied both sequential (order-based) and simultaneous heuristic algorithms to solve the problem. Additionally, we conducted a sensitivity analysis by varying the weight values to assess how differences in player preferences affect the overall outcome.

The heuristic algorithms were implemented using Python 3.12. All experiments were performed on a machine equipped with an Intel® Core™ i7-1360P 2.20 GHz processor, 16.00 GB of RAM, and running the Windows 10 operating system. CPU times are reported in seconds.

4.1 Experimental setup

This study evaluates the performance of the local-opt and global-opt models using a test dataset. In the test scenario, four players start from the same origin point. Each player can set their transportation preference. There are three transportation modes, truck, rail, or water, each player could choose one of them to move toward the next logistics hub. Upon reaching a hub, another transportation mode or route can be used to continue, until to the destination. Each route for every mode has a limited transportation capacity, which may lead to competition among players when preferences overlap. The structure and transportation characteristics of the test problem are illustrated in Figure 1.

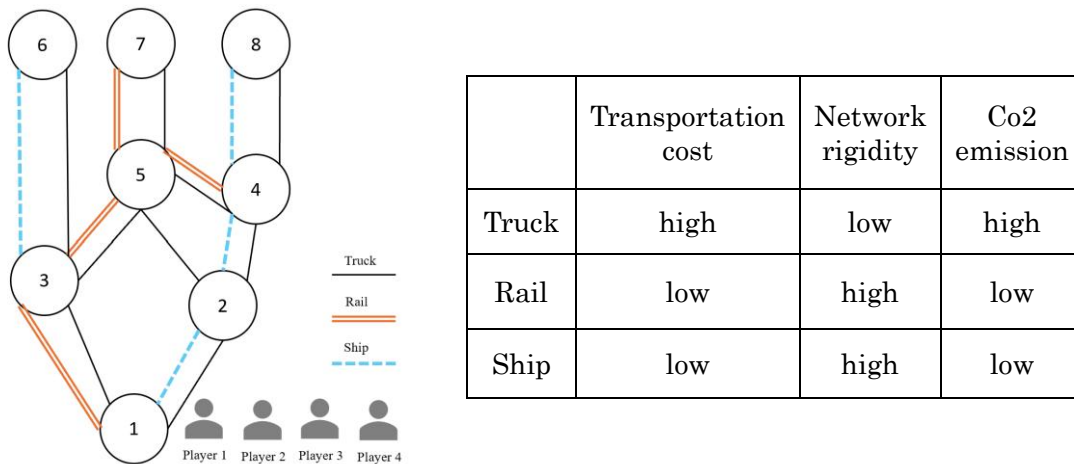


Figure 1. The structure and transportation characteristics

4.2 Results and discussions

4.2.1 Comparison of Individual and System-wide Optimization Models

To evaluate the performance of the individual optimization model (Local-opt) and the system-wide optimization model (Global-opt), we applied stochastic variations to key parameters such as demand, transportation capacity, and the weight coefficients of players. Under this setting, we conducted 100 independent simulations for each model.

As shown in Figure 2, the Global-opt model consistently achieved a lower total objective value than the Local-opt model, indicating better performance in terms of network-wide efficiency. However, it exhibited slightly higher standard deviation compared to Local Optimization. This suggests that while the global approach is more efficient on average, it is also more sensitive to variations in parameters such as demand or capacity. These findings highlight a trade-off

between efficiency and robustness, which is crucial for decision-makers in uncertain logistics environments.

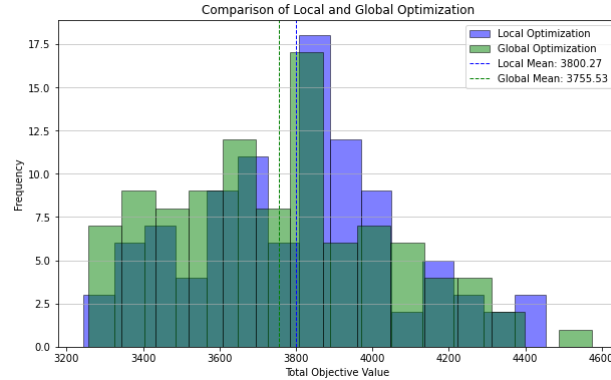


Figure 2. Total Objective Value Comparison: Local-opt vs. Global-opt

4.2.2 Effectiveness situation of Global-opt model

In this experiment, we reset the parameters to their baseline values and modified only the players' transport preferences to evaluate the impact of player characteristics. Two scenarios were tested:

- *Scenario 1 (Heterogeneous Preferences)*: Each player has a distinct priority (e.g., player 1 prioritizes cost, while player 2 focuses on minimizing rigidity).
- *Scenario 2 (Homogeneous Preferences)*: All players are aligned in their preference, such as focusing on minimizing rigidity.

The results, illustrated in Figure 3, reveal that the Global-opt model is particularly effective under *homogeneous* conditions. In such cases, limited transport resources (e.g., truck) tend to intensify competition among players, often leading to inefficiencies in the Local-opt model. By contrast, the Global-opt model can allocate resources strategically, thereby minimizing the total cost, rigidity, and CO₂ emissions of the network.

On the other hand, in *heterogeneous* scenarios—where players have differing priorities—the competition for resources tends to be lower, and the Local-opt model can achieve performance levels similar to those of the global model.

These findings suggest that under conditions of high resource contention, the importance of global optimization increases significantly.

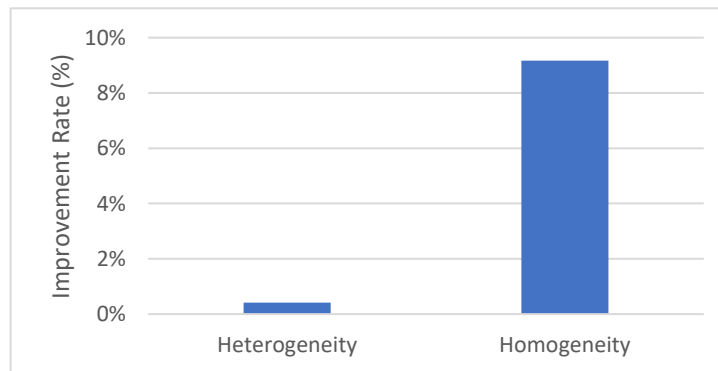


Figure 3. Comparison of improvement rates using Global-opt Model under Player Preferences

4.2.3 The Optimized Routes Under Homogeneous Player Preferences

As mentioned in the previous section, the Global-opt model is more effective when players share similar priorities. In this section, we analyze how route selections and transportation mode choices vary under a homogeneous preference environment.

We assume that all players have the same priority on rigidity, setting their weights as $\omega_{p1,p2,p3,p4}^{rigid} = 1.0$. Based on this condition, we run both the Local-opt and Global-opt models and examine the resulting transportation modes and routing paths. The results are summarized in Table 1 and Figure 4.

The findings show that the total objective value is optimized in the Global-opt model, indicating a more efficient outcome. Notably, truck transportation is more frequently selected when rigidity minimization is prioritized. We also observe changes in routing behavior. For example, Player 3 initially chooses the route:

1-Truck and Ship \rightarrow 2-Truck and Ship \rightarrow 4-Truck \rightarrow 8,
but after applying the Global-opt model, the route changes to:
1-Truck \rightarrow 2-Truck \rightarrow 4-Truck \rightarrow 8.

This shift can be explained as follows: since truck transport offers greater flexibility, players tend to prefer it in order to minimize rigidity. However, due to capacity constraints, not all players can use the truck mode exclusively. In the Local-opt model, where there is no central collaboration, players make decisions independently—often resulting in suboptimal reallocation when route conflicts occur.

In contrast, the Global-opt model acts as a central mechanism, allowing for collaborated decision-making from a network-wide perspective. This enables more strategic allocation of transportation resources, resulting in improved outcomes for all players.

Table 1: The optimized transportation routes and objective values

	Local-opt (Priority Order: [4, 1, 2, 3])		Global-opt	
	Route	Objective value	Route	Objective value
Player 1	1-T-3-T-6	1080	1-T-3-T-6 1-R-3-T-6	1140
Player 2	1-T-2-T-4-T-5-R-7 1-T-3-T-5-R-7	740	1-T-2-T-4-T-5-R-7 1-T-3-T-5-R-7	780
Player 3	1-T-2-T-4-T-8 1-S-2-S-4-T-8	2200	1-T-2-T-4-T-8	1120
Player 4	1-T-2-T-4-T-5-T-7	900	1-T-3-T-5-T-7 1-T-3-T-5-R-7	920
Total		4920		3960

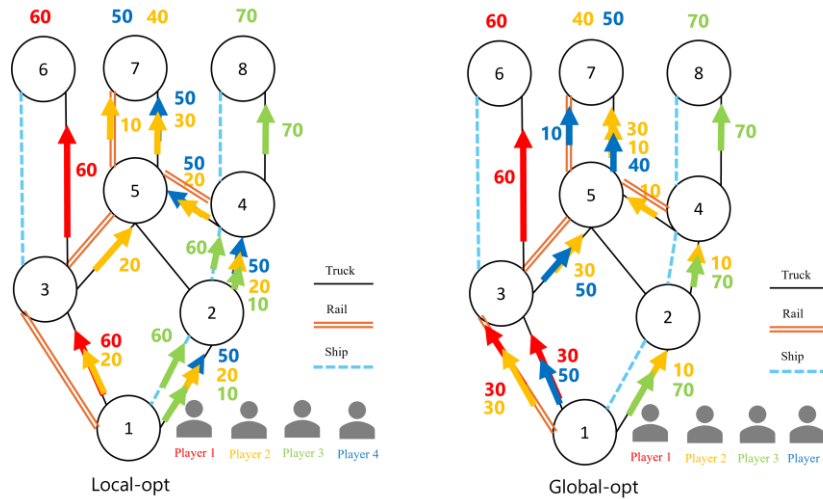


Figure 4. The transportation routes in Local-opt and Global-opt models

5 Conclusion

This study developed multi-objective optimization models for both individual (Local-opt) and system-wide (Global-opt) strategies, using sequential and simultaneous approaches to represent the behaviors of multiple logistics players. Through a series of numerical experiments, we investigated how different optimization approaches influence the overall efficiency of logistics network. Specifically, we compared Local-opt and Global-opt models across various scenarios. The results revealed that the Global-opt model consistently achieved better objective values, particularly under conditions of limited transportation capacity. A notable finding emerged in scenarios with homogeneous player preferences, where the Global-opt model effectively coordinated resource allocation, minimized conflicts, and enhanced overall performance. These findings underscore the significance of centralized collaboration mechanisms in achieving efficient and sustainable logistics within Open Logistics Networks.

Future research may focus on extending the model to incorporate additional objective functions based on real-world case studies and exploring incentive mechanisms to promote collaboration among competitive players.

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Durable Freight Routing in Hyperconnected Logistic Networks

Praveen Muthukrishnan¹, Saikrishnan Sankar¹, Sahrish Jaleel Shaikh¹, James Chris Gaffney¹,
Benoit Montreuil¹

Physical Internet Center, Supply Chain & Logistics Institute,
H. Milton Stewart School of Industrial & Systems Engineering,
Georgia Institute of Technology, Atlanta, United States

Corresponding author: pmuthukr3@gatech.edu

Abstract: *In the context of Physical Internet-based hyperconnected logistics, regional and gateway hubs promote freight consolidation between regions and urban areas. Several routing protocols, including dynamic directional routing, have been proposed to efficiently identify the best next-hop hubs based on the origin-to-destination direction. While these protocols improve hub-level decision-making, they often overlook the impact of road-level traffic dynamics, particularly in congested metropolitan regions where passenger vehicle interactions can disrupt freight movement. To address this gap, this paper introduces durable routing – a departure-time-dependent approach that leverages historical traffic patterns to predefine reliable, congestion-resilient paths. Unlike purely reactive protocols, durable routing anticipates predictable traffic cycles, ensuring stable transit times even under moderate congestion. This approach supports high-confidence dispatching, enhances route predictability, and promotes balanced modal distribution, reducing overall network congestion while maintaining service-level guarantees. We further present case study results from the state of Georgia, analyzing how factors like day-of-the-week, hour-of-the-day, and risk tolerance thresholds influence durable route selection, demonstrating the scalability and adaptability of this approach to diverse regional contexts.*

Keywords: Physical Internet, Durable Routing, Resilient Routing, Hyperconnected Logistics

Physical Internet (PI) Roadmap Fitness: ☒ PI Nodes, ☒ PI Networks, ☒ System of Logistics Networks, ☒ Logistics/Commercial Data Platform

Targeted Delivery Mode-s: ☒ Paper, ☒ In-Person presentation

1 Introduction

Freight Logistics today primarily relies on the combination of point-to-point transportation and hub-and-spoke networks, with freight moving through infrastructures dedicated to specific shipping and transportation businesses (Crainic & Montreuil 2016). The Physical Internet (PI) challenges this paradigm by introducing an open, hyperconnected logistics web grounded in hierarchical spatial structuring and multi-plane meshed hub networks. This paradigm promotes consolidation, sustainability, and systemic efficiency (Montreuil, 2011; Montreuil et al., 2018).

This paper examines regional and inter-regional freight flow through strategically located regional/inter-regional hubs that function as transit, sortation, or cross-docking centers (Muthukrishnan et al. 2024). These hubs are optimized for connectivity to key logistics infrastructure and intermodal connections, such as interstates, ports, airports, and railyards (Grover et al., 2023). However, the road links between hubs, particularly those traversing high-traffic metropolitan areas, present persistent challenges in terms of speed, reliability, and predictability.

This issue is particularly evident on interstates passing through metropolitan regions. While GPS-based routing dynamically suggests alternate exits to avoid congestion, widespread use of these recommendations often leads to secondary bottlenecks, increasing travel time uncertainty. An alternative solution involves proactively analyzing traffic patterns to identify road routes between hubs that minimize congestion while ensuring satisficing and reliable travel times. By anticipating bottlenecks and making strategic route adjustments, freight truck movement can avoid excessive delays without major detours.

In this paper, we introduce **durable routing** as a novel approach to freight movement optimization, addressing the need for consistent and predictable travel times in variable traffic environments. A **durable route** is defined as a predefined, departure-time-dependent road path that consistently delivers predictable travel times across a range of traffic conditions. These routes are identified using historical traffic data that capture temporal patterns—such as weekday/weekend cycles and peak/off-peak variations—and are strategically selected to ensure reliability even under moderate congestion.

Unlike dynamic real-time routing, which continuously adjusts based on current traffic data, or static shortest-path routing, which overlooks temporal variation in congestion, durable routing leverages repeatable traffic patterns to **enable pre-scheduled, high-confidence dispatching decisions**. This predictability supports both forward and deferred truck dispatching while maintaining robust (e.g. 99%) service-level guarantees on arrival time to destination. Furthermore, durable routing promotes **balanced modal distribution across the road network**, shifting freight volume from heavily trafficked interstates to underutilized but reliable state and local roads. Such rebalancing enhances network resilience and alleviates congestion hotspots.

Previous works on routing in hyperconnected hub networks, including directional routing protocols (Shaikh and Montreuil 2024, Shaikh et al. 2025), account for hub-level congestion in dispatch protocols. However, these studies typically overlook **road-level traffic dynamics** resulting from interactions between freight and passenger vehicles. Our framework complements and extends this body of research by embedding road network congestion directly into the route selection process.

We demonstrate the proposed framework through a case study focused on freight flows in the state of Georgia, USA. Our findings indicate that durable routing is both **scalable and regionally adaptable** and can be seamlessly integrated with existing dynamic dispatch protocols to enhance overall efficiency and reliability in hyperconnected logistics networks. To our knowledge, this is the first formal articulation and application of durable routing in the context of freight logistics.

2 Methodology

This section provides a detailed explanation of the methodology used in our framework as synthetically shown in Figure 1. Within the scope of multi-tier hyperconnected networks, we concentrate the description on freight transport using trucks operating across both regional/inter-regional hub networks and gateway hub systems. To this end, our road network is limited to routes suitable for truck traffic - specifically Interstates, U.S. highways, and State routes. The method can be implemented to include multimodal routing, for example leveraging trucking and railroading.

2.1 Identifying Critical Nodes

The proposed methodology begins with analyzing inbound and outbound freight volumes and routes associated with various destination clusters. This is followed by identifying major road intersections and cities within the target geographic area, which could serve as potential locations for gateway or regional hubs. From this stage forward, we will refer to these critical connection points as nodes.

2.2 Finding Candidate Routes Between Node Pairs

After identifying the nodes, the next crucial step is to determine a set of candidate routes that freight trucks are likely to take between each pair of nodes. We first begin by identifying the shortest route based on annual average travel time for each origin and destination node pair, serving as a baseline route. To expand the route set, we iteratively adjust segment weights to uncover alternative routes that deviate from this baseline while remaining feasible for freight transport.

Given the tendency for many of these routes to share significant overlap, a post-processing step is applied to eliminate highly similar routes, retaining only those that differ by at least 20% of their total segments. In this filtering process, we intentionally retain routes that includes critical U.S. highways and state roads in addition to the Interstates, recognizing its importance in regional/inter-regional freight movement to regions where the Interstate network is sparse or indirect. This ensures that the final set of candidate routes captures a realistic and diverse range of truck-friendly paths, all within a fixed percentage deviation from the shortest route. By preserving a broader set of plausible freight corridors, this approach enhances the resiliency of logistics systems in the face of potential disruptions such as traffic congestions, road failures, or policy restrictions.

2.3 Generating Day & Time Dependent Travel-Time Distribution on Candidates

The next phase involves examining traffic patterns along the sets of candidate road routes for each node pair. Specifically, we assess how dispatch times and risk-tolerance thresholds - determined by the *day-of-the week* and *time-of-the-day* affect the freight flow efficiency on these routes. This step is essential for capturing delay patterns induced by traffic congestion from passenger vehicles, accidents, and other roadway disruptions. By incorporating these dynamics, we can more accurately estimate the expected truck travel time between intersections.

To support this analysis, we utilize the National Performance Management Research Data Set (NPMRDS & IEEE, 2023), a comprehensive data source that provides speed and travel-time metrics for both freight and passenger vehicles. It aggregates data in 5-minute, 15-minute, or 1-hour increments and spans the entire National Highway System (NHS), and additional roadways near 26 key border crossings with Canada (20 crossings) and Mexico (6 crossings). The spatial resolution is based on Traffic Message Channel (TMC) location codes, each representing a unique, directional roadway segment. In urban areas, a TMC typically covers about half a mile to a mile while in rural areas it may span five to ten miles. With coverage of more than 400,000 TMCs and billions of observations, NPMRDS offers detailed insights into average speeds, travel times, and traffic volumes across both freeways and arterial roads—making it a critical resource for evaluating real-world freight mobility and performance. In particular, the NPMRDS offers a Massive Data Downloader feature that allows users to customize data exports by selecting specific regions, road segments, date and time ranges, and probe measures such as speed, travel time, and volume. Although the data is not available in

real time, it is updated monthly and includes historical records dating back to 2017, with coverage extending up to the month preceding the current one.

Each candidate road route identified between node pairs in the previous step consists of a sequence of TMC segments. By leveraging NPMRDS data, we can analyze the distributions of travel times on each segment based on a given departure time, characterized by time-of-the-day and day-of-the-week across year(s). By aggregating the distributions of all TMC segments within a route, we can construct a comprehensive, departure-time-dependent distribution of travel time on each candidate route. This enables a more realistic and dynamic representation of freight movement that accounts for temporal variations in traffic conditions.

Although the process of generating these temporal distributions for all candidate routes is computationally intensive, it is performed only once per geographic region. The resulting data can then be efficiently stored and reused in future planning, simulation, or optimization tasks. In the future, this process could be further streamlined through the application of machine learning or artificial intelligence techniques to accelerate the generation and refinement of route-level probe measure distributions.

2.4 Assessing Candidate Routes and Suggesting the Most Durable Route – Based on Departure Time and Robustness Level

At the start of this step, we have day- and departure-time-dependent travel time distributions for all candidate routes. For example, Route 1 from Valdosta to Augusta has this distribution of travel times on Fridays at 10:00 AM. These distributions form the basis for assessing the durability of each route. Given the origin-destination choice and operating conditions—such as day, time, and desired robustness level—the model ranks the candidate routes based on robust-time and recommends the high-durable route at that operation condition. This selection balances efficiency and reliability, considering expected traffic variability to support more resilient freight planning.

3 Case Study Results and Discussions

In this section, we demonstrate the application of our framework for identifying durable routes using Georgia, USA, as a test case. Georgia has an extensive transportation infrastructure, freight operations and well-established logistics networks, enabling demonstration at scale.

3.1 Georgia Road Infrastructure and Key Intersection Cities

We begin by pinpointing key freight corridors—including major Interstates like I-75, I-85, I-285, and I-16, as well as significant State and U.S. routes such as GA-400 and US-27. We then identify for test bed 50 network nodes in urban areas that serve as frequent freight origin and/or destination and lie at the intersections of Interstates, principal and other minor arterials. These nodes represent potential locations for regional/gateway hub networks in the context of multi-tiered hyperconnected networks. The network node set can be altered as needed.

The sampled set of key corridors also includes the 19 designated corridors identified under the Governor’s Road Improvement Program – GRIP (GDOT, 2015) which aims to enhance connectivity to the Interstate Highway System. GRIP seeks to place 98% of Georgia’s population within 20 miles of a four-lane highway, significantly improving access in rural areas. Beyond promoting safer travel, the program enhances freight mobility by increasing the

availability of truck-accessible routes and alleviating congestion on primary Interstates through better distribution of freight traffic across multiple corridors.

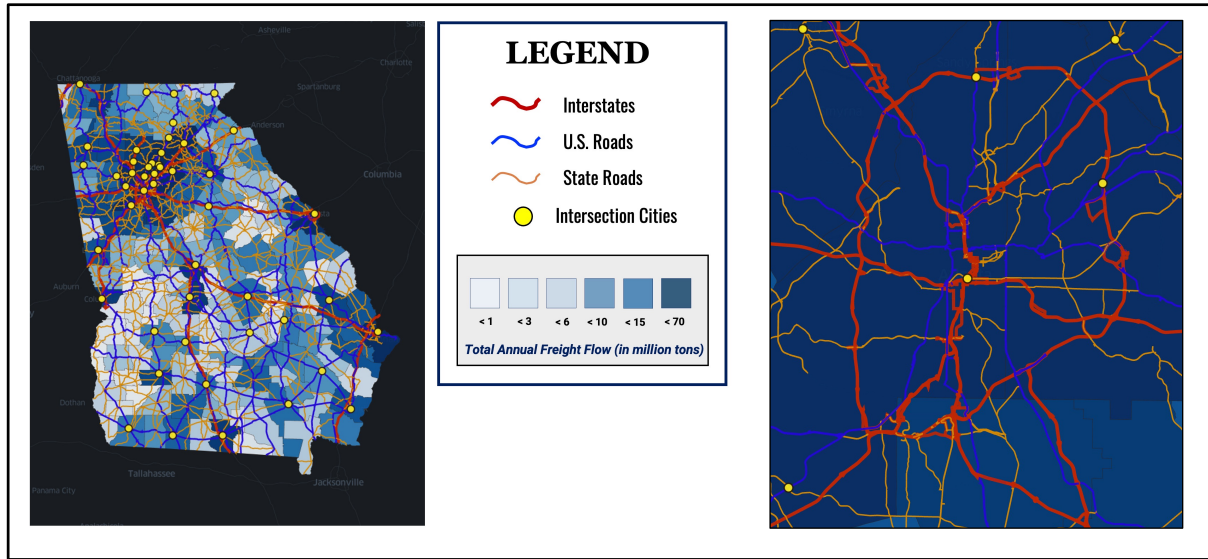


Figure 1 Sample of key network nodes of the Road Infrastructure of Georgia (50, Left) and Metro Atlanta (6, Right)

Figure 1 presents the Georgia road network used in our analysis, highlighting key network nodes, as well as counties color-coded based on their respective annual truck freight volumes comprising their inbound, internal, and outbound freight movements. The freight movement data is sourced from Freight Analysis Framework (BTS, 2024) which provides estimates of shipment weight and volume for different commodity types and modes of transportation at a county-to-county level to support planning, policymaking, and operational decisions at the state and local levels. Figure 2 makes vivid that a greater number of network nodes are located within counties exhibiting higher freight volumes, reflecting the natural co-location of freight demand, infrastructure connectivity, and economic activity.

Then, we utilize the NPMRDS dataset to extract the relevant TMCs for the identified freight corridors, comprising of 2067 Interstate segments, 6242 US routes and 11419 State routes, resulting in a total of 19728 TMC segments. It is important to note that TMCs are direction-specific—meaning, for instance, that the southbound and northbound segments of a roadway are treated as distinct entities. In the database, each TMC segment has a defined length and an associated average truck speed, which we use to calculate the average travel time.

3.2 Identifying Candidate Truck Routes Between Network Node Pairs

The next phase involves identifying a set of candidate truck routes between each pair of nodes, which may either directly represent hub-to-hub connections or form a critical segment of overall hub-to-hub link, with additionally incorporating first-mile and last-mile links between the cities and their respective hubs. Each link in this context is defined as a sequence of ordered pairs of TMC segments, arranged in the direction from the origin node to the destination node.

To systematically identify these candidate routes, we construct a directed network graph where the nodes correspond to the endpoints of TMC segments, and the edges represent the TMCs themselves. This structure allows for efficient route calculation and ensures that the spatial continuity of truck movements is preserved. For each node pair, we initiate the process by determining the shortest path between the origin and destination, based on the average travel time over entire year. This path serves as a baseline for comparison. Subsequently, we employ an iterative approach to identify two additional freight routes. To achieve this, we dynamically

adjust the weights of the TMC segments by applying a factor that accounts for variations in travel conditions, thereby generating alternative paths that deviate by no more than 20% from the annual average travel time of the shortest path. This method ensures that the identified routes are not only efficient but also robust to minor variations in travel conditions.

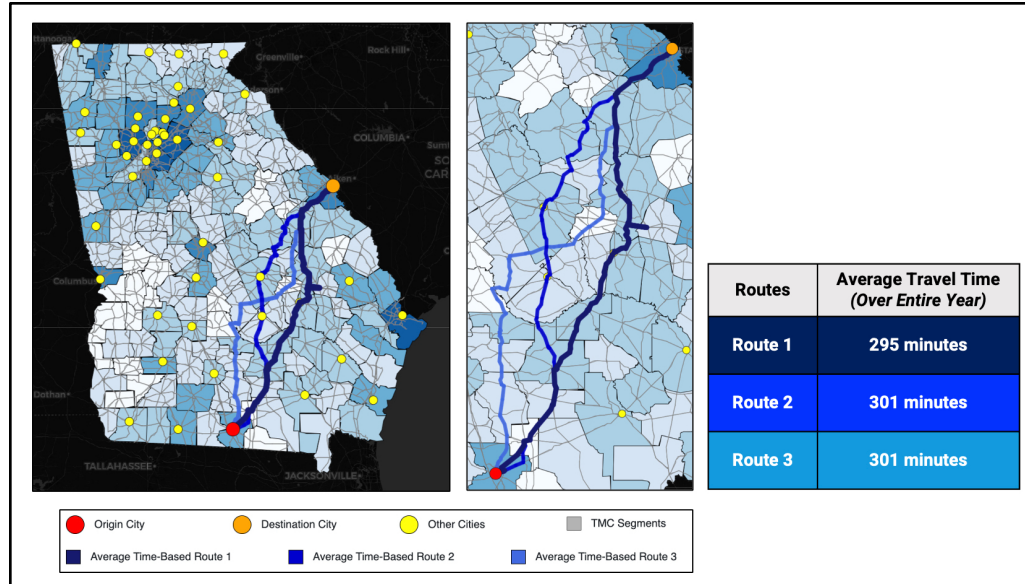


Figure 2 Three Candidates for Durable Route from Valdosta Node to August Node

Following the route generation, we conduct a post-processing step to validate and enhance the diversity of the identified routes. This step involves verifying that the alternate routes include significant state and U.S. routes, thereby avoiding over-reliance on any single corridor and ensuring practical applicability for freight transport. By incorporating a mix of major roadways, the resulting routes are more likely to be operationally feasible and resilient to disruptions, when incorporating traffic patterns. Figure 2 with the routes numbered in ascending order of their annual average travel time – with *Route 1* having 295 minutes, and *Routes 2 and 3* each having 301 minutes. On an annual average, the travel times for these routes show minimal variation, with only a 6-minute difference. Further, we propose conducting field studies, which would involve ground-truthing the routes through real-world observations and stakeholder consultations. Such validation would not only enhance the accuracy of our analysis but also provide valuable insights into the practicality and reliability of the proposed alternate routes.

3.3 Incorporating Travel Time Distributions on Candidate Routes

With the candidate freight routes identified, the next step is to incorporate the travel time distributions along these routes for all inter-node links. For this study, we focus on analyzing traffic patterns for the year 2024. However, future studies could expand this scope to include multiple years, allowing for the identification of long-term trends and seasonal variations.

3.3.1 Extracting Travel Time Data for Individual TMC Segments

We begin by extracting average travel time data for trucks from the NPMRDS, capturing measurements at 15-minute intervals throughout 2024 for the TMC segments that make up the links of the candidate routes. This data reveals substantial variation in travel times, exhibiting

distinct day-of-the-week and time-of-the-day seasonality, reflecting the dynamic nature of freight traffic.

3.3.2 Calculating Travel Time Distributions of Candidate Routes

Given this variability in the travel times of TMC segments, accurately incorporating these travel time variations into the candidate routes, presents a significant modeling and computational challenge. To address this, we simplify the analysis by focusing on hourly departure time variations for these links (*instead of every 15-minutes*), striking a balance between capturing realistic traffic dynamics and maintaining computational efficiency. Specifically, for each candidate route, we estimate the travel time from the origin to the destination based on hourly departures from the origin throughout the year.

Many of these links span multiple hours. The primary difficulty in estimating these departure-time-dependent travel time distributions is in determining which TMC segment is reached at each hour along the route and applying the appropriate average travel time for that segment, aligning the link traversal with the corresponding time window.

3.4 Suggesting Durable Routes in Different Operational Settings

Now, to demonstrate the operationalization of durable routing, we here evaluate the robustness of multiple candidate routes for a given node pair by analyzing the variability in their travel time distributions. The tested pair has a Valdosta node as origin and an Augusta node as destination. Figure 2 for illustration of alternative routes. Durable routes are characterized by their ability to consistently provide reliable travel times, even under uncertain and variable traffic conditions. We introduce a method to quantify this reliability through robust travel time thresholds, which reflect the maximum travel time not exceeded on a specified percentage of days (e.g., 99%, 70%) for a given departure time.

Our analysis focuses on three key dimensions: (1) variation across days of the week for a fixed departure time, (2) variation across departure times within the same day, and (3) variation across robustness levels for the same route and departure window. These complementary perspectives allow us to assess the stability and adaptability of durable routing in different operational contexts. To make the analysis interpretable and actionable for decision-makers, we classify each candidate route into one of three durability categories—**high-durable**, **medium-durable**, and **low-durable**—based on its statistical performance at the specified robustness threshold. In Figures 4 to 6, this classification is visually represented in each plot through a consistent color scheme. **Dark purple** indicates a *high-durable route*: these routes exhibit tightly clustered travel time distributions with short right tails and low robust travel time values. **Light purple** represents a *medium-durable route*: these routes show moderate spread and longer tails, with higher variability in travel time. **Light red** marks a *low-durable route*: characterized by wide distributions and long right tails, indicating significant risk of delay under adverse traffic conditions.

Each subplot in Figures 4 to 6 displays a histogram of historical travel times, with the x-axis denoting travel time in minutes and the y-axis representing the proportion of observed days falling into each time bin. An overlaid orange **kernel density curve** smooths the histogram to visualize the shape of the travel time distribution. Blue text represents the average travel time for the route over the entire year, the vertical green line indicates the average travel time for the selected day and hour, and the dashed red line shows the travel time at the chosen robustness threshold (e.g., 99%) for that day and hour, marking the maximum travel time expected to be exceeded just 1% of the time. The shape of the right tail in plots of Figures 4 to 6 is especially important in understanding route durability. A long or heavy right tail suggests greater variability and vulnerability to traffic disruptions—even if the average travel time appears

favorable. In contrast, shorter, steeper tails reflect more predictable route performance with fewer extreme cases, making such routes more desirable for reliable freight operations.

3.4.1 Variation based on Hourly Departure-Time

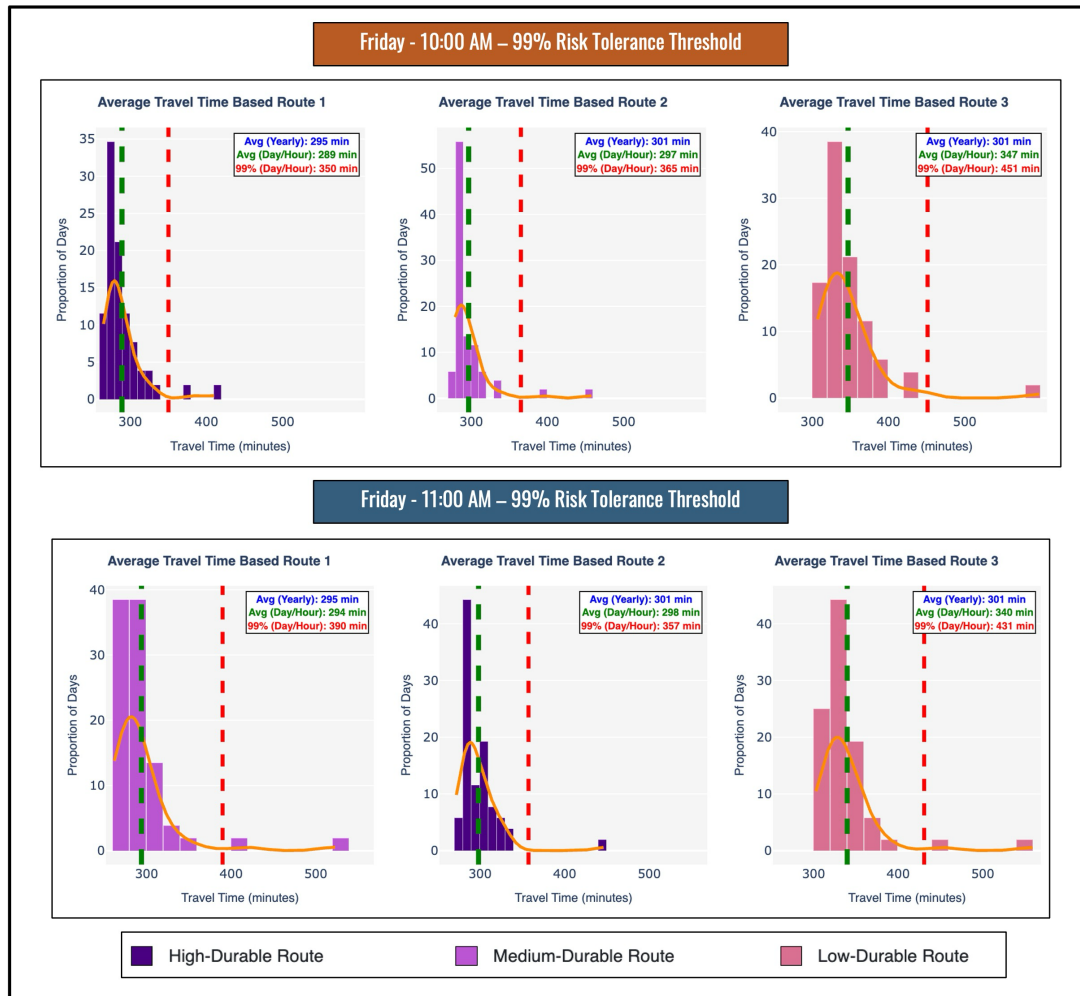


Figure 3 Contrasting the durable performance of three alternative routes from Valdosta to Augusta nodes based on 10am vs. 11am departure

Figure 3 presents the travel duration distribution of three routes from the Valdosta node to the Augusta node based on 1-hour departure time variations on Fridays at 99% robustness. On an annual average, the travel times for these routes show minimal variation, with only a 6-minute difference.

At 10:00 AM, Routes 1 and 2 have similar average travel times of 289 and 297 minutes, respectively, with corresponding 99% robust travel times of 350 and 365 minutes. At this hour, Route 1 emerges as the high-durable option under the 99% risk threshold.

However, by 11:00 AM, while Route 2 maintains similar average and 99% robust travel times, Route 1's 99% robust time increases significantly, widening by 40 minutes from 350 to 390 minutes. This shift indicates that Route 1, despite being the shortest on average, becomes less consistent due to increased congestion. In contrast, Route 2 demonstrates greater stability, making it the high durable route at 11:00 AM.

This analysis underscores that small adjustments in departure time can significantly influence which route is deemed the high-durable route, highlighting the dynamic nature of travel time reliability.

3.4.2 Impact of Days-of-the-Week Factor

Figure 4 illustrates the proposed durable route from Valdosta to Augusta based on different days of the week at 10:00 PM at a 99% risk-tolerance threshold. On Mondays at 10:00 PM, Route 1 has an average travel time of 285 minutes with a 99% robust time of 320 minutes, while Route 2 averages 296 minutes with a 99% robust time of 359 minutes. This makes Route 1 the high-durable option on Mondays 10:00PM.

However, on Sundays at 10:00 PM, the situation shifts. Route 1 averages 288 minutes with a 99% robust time of 360 minutes, while Route 2 has a similar average of 290 minutes but a significantly lower 99% robust time of 325 minutes. This makes Route 2 the more durable choice on Sunday nights.

This variation highlights that the high-durable route can change depending on the day of the week, even at the same departure hour.

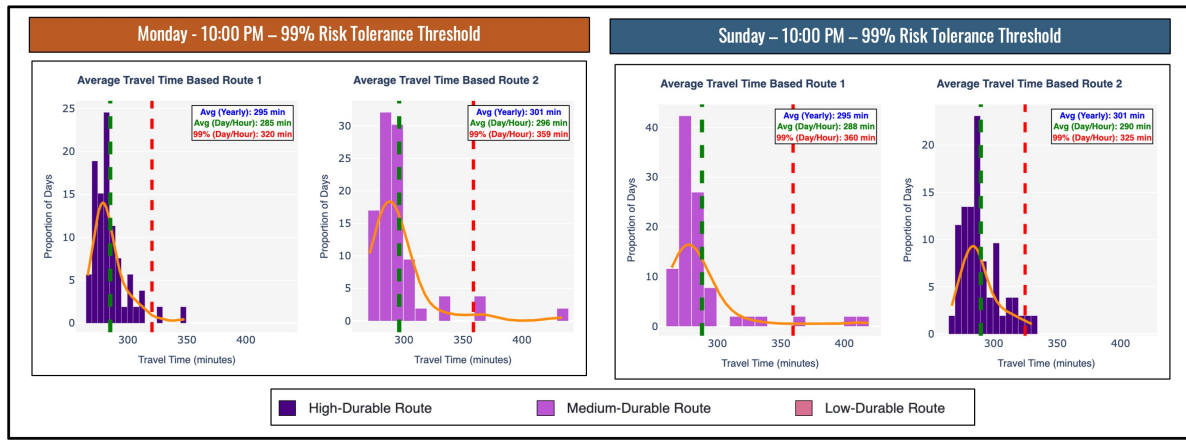


Figure 4 Durable routes from Valdosta to Augusta nodes on Sunday vs. Monday

3.4.3 Impact of Risk-Tolerance Thresholds

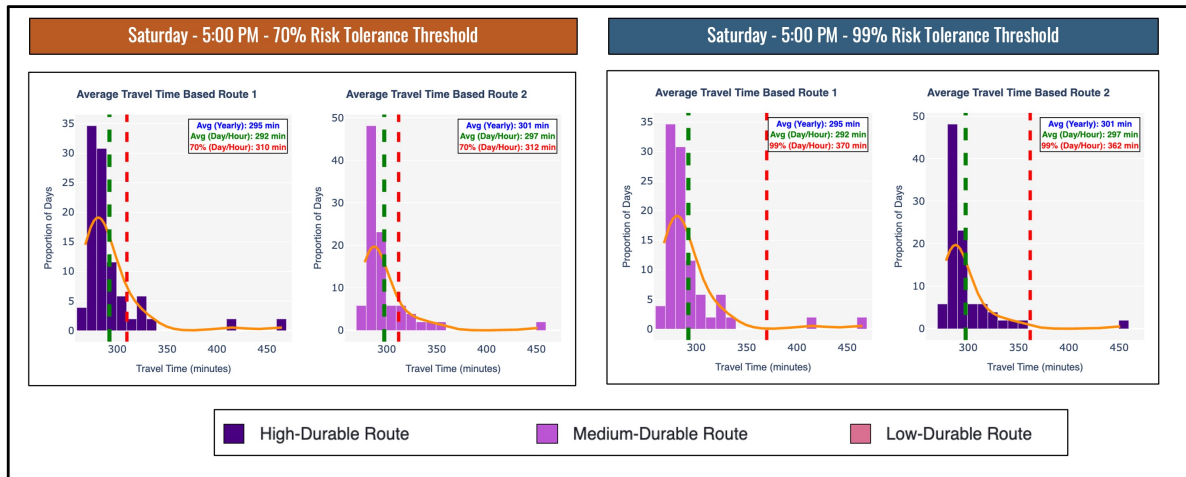


Figure 5 Valdosta to Augusta nodes: Proposed durable route based on different risk-tolerance thresholds

Figure 5 presents the proposed durable route from Valdosta to Augusta, with a departure at 5:00 PM on Saturdays, based on different robustness levels. At this hour, Routes 1 and 2 have similar average travel times, at 292 and 297 minutes respectively, with corresponding 70% robust times of 310 and 312 minutes. Under this threshold, Route 1 emerges as the high-durable route. However, when the risk threshold is raised to 99%, Route 1's robust time increases to 370

minutes, while Route 2's remains at a lower 362 minutes, making Route 2 the high-durable choice under this higher threshold. This highlights that the selection of a high-durable route can vary significantly based on the chosen risk tolerance, even if the route is not the shortest on average. This consideration is particularly important for trucks transporting time-sensitive freight.

These visuals in Figures 4 to 6 highlight the fact that durability is a function of both route and context—not an inherent attribute of the path itself, but a reflection of its behavior under specific conditions. By evaluating robustness at different times of day, days of the week, and risk tolerance thresholds, planners can identify context-aware durable routes that balance speed with consistency. This durable route classification and visualization approach thus supports data-driven route selection, enabling logistics planners to make informed decisions that align with service level commitments and operational resilience goals.

4 Conclusion and Future Research

This paper introduced durable routing as a novel approach to enhance freight transportation reliability in hyperconnected logistics networks. Our Georgia-based case study demonstrated how the choice of high-durable route varies significantly based on temporal factors – *such as day-of-the-week and time-of-the-day* - and risk tolerance levels. Notably, the route with the shortest average travel time over the year often proved less durable under higher risk tolerance thresholds, as it exhibited greater vulnerability to delays during peak congestion periods. These findings highlight the critical importance of incorporating both temporal patterns and risk considerations into freight routing decisions.

This work complements existing Physical Internet directional routing protocols that optimize hub-level decisions but often overlook time-dependent traffic dynamics on connecting road segments. The integration of durable routing with these protocols offers promising opportunities for future research, including:

- **Developing hybrid models combining durable route planning with dynamic dispatch optimization:** These integrated frameworks would optimize dispatch timing, hub-selection, and durable-route choice decisions. By coordinating these elements, logistics planners could strategically adjust time departures to coincide with high-durable route while maintaining delivery commitments and consolidation opportunities.
- **Exploring the impact of seasonal variations through multi-year traffic pattern analysis:** Extending beyond daily and weekly patterns, this research would analyze multiple years of traffic data to identify holiday-related congestion, weather influences, annual events, and long-term traffic trends. These insights would enable more sophisticated planning models that adapt routing recommendations based on seasonal factors and predictable disruptions.
- **Extending the framework to incorporate multimodal transportation options:** This direction would expand durable routing to include rail connections, last-mile delivery alternatives, and intermodal transfer points. The research would identify optimal conditions for mode switching, particularly around congested urban interfaces, creating more flexible and efficient logistics networks that can bypass road congestion through alternative modes when advantageous.

By addressing the gap between hub-level and road-level optimization, durable routing contributes to more reliable, predictable, and efficient hyperconnected logistics systems that can better withstand the variability inherent in shared transportation infrastructure.

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Towards a Demand Estimation Framework applied to Hyperconnected Transport Systems in Regional Areas

Liz Araceli Cristaldo¹, Eva Petitdemange¹, Matthieu Luras^{1,2}, Benoit Montreuil^{2,1}

¹Industrial Engineering Center, IMT Mines Albi – University of Toulouse, Albi, France

²Physical Internet Center, ISyE, Georgia Institute of Technology, Atlanta, USA

Corresponding author: liz.cristaldo_jimenez@mines-albi.fr

Abstract: *This paper proposes a modular, utility-based demand estimation framework tailored to hyperconnected regional transport systems, inspired by Physical Internet (PI) principles. By treating both passenger and freight flows as standardized Logistic Units (LUs), the framework unifies diverse mobility needs into a single decision-support model. It dynamically adjusts user preferences across multiple criteria: cost, time, emissions, comfort, reliability, and safety, and evaluates transport demand under varying service conditions. The approach is structured in three phases: independent demand modeling, transport network integration, and utility-driven demand allocation. Eight experimental scenarios are developed, combining trip variability, vehicle availability, and utility calculation methods. Applied to the ECOTRAIN project in the Occitanie region of France, the framework models eleven user profiles across six transport modes. The study demonstrates how PI-aligned, data-driven modeling can support strategic, tactical, and operational decisions for more inclusive, sustainable, and efficient regional mobility.*

Keywords: *Physical Internet, Hyperconnected, Demand Estimation, Regional Transport, Supply Chain Management, Utility-Based Model, Mixed Passenger-Freight Transport, Decision-Support Tool.*

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

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

1 Introduction

Transport services face increasing pressure to accommodate the evolving expectations of both passengers and freight carriers, particularly around cost, sustainability, and efficiency. However, the **requirements in urban areas do not directly transfer to regional contexts**, needing different approaches. While urban networks benefit from consistent infrastructure, advanced technologies, and competitive offerings, regional systems are constrained by low population density, sparse demand, limited infrastructure, and socioeconomic disparities, as noted by Sieber et al. (2020).

From a **passenger perspective**, these constraints make it difficult to operate economically viable public transport, which often leads to a near **“private car monopoly”**. This situation creates multiple problems: first, a limited transport offer fails to serve diverse mobility needs, leaving groups like the elderly, youth, and individuals with disabilities without adequate travel options; second, an overreliance on cars increases emissions, undermining sustainability goals;

and finally, a combination of infrastructure deficits, long distances between towns, and limited understanding of user expectations hinders the design of effective mobility solutions, whether through scheduled routes, on-demand services, or innovative multi-modal solutions.

Freight transport in these regions faces similarly difficult conditions. As Sieber et al. (2020) point out, routes are typically longer and less direct than in dense urban networks, making service less profitable and limiting the number of logistics providers. Those that do operate often do so in isolation, with minimal collaboration. Moreover, freight requirements for agricultural, livestock, or other region-specific products do not always match the standardized logistics practices used in urban markets. Consequently, local **freight customers' expectations** regarding cost-effectiveness, reliability, or specific handling **frequently go unmet**, intensifying the mobility deficits already observed on the passenger side.

Collectively, these challenges highlight a **pressing need for context-specific solutions**, leading to a central question: *How can transportation services in regional areas be made more accessible, efficient, and sustainable?* To answer this question, one must first understand how transport demand in regional areas differs from urban contexts in terms of **user composition** (passengers and freight operators), **expectations** (cost, trip time, environmental impact, reliability, comfort, safety), and **spatial characteristics** (longer distances, lower population density, weaker network connectivity).

Several existing approaches are relevant to regional transport demand estimation. **Utility-based models** align transport offerings to potential users, modeling how different traveler and freight segments select modes based on their preferences. Meanwhile, **Physical Internet (PI) principles**, introduced by Montreuil (2011), emphasize **flow consolidation** (particularly through containerization) and **synchronization** to improve transport efficiency in fragmented networks. Building upon these ideas, **our proposal integrates utility-driven models within a PI framework**, pairing containerization and synchronized transport modes for both passenger and freight mobility. By providing a demand estimation component, we aim to guide operators toward more efficient, responsive, and sustainable regional transport systems.

To address remaining gaps, this paper introduces a **demand estimation framework** that dynamically adjusts the relative importance of transport features based on context, thereby improving accuracy in low-density, irregular demand environments. By merging passenger and freight requirements into a unified utility model, the framework proposes a **“multipurpose transport system”** concept tailored to regional conditions. The **core concept** of this proposal consists of treating all entities, people or goods, as standard “logistic units” (LUs), akin to the PI-containers proposed by Montreuil et al. (2014). These modular, standardized units enhance interoperability across different transport modes. Within this framework, LUs travel in mode-specific “shuttles” operating on arcs that connect origin–destination (O–D) pairs. Each arc designates which vehicle types are permitted, reflecting the capacity and accessibility of the route.

Finally, **the study aims** to predict, for specific time frames, the volume of LUs traversing each arc and using each type of shuttle in the network. By capturing these flows under diverse conditions, operators can better match transport capacity to demand, mitigating the challenges inherent in low-density regions and enabling more sustainable, economically viable services. This paper proposes a novel, unified demand estimation model tailored to regional transport systems by integrating utility-based decision modeling with Physical Internet principles.

The remains of this paper is structured as follows: **Section 2** presents the literature review, describing existing approaches to transport demand estimation and their relevance to regional transport. **Section 3** introduces the proposed demand estimation framework, detailing its

methodology and the experimental scenarios used to evaluate different transport configurations. **Section 4** applies the framework to a case study, demonstrating its practical implementation in a regional transport setting. Finally, **Section 5** discusses key findings, draws conclusions, and explores research avenues.

2 Literature Review on Transport Demand Estimation

Accurate transport demand estimation in regional areas presents two core challenges: first, understanding context-specific expectations of users (both passengers and freight operators); and second, adapting or designing methodologies that reflect these expectations in low-density, infrastructure-limited territories. One foundational concept in demand modeling is **utility theory**, which underpins many estimation frameworks by quantifying the attractiveness of transport options from the user's perspective. As Cowie (2009) notes, individuals seek to maximize their utility and will switch modes if they perceive higher benefit elsewhere.

The literature presents a variety of utility-based modeling strategies. While each approach brings valuable insights into transport behavior, most were developed for urban contexts with dense networks and predictable flows. Below, we organize these methods into four main categories: (1) traditional econometric models, (2) dynamic/adaptive models, (3) machine learning approaches, and (4) freight-specific and regional models.

Econometric models, particularly the Multinomial Logit (MNL) and Nested Logit structures, are widely used in passenger demand analysis due to their simplicity and interpretability. Ranjan and Sinha (2024), for example, applied MNL models to assess urban passenger mode choices by evaluating factors such as travel time, cost, comfort, and noise exposure. While the model effectively captures mode preferences in congested and service-limited urban settings, it relies on static preference weights and does not account for how user behavior may shift throughout the day or across changing conditions. Liu et al. (2019) extended the traditional framework by using Nested Logit models to study multimodal travel behavior, integrating both stated and revealed preference data. Although demographic variables like age, gender, and income were considered, the model still grouped users into coarse segments and assumed fixed utility weights, limiting its responsiveness to evolving user expectations. These foundational models offer a solid base for demand modeling but fall short when dealing with adaptive or highly dynamic decision-making environments.

To overcome the limitations of fixed-preference models, several studies have developed **dynamic approaches** that better reflect evolving travel behavior. Ferrari (2014) introduced a freight-focused model using random utility maximization with cost functions that adapt in real time to changes in infrastructure usage and congestion levels. This model improved modal split predictions by accounting for feedback between demand and supply conditions. In the passenger domain, Zannat et al. (2024) applied an agent-based microsimulation framework that allows individual utility scores to shift depending on the scenario, thus capturing context-sensitive decisions. Similarly, Mohri et al. (2024) examined crowd-shipping dynamics using a binomial logit model that includes adaptive variables such as users' available time, expected compensation, and socioeconomic factors. While these models provide greater flexibility and realism than their static counterparts, they remain rare in rural and regional contexts and are often restricted to either passenger or freight flows in urban areas.

Machine learning models offer powerful tools for capturing non-linear relationships and high-dimensional interactions in transport decision-making. Nam and Cho (2020) utilized deep neural networks to analyze urban mode choice behavior, demonstrating that these models can outperform traditional logit models by learning complex dependencies among variables such as cost, travel time, and frequency. However, their applicability is limited by their "black-box"

nature, high data requirements, and limited interpretability—factors that reduce their practicality for real-time decisions or for data-scarce rural environments. In a related effort, Beuthe et al. (2008) compared multi-criteria decision-making methods with neural networks to assess freight transport preferences. Their results show better predictive accuracy but rely on static input weights, again limiting adaptability. Although promising in terms of accuracy, these models are not yet widely adopted for regional transport planning due to technical complexity and limited data availability.

A smaller body of literature directly addresses the unique challenges of freight and passenger demand estimation in **low-density regions**. Jourquin (2022) investigated interregional freight mode choices using Box-Cox transformations, which helped manage non-linearity and multicollinearity among variables such as cost, transit time, and distance. However, the study focused primarily on strategic freight planning and did not incorporate broader attributes such as safety or reliability, nor did it account for passenger flows. Habib (2015), in contrast, developed a utility-theoretic model for older adults in Canada’s National Capital Region (NCR), combining random utility maximization with a Cobb-Douglas formulation to estimate both mode choice and travel distance. The study revealed how urban form and accessibility influence transport decisions and highlighted the risk of social exclusion in areas with poor mobility options. While these studies provide valuable insights into regional mobility, they are typically single-purpose—focusing on either freight or passengers—and seldom adopt an integrated, modular perspective capable of modeling both within a unified framework.

Despite the strengths of existing methodologies, certain limitations persist in their adaptability and scope. Most methodologies focus exclusively on either passenger or freight transport, with mixed passenger-freight analysis being rare. Notable exceptions explore urban crowd-shipping but remain limited to specific contexts. Furthermore, most methodologies are tailored to urban environments, addressing challenges like congestion and multimodal networks, while regional or low-density areas are largely unexplored despite their distinct mobility challenges. These complexities highlight the need for **adapted** demand estimation methodologies. Additionally, many approaches evaluate standard features such as travel time, cost, and comfort but often assume static user preferences, failing to account for temporal variability, such as changes throughout the day or week. While dynamic approaches like evolving cost functions in freight-focused studies offer promise, they are rarely extended to passenger transport, highlighting the need for **adaptable** methodologies. Consequently, our proposition is a methodology to address the identified gaps by providing a tailored demand estimation framework adapted to hyperconnected, low-density transport systems.

3 Demand Estimation Framework Proposal

The methodology is structured to first clarify demand independently of supply (Phase A), then incorporate the constraints and characteristics of the network (Phase B) and finally estimate the actual demand allocation (Phase C).

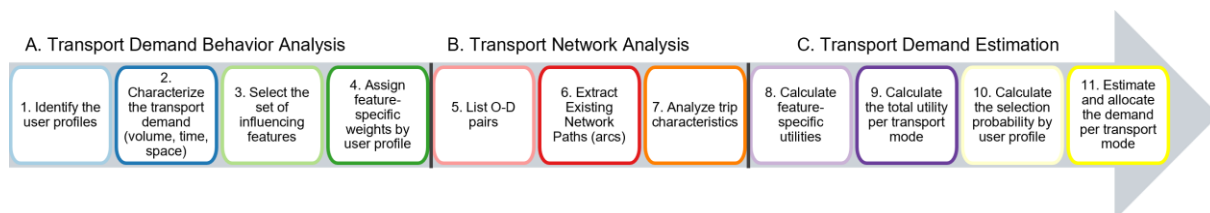


Figure 1. Regional Transport Demand Estimation Framework Proposal

In the spirit of the Physical Internet (PI), this demand estimation framework adopts a modular and interoperable structure that separates user behavior analysis from transport supply

constraints. Inspired by the encapsulation logic of PI containers, it introduces the concept of Logistic Units (LUs), a unified measurement approach used for both freight and passengers. LUs are standardized, modular representations of individuals or cargo units, enabling integrated processing, analysis, and flow management across all transport modes.

This separation and standardization support PI principles by enabling scalable, dynamic, and flexible planning, where diverse flows can be matched to available network services based on evolving preferences and real-time conditions.

A. Transport Demand Behavior Analysis

This phase provides a supply-independent overview of demand:

1. **Identify the User Profiles:** Determine who (or what) is traveling (e.g., students, managers, containers), noting any distinguishing traits.
2. **Characterize the Transport Demand:** Specify origins, destinations, travel times, and volumes for each LU, providing the maximum *latent demand* without capacity or schedule limits.
3. **Select the set of Influencing Features:** List the key factors that affect travel choices (cost, travel time, emissions, comfort, reliability, safety).
4. **Assign Feature-Specific Weights by User Profile:** Each profile can have *fixed* or *evolving (adaptive)* preferences. For instance, a user who initially prioritizes cost may later decide that travel time matters more.

B. Transport Network Analysis

In this phase, the theoretical demand is evaluated against the network's actual configuration:

1. **List Origin-Destination (O-D) Pairs:** Identify which city pairs (or nodes) have demand.
2. **Extract Existing Network Paths (arcs):** Specify which routes connect these points along with the transport mode they can carry.
3. **Analyze Trip Characteristics:** Determine whether each transport mode's attributes remain *constant (average)* or vary according to *schedule-based factors (variable)*. In the constant approach, attributes are treated as stable throughout the day, providing a simplified baseline. By contrast, variable (schedule-based) attributes reflect time-dependent conditions such as rush-hour traffic or limited-service availability (e.g., no buses at night).

C. Transport Demand Estimation

Finally, this phase combines (A) the demand profiles and preferences with (B) the network's operational data to determine how many LUs actually use each mode, under real constraints:

1. **Calculate Feature-Specific Utilities:** This step can be conducted in two ways. In the *a priori (single) calculation*, LUs choose a transport mode at the start of their trip, relying on average or schedule-based parameters, and do not revisit that choice. Conversely, under the *per-segment calculation*, LUs re-evaluate their options after each segment, accounting for changes such as delays or shifting preferences.
2. **Calculate the Total Utility per Transport Mode:** In this step, the user-defined weights are applied to the feature - specific utilities, producing an overall utility score for each transport mode. A higher total utility implies a stronger preference, reflecting how different user profiles perceive and prioritize the available transport options. This calculation reveals how well each mode aligns with the specific preferences of diverse user groups.

3. **Calculate the Selection Probability by Transport Mode:** In this step, each transport mode's overall utility is translated into the probability that a given user profile will select that mode over the available alternatives. By comparing the utility of each mode to the total utility of all modes, the model determines the likelihood that a particular user group will opt for one mode versus another. This calculation is performed for every user profile and transport mode, generating a comprehensive distribution of preferences across all options.
4. **Estimate and Allocate the Demand per Transport Mode:** This step calculates each mode's potential demand by integrating user preferences and computed utilities over time. Although passenger and freight flows are managed within a unified framework, the demand calculations remain segmented to clearly identify specific capacity requirements. In an *unlimited capacity* scenario, every LU (passenger or cargo) uses its preferred mode without restriction. By contrast, under a *limited capacity* scenario, once a transport mode reaches capacity, any additional LUs remain unserved, modifying the initial allocation. The final allocation thus reveals how many LUs each mode carries per O-D pair and time interval, as well as any unmet demand.

4 Application Case

Regional territories across France, home to over 22 million people, face growing mobility challenges due to car dependency, sparse public transport, and long distances to essential services such as schools, healthcare, and markets. In the Occitanie region, for example, Méloix and Péalaprat (2021) report that nearly 700,000 workers live within five kilometers of their workplace, yet more than two-thirds of these short-distance commutes are made by car. This reflects broader structural limitations in transport accessibility, sustainability, and social inclusion.

To address these issues, the French **ECOTRAIN initiative**, proposed by ADEME (2022), aims to revitalize underused railway lines by introducing autonomous, modular shuttles capable of transporting both passengers and freight. This innovative solution aligns with **Physical Internet (PI)** principles by promoting modularity, interoperability, and the shared use of infrastructure to support flexible, demand-responsive services in low-density territories.

The proposed demand estimation framework is applied to a simplified ECOTRAIN network connecting eight cities in the Occitanie region in France: *Toulouse, Castres, Montpellier, Revel, Castelnau-d'Aud, Carcassonne, Narbonne, and Béziers* (see Figure 2). The network integrates urban and peri-urban nodes, where **both passenger and freight flows** are modelled using **Logistic Units (LUs)**, a unifying measurement inspired by **PI container logic**. By representing all flows as modular, standardized entities, the system supports **PI-aligned operational planning** that **challenges conventional distinctions between freight and passenger transport**.

The model includes **11 user profiles**, representing both passengers and freight, each with different behavioral preferences and priorities. On the passenger side, profiles include primary, secondary, and tertiary students; farmers; intermediate and blue-collar workers; white-collar professionals; elderly people and tourists. On the freight side, the profiles cover industrial goods, consumer goods, and perishable goods. Each of these user types evaluates transport options based on six features: **cost, travel time, environmental impact, comfort, safety, and reliability**. These features were selected based on a literature review of factors that users most commonly consider when choosing between transport modes, particularly in multimodal and regional mobility contexts.

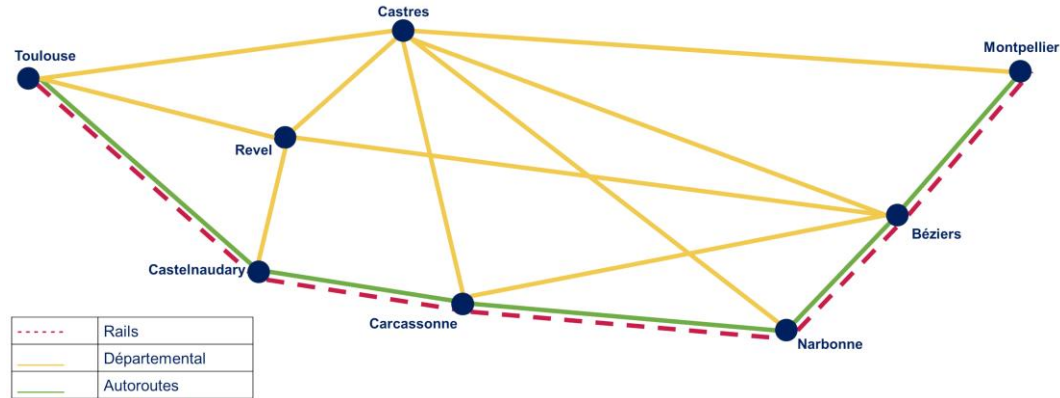


Figure 2. Network of nodes and arcs representing the case study

The relative importance, or weight, assigned to each feature is also based on findings from existing studies that analyze user preferences across demographic groups and freight types. These preferences are not static; they evolve over time and context and are defined in a dynamic profile-weight matrix that allows the model to reflect temporal sensitivity and adaptive behavior. Table 1 presents an example of this matrix at 8:00 AM, illustrating how different user profiles prioritize transport features at that moment in the day.

Table 1. Profile-Specific Weights for Transport Features at 8:00 AM

User Profile	Cost	Travel Time	Environmental Impact	Reliability	Comfort	Safety
Primary Students	0,2	0,2	0,1	0,2	0,1	0,2
Secondary Students	0,2	0,2	0,2	0,2	0,1	0,2
Tertiary Students	0,2	0,2	0,1	0,2	0,2	0,2
Farmers	0,2	0,2	0,2	0,2	0,2	0,2
Intermediate Workers	0,2	0,2	0,2	0,2	0,1	0,2
Blue-collar Workers	0,2	0,2	0,1	0,2	0,1	0,2
White-collar Workers	0,2	0,2	0,2	0,2	0,1	0,2
Elderly	0,2	0,1	0,1	0,2	0,2	0,2
Tourists	0,1	0,2	0,1	0,2	0,1	0,1
Industrial Goods	0,2	0,2	0,2	0,2	0,2	0,2
Consumer Goods	0,2	0,1	0,1	0,2	0,1	0,2
Perishable Goods	0,2	0,2	0,1	0,2	0,2	0,2

Note: Weights represent the relative importance (0–1 scale) of each feature for each user profile. Rows sum to 1, with values shown in rounded form for clarity.

To serve these diverse user profiles, the modeled transport system offers a range of mobility options. The ECOTRAIN system includes ECOTRAIN_P and ECOTRAIN_F, modular, autonomous rail shuttles operating on shared infrastructure, with dedicated wagons separating passenger and freight flows. This design enables mixed-use operations in alignment with Physical Internet (PI) principles of modularity and interoperability. Complementing this system are the conventional passenger trains. TER (Transport Express Régional) which connects regional destinations over short to medium distances with frequent stops. Intercités, which serve longer routes with fewer stops, and TGV (Train à Grande Vitesse) which operate on dedicated high-speed rail infrastructure, offering long-distance travel with limited stops. In addition to rail services, the system includes private vehicles, typically used for individualized, flexible mobility, and trucks, which serve freight needs and often operate independently.

Each of these transport modes is defined by a set of dynamic service attributes, including travel time, monetary cost, CO₂ emissions, waiting times, and the number of required transfers, and fluctuate throughout the day. The transport network itself is represented by a set of arcs, each corresponding to a direct connection between two nodes (origin and destination). Every arc is associated with a predefined hourly capacity per vehicle type.

To simulate realistic user behavior and evaluate how transport demand responds under varying system configurations, the study introduces eight experimental scenarios built around three key dimensions. The 1st dimension concerns **trip characteristics**, which may be either **constant** or **variable** throughout the day. In the constant case, attributes such as travel time, cost, number of transfers, and emissions are averaged to provide a simplified baseline. In the variable case, these same features fluctuate depending on real-world conditions, offering a more realistic representation of the transport system.

The 2nd dimension focuses on the **utility calculation method**, which defines how users select their mode of transport. In the **a priori** approach, users make their choice at the beginning of the journey based on expected conditions and do not revisit this decision. In contrast, the **per-segment** approach allows users to reassess their transport mode after each segment of the trip. This dynamic method captures real-time adaptability, as users react to situations such as delays, missed connections, or improved alternatives.

The 3rd dimension addresses **vehicle availability**, which in this context refers to scheduling constraints. In the **unconstrained** setting, all transport modes are considered to be available at all times, giving users unrestricted access to their preferred option. In the **constrained** setting, however, transport modes operate on realistic schedules, some may not be accessible during specific times (e.g., limited night service for trains). If a user's preferred mode is unavailable at their selected time, they are assumed to exit the system altogether, resulting in unserved demand. This setup helps evaluate whether offering specific services at particular times would generate sufficient demand to justify their operation.

All scenarios use the same O-D pairs and time intervals, incorporating adaptive user preferences that adjust based on context. This setup allows for a consistent comparison of how transport demand responds to varying trip characteristics, decision-making methods, and mode availability. Table 2 summarizes the eight scenario configurations and their relevance across strategic, tactical, and operational planning levels.

Table 2. Experimental Scenario Configurations

Scenario	Utility Calculation	Trip Characteristics	Vehicle Availability (Scheduling)
1	A Priori	Variable	Constrained
2	A Priori	Variable	Unconstrained
3	A Priori	Constant	Constrained
4	A Priori	Constant	Unconstrained
5	Per-Segment	Variable	Unconstrained
6	Per-Segment	Variable	Constrained
7	Per-Segment	Constant	Unconstrained
8	Per-Segment	Constant	Constrained

Scenario 1 serves as a baseline for assessing demand behavior under moderately realistic conditions. It assumes a utility calculation based on user preferences fixed at the beginning of the trip (a priori), variable trip characteristics that evolve throughout the day, and limited vehicle availability based on scheduled service times. Under this scenario, users can only access

transport modes that are available at their selected time. If a mode is unavailable due to schedule constraints, the user exits the system, resulting in unmet demand.

The initial demand input used in the model, obtained during the transport demand behavior analysis phase, was treated as deterministic, reflecting fixed hourly values for each user profile and O-D pair. To evaluate how demand variability might impact vehicle requirements and modal allocation, a probabilistic version of the demand was also tested using a **Poisson distribution**, applied independently to each deterministic value. This allowed us to simulate realistic fluctuations in user arrivals over time. Comparisons between the original (deterministic) and Poisson-simulated (stochastic) demand distributions revealed less than 1% variation in total values, confirming the model's robustness under stochastic assumptions and validating its suitability for scenario-based analysis.

The first key discovery is that unmet demand in Scenario 1 is primarily driven by service unavailability at specific time slots, particularly in the early morning. This is not the result of capacity saturation, but rather of transport modes being unavailable at the time of user demand. For example, in the Béziers–Carcassonne corridor at 6:00 a.m., although ECOTRAIN_P and cars are both heavily used, a portion of users remain unserved due to insufficient scheduling coverage. This suggests that even small adjustments in timetables could reduce unmet demand.

A second discovery concerns the spatial separation of passenger and freight flows. The most vehicle-intensive O-D pairs for passengers differ from those for freight. For example, O-D pairs like Montpellier–Narbonne see high car and ECOTRAIN_P demand, while others like Béziers–Castres are primarily served by ECOTRAIN_F and trucks. This segmentation indicates potential for **co-loading** strategies where infrastructure can be optimized for both passenger and freight flows.

5 Discussion, Conclusions and Research Avenues

This research models both passenger and freight flows by representing them as uniform logistic units (LUs). Despite the shared LU format, each user profile maintains its own weighting system, reflecting differentiated expectations for cost, time, environmental impact, safety, comfort, and reliability. By assuming that these weights can shift throughout the day, the model acknowledges that preferences may change under varying travel conditions.

One limitation of the current implementation is the absence of real-time data on passenger movements and immediate service availability. In practice, capturing precise user profiles and evolving preferences could further refine the allocation process and improve the realism of the model's outputs. These dynamic layers would enable even more responsive and accurate demand estimation in live operational settings. Second, the concept of modularity, central to the framework, relies on the practical compatibility of infrastructure and vehicle standards across modes, which may not yet be fully realized in many regional systems.

Despite these constraints, the use of a unified modelling framework to capture heterogenous demand offers significant advantages. By understanding how different user profiles respond to specific transport features, operators can tailor better services, reduce car dependency, and potentially decrease emissions. This is particularly impactful for underserved populations, such as elderly residents in regional areas, who often face limited transport access that contributes to social isolation or forced migration to larger cities.

There are also broader economic and environmental implications. Freight operators may benefit from cost reductions through shared infrastructure and mode consolidation, while communities can gain access to a wider range of goods at potentially lower prices. This **virtuous circle**,

where improved transport supply drives usage, which in turn justifies service expansion, highlights the potential of multipurpose transport systems to support regional development.

The proposed framework offers actionable insights into regional transport planning. By identifying unmet demand due to scheduling or capacity gaps, operators can make more informed decisions about service timing and vehicle deployment. Additionally, the shared-use logic of LUs encourages coordination between freight and passenger operators, reducing costs and improving coverage.

Looking ahead, future work could focus on integrating real-time data streams, such as dynamic passenger and freight positions or live service status, to improve adaptability to disruptions and behavioral shifts. Expanding the model to include behavioral feedback loops and predictive elements would further support its use in operational decision-making.

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Identification of the potential contribution of the physical Internet to the issues and challenges of the coffee supply chain in Ethiopia.

Mesay Shemsu NASIR^{1,2,3}, Eva Petitdemange¹, Séverine Durieux¹,

Emmanuel Duc².

1. Centre Génie Industriel, Université Toulouse, IMT Mines Albi, Albi, France.
2. Université Clermont Auvergne, Clermont Auvergne INP, Institut Pascal, F-63000 Clermont-Ferrand, France.
3. College of Technology and Built Environment, Addis Ababa University, 2QR7+584, King George VI St, Addis Ababa, Ethiopia.

Corresponding author: mesay.nasir@mines-albi.fr

Abstract: Our article explores the challenges and problems associated with managing the coffee supply chain in developing countries and examines how the physical Internet can solve them. To do this, we look at the case of the Ethiopian coffee supply chain. By leveraging hyperconnected logistics, multimodal transport and digital supply chain solutions, we highlight opportunities to improve economic, environmental and societal sustainability. Our literature review identifies key barriers such as supply chain fragmentation, lack of real-time visibility and inefficient transport and storage. We propose that the principles of the physical Internet should be harnessed to improve traceability, reduce waste and promote fair trade, particularly in the coffee supply chain, where they have not been used before. This research contributes to the wider debate on sustainable, resilient and inclusive global supply chains.

Keywords: Physical Internet, Coffee Supply chain, Supply Chain Management, Developing countries, Food supply chain, Collaboration, Sustainability.

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

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

1 Introduction

From a logistics perspective, the coffee supply chain is a major topic as it is not only the second most consumed beverage in the world, but also the second most traded commodity after oil (Murthy & Madhava Naidu, 2012). As a result, there are huge flows of coffee-related products, data and information around the world. In the global coffee supply chain, Ethiopia, known for its specialty coffee varieties, is the seventh largest contributor to coffee exports (Capital Newspaper, 2023).

Coffee is a fruit - a kind of cherry. Like many fruits, it has an outer skin under which is the pulp or flesh of the fruit, and then a seed inside, wrapped in different types of layers. There are

various ways of processing coffee to remove the different layers to obtain the coffee bean, which is then roasted and ground to produce a coffee ready for brewing.

Understanding these processes is key to identifying logistical inefficiencies and process misalignments in the supply chain. There are two types of processes in the Ethiopian coffee supply chain. (Tadesse, 2024) has mapped the processes and actors in the supply chain (Figures 1 and 2). The Ethiopian coffee supply chain from farm to export involves many actors with overlapping roles, uncertainties and disruptions that affect the supply chain, and constantly changing government regulations. This makes the Ethiopian coffee supply chain very complex and gives rise to a series of problems and/or difficulties.

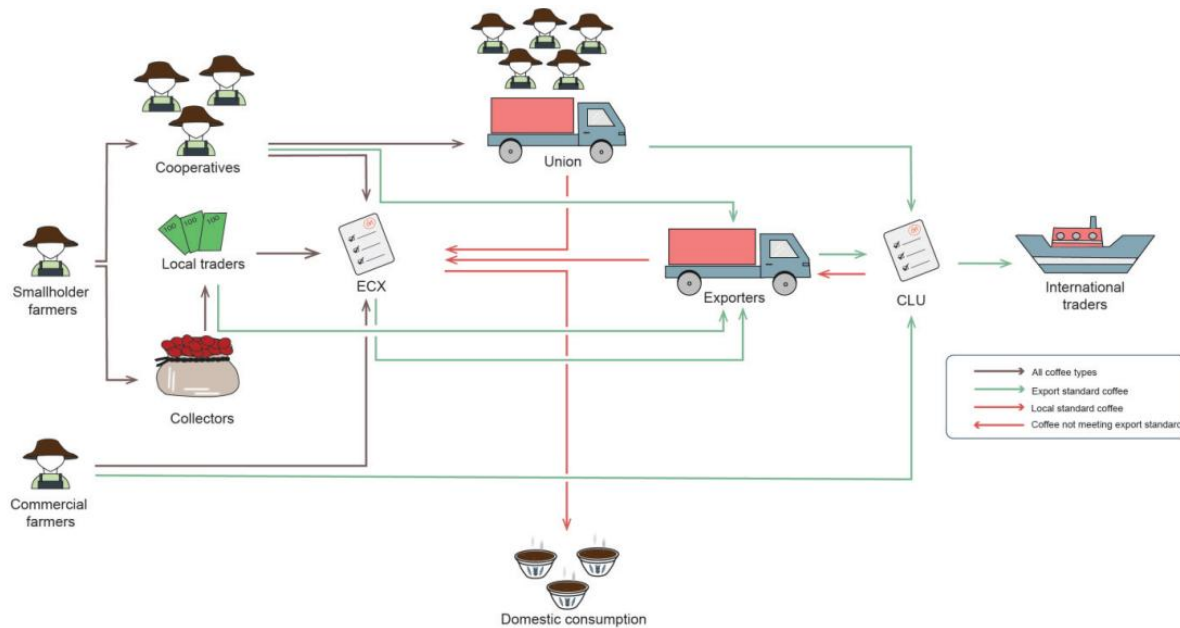


Figure 1: The Ethiopian coffee supply chain (ECX: Ethiopian Commodity Exchange, CLU: Coffee Liquoring Unit)(Tadesse, 2024).

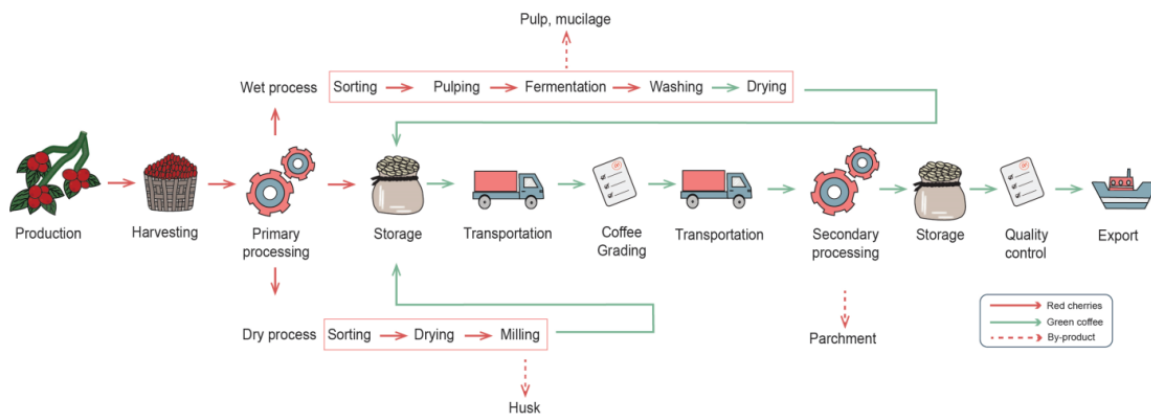


Figure 2: Logistics activities in the coffee supply chain for the export (Tadesse, 2024).

One of the main objectives of this research work is to identify the supply chain issues concerning Ethiopian coffee and to assess their similarities with the challenges posed by several global supply chains. Our objective is to assess the possibility of leveraging conceptual frameworks and innovations used in other supply chains to solve or mitigate the Ethiopian supply chain problems. In particular, the Physical Internet (PI), first introduced by (Montreuil, 2011), has attracted a great deal of research interest over the last decade, especially in relation to the challenge of global sustainability. As a result, solutions to various theoretical and applied supply chain problems are constantly being developed within PI (Matusiewicz, 2024).

However, its application to coffee supply chain problems has not yet been studied. This is why we first wanted to study the extent to which the physical Internet (PI) could be used to solve the problems of the Ethiopian coffee supply chain.

This article is structured as follows. Section 2 describes the methodology. In section 3, we summarize the challenges we have identified in the supply chain. A mapping of Physical Internet capabilities that can be exploited to address the challenges in the coffee supply chain is then presented in section 4. Section 5 then discusses the importance of applying PF in the supply chain of a developing country such as Ethiopian coffee and the associated challenges that need to be addressed. Finally, section 6 concludes with the main findings and research perspectives.

2 Methodology

To answer the research question about the applicability of PI to the Ethiopian coffee supply chain, the following methodology was followed. First, a stakeholder interview is conducted to get deep insights into the problems of the Ethiopian coffee supply chain. The number and profiles of interviewees is presented in Table 1.

Table 1: Interviewee profiles

Supply chain actor	Number interviewed
Local Exporter	3
International trader	2
Artisan café owners affiliated with specific coffee farms	4
Representatives of associations of coffee traders	3
Representatives of coffee trading unions	1
Total number of Interviews	13

The interview notes were then compiled and summarized into major clusters which are presented in section 3. This is followed by formulation of a set of keywords associated with the clusters of problems identified. By combining these keywords with the terms coffee supply chain and Physical Internet and PI, a set of literature search queries was formed. These queries were plugged into the research database Web of Sciences to yield a combined set of 173 articles.

Upon close examination and thorough reading, after careful scrutiny and extensive reading, a set of papers deemed relevant to the research question was selected. A total of 48 articles were selected for this article, including 10 general reference articles.

3 Key Supply chain Challenges Identified

The interview notes distill to the category of supply chain problems below. Where available, corroborations from literature are also presented.

- a) *Infrastructure inefficiencies*: facilities such as warehouses, de-pulping and washing stations as well as testing laboratories are used sub-optimally, as manifested in:
 - Overcrowding of some warehouses while others are underloaded;
 - Lack of transport fleets while transport service is available in the capacity pool;
 - Queues at de-pulping and hulling stations, as well as quality testing laboratories;
 - Specialized facilities are not well equipped for their intended use, in terms of housing the right set of milling, washing, sorting and handling equipment. Human labor is also used extensively in handling tasks, which reduces efficiency;

- Planning of the layout within large facilities is not done with operational optimality in consideration, which also increases inefficiency.
- b) *Lack of Information sharing among stakeholders*: Not all stakeholders have up-to-date information on available stocks and transport services, which limits choice and can lead to sub-optimal decisions. Access to technology, difficulty of implementation in terms of skilled labour, cost of implementation and resistance from stakeholders are all challenges to obtaining information. This is also corroborated by (Tadesse *et al.*, 2024).
- c) *Market demand and price volatility*: There is high variability in international demand for coffee. As corroborated by (Worako *et al.*, 2011), the Ethiopian coffee supply chain is affected by high price volatilities.
- d) *Climate change risks*: A majority of the Ethiopian Coffee is harvested from small-holder farms. These farms are closely linked to some of the oldest natural forests in Ethiopia (Davis *et al.*, 2018). The forests are vulnerable to several effects of climate change and human activities such as deforestation.
- e) *Logistics cost fluctuations*: There are significant volatilities in logistics costs. Causes contributing to these fluctuations include, but are not limited to: lack of information on available supply of transportation and inventory services leading to speculative pricing and/or oligopoly, presence of information brokers between actors of the supply chain, political and/or security instabilities.
- f) *Disruptions to operational continuity*: The coffee supply chain is vulnerable to disruption of flows. Interviewees have stated a number of risks in this regard including:
 - Security issues;
 - Theft of coffee: a significant number of instances for the theft of coffee are reported by anonymous sources (Bogale, 2023); there is also a market for a local trading of export-standard coffee as reported by (Metekia, 2022);
 - Transport infrastructure problems: the Ethiopian rural road network is vulnerable to weather effects; e.g., landslides which block key arterials of the road network are common during rainfall seasons.
- g) *Regulatory uncertainty*: The policies and regulations governing the coffee supply chain in Ethiopia had not been largely based on evidence; rather, they have been highly dependent upon the incumbent government's political priorities throughout the years (Mas Aparisi, 2024).
- h) *Data Scarcity*: the existing data repositories are incomplete in many forms including temporal continuity, spatial coverage and type of data collected in terms of giving a full picture of the supply chain.
- i) *Packaging and handling problems*. Coffee is very sensitive to environmental conditions in terms of temperature, humidity and chemicals. However, packaging is widely done using 60Kg pockets which are then stacked and containerized for shipping. The issues related to this process are:
 - *Standardization and quality*: There is neither an accepted standard for the 60Kg bags nor a list of approved suppliers for the bags. This means exporters are sourcing these bags from all available suppliers to meet order timelines. Such practice may lead to procuring packaging that can potentially harm the coffee quality in terms of its chemical content or in preserving the coffee;
 - *Ample supply of bags*: There isn't a cultivated local capacity to produce bags that are sufficient for the export volume of coffee. Furthermore, it has reliability issues regarding meeting orders on time. Although the exact problems of the

logistics of 60Kg bags needs to be investigated further, inadequate supply of bags is a topic that has been present in interviews;

- Handling of coffee in warehouses, mills and during transportation is not under carefully controlled conditions. This can potentially incur reduced pricing and/or rejection of the coffee from export markets.

After careful examination of the above problems, the authors hypothesize that the physical internet can offer a viable set of solutions to some of the problems above. Accordingly, the section below presents a review of literature linking the physical internet concept to problems similar to the above problems in the coffee supply chain.

4 Mapping Physical Internet Capabilities to Coffee Supply Chain Challenges

To find evidence supporting the hypothesis, we devise the following set of queries consisting of keywords derived from the problem in section 3:

- Efficiency & Optimization: TITLE: *Physical internet*; AND ABSTRACT: "*efficien**" OR "*inefficien**" OR "*optim**" OR "*perform**" OR "*utilization*" OR "*resource**" OR "*facilit**" OR "*productivity*" OR "*inventory*" OR "*infrastructure*"
- Uncertainty or volatility: TITLE: *Physical internet* AND ABSTRACT: "*uncertain**" OR "*volatil**" OR "*instabil**" OR "*variab**" OR "*risk*" OR "*unpredictab**" OR "*requirement**" OR "*data need**" OR "*lack of data*" OR "*inaccurate data*" OR "*erroneous data*" OR "*uncertain data*" OR "*data reliability*" OR "*unreliable data*" OR "*trace**"
- Quality & Packaging: TITLE: *Physical internet* AND ABSTRACT: "*quality*" OR "*pack**" OR "*sensitive material*" OR "*perishable*"

Table 2: Examples of PI solutions with their degree of maturity that could be used to solve problems in the coffee supply chain

Problem	PI Solutions			
	Conceptual framework	Algorithms & Simulation models	PI prototypes & IT infrastructure	Operational System
Inefficient utilization of resources	(Adamczak <i>et al.</i> , 2018)	(Chen <i>et al.</i> , 2018)		
Poor logistics infrastructure	(Tran-Dang & Kim, 2018)	(Dang Hoa & Kim, 2018)	(Osmólski <i>et al.</i> , 2019)	
Uncertainty, volatility & disruptions	(El Ouadi <i>et al.</i> , 2021)	(Yang <i>et al.</i> , 2017)		(Achamrah <i>et al.</i> , 2024)
Regulatory & policy environment	(Moshood & Sorooshian, 2021)	(Lemmens <i>et al.</i> , 2019)		

Scarcity and Inaccuracy of Data	(Sun <i>et al.</i> , 2024)			
Quality and traceability	(Hasan <i>et al.</i> , 2021)	(Chen <i>et al.</i> , 2018)	(Lin & Cheng, 2018)	
Ecological impact & sustainable development	(Puskás & Bohács, 2021)	(Chen <i>et al.</i> , 2018)		

Upon inserting these queries were plugged into the research database Web of Sciences we got a total of 173 articles. Among these we selected 146 for further reading, based on their relevance to the research question. These articles were thoroughly reviewed in a second-round review and mapped according to their relevance to similar problems in the coffee supply chain.

The mapping was further refined to 38 articles as given in Table 2.

Table 2 illustrates some of the capabilities of PI to address challenges similar to those in the Ethiopian coffee supply chain that we have identified through our more comprehensive literature review.

Looking at PI's contribution to each challenge separately, we envisage the following opportunities:

- a) *Inefficient Utilization of Resources*: PI can be leveraged to optimize resources in transportation, handling and inventory areas through open-access logistics networks and AI-driven planning. Storage space in trucks can be maximized using the differently sized modular boxes belonging to different shipping actors. This also reduces empty returns maximizing potential for dual export and local markets. The real-time response and coordinating capabilities of PI can be utilized to coordinate coffee shipments from farming areas like Kaffa to Addis Ababa, ensuring full truckloads and shared routes among cooperatives.
- b) *Poor Logistics Infrastructure*: Unpaved rural roads and sub-optimal Ethiopian Commodity Exchange (ECX) hubs, hamper coffee transport and storage, especially during rainy seasons. The Physical Internet can introduce modular, scalable infrastructure designed for resilience. Sensor-equipped standardized containers and trucks able to navigate more rugged terrain can be leveraged to reduce dependence on advanced roads. PI can also offer upgrading frameworks for warehouses, auction centers and hubs to replace or upgrade ECX facilities. Using the tropical sun, which Ethiopia has ample of, a significant proportion of energy requirements could be fulfilled without waiting for full rural electrification.
- c) *Uncertainty, Volatility & Disruptions*: Challenges like weather disruptions, market price swings, and operational disruptions can be met by PI through predictive analytics and real-time adaptability. Data platforms integrate historical and live data (e.g., weather, market trends) to forecast disruptions and optimize routes. For instance, if rains block a rural road, PI systems can reroute coffee via alternative hubs, minimizing delays. Applications such as blockchain can enable traceability, ensure contract stability and reduce potential price volatility that impacts farmers.
- d) *Regulatory & Policy Environment*: Ethiopia's regulatory environment lacks evidence-based policy frameworks for digital logistics, data security, and industrial collaboration, slowing innovation in the coffee sector. PI requires and promotes policy evolution by necessitating standardized protocols that align stakeholders. PI's implementation can

- drive government action to enact laws for container standards, cyber-physical security of infrastructure, and cross-border trade, fostering public-private partnerships.
- e) *Scarcity and Inaccuracy of Data*: Limited and inaccurate data on yields, quality, and logistics in Ethiopia's coffee supply chain hinders planning and transparency. There is an immense opportunity to extract vast quantities and different kinds of data on the coffee supply chain by deploying IoT sensors and shared data platforms to collect real-time, accurate information across the supply chain. PI's open-access networks enable farmers, cooperatives, and exporters to contribute and access data on production volumes, transport status, and market needs. For instance, sensors on PI containers could track coffee starting from Yirgacheffe farms to the Djibouti port, feeding a stream of data to cloud platform that corrects yield estimates.
 - f) *Quality and Traceability*: PI can very well be used to meet coffee's quality sensitivity and need of precise handling. PI enhances quality and traceability through smart containers equipped with sensors monitoring variables like moisture and temperature, tailored to Ethiopian coffee's needs. PI's blockchain-based platforms can secure end-to-end traceability, recording each step from farm to export, verifiable by buyers. This firmly establishes market trust and sustainable revenue.
 - g) *Ecological Impact & Sustainable Development*: Ethiopian coffee is largely produced by small-holder farms, which are ecologically connected to some of the oldest natural forests, in a natural manner without fertilizer additions to the soil (Davis *et al.*, 2018). These facts render the Ethiopian coffee supply chain one of the greenest export industries in Ethiopia. PI can build on this further by drawing power from Ethiopia's green electricity generated from hydropower (International Trade Administration, 2024). This will strengthen the strategic sustainability of the coffee supply chain.

5 Discussion: Challenges & Feasibility of PI Implementation in Ethiopia

The reviewed literature shows the potency of PI to solve the coffee supply chain's problems. However, we see that there are barriers to be overcome in the Ethiopian coffee supply chain and in supply chains in developing countries at large, before PI can be implemented. These are detailed below.

1. Technological Barriers

- **Unreliable Communication Networks**: Limited network reliability and availability hinder real-time data sharing, reducing PI's responsiveness and traceability capabilities critical for coffee quality monitoring.
- **Lack of Localized Solutions**: Developing PI-specific technologies, such as innovative containers from local materials, affordable wireless sensor networks, and quality-monitoring systems tailored to coffee's sensitivity (e.g., moisture, temperature), remains a scientific and technical challenge.
- **High Adoption Costs**: Implementing PI requires substantial investment in infrastructure (e.g., IoT sensors, cloud platforms), trained specialists, and farmer acclimatization, posing financial challenges for small-scale producers and cooperatives.

2. Policy and Regulatory Gaps

- **Lack of PI Frameworks**: Ethiopia lacks policies for PI standardization, data security, and cross-departmental coordination, impeding collaboration between universities, industry, and government for sustainable logistics.
- **Insufficient Incentives**: Limited government funding, trade barrier reforms, and labor laws to mitigate Industry 4.0 job losses discourage private sector investment in PI technologies.

- **Leadership Deficit:** Without proactive government leadership in digital platforms, cybersecurity, and skilled labor development, PI implementation lacks the regulatory push needed for stakeholder alignment.

3. Trust and Data Sharing Issues

- **Stakeholder Reluctance:** Smallholder farmers and other actors hesitate to share data (e.g., yields, pricing) in a perceived low-trust environment, fearing exploitation or competitive disadvantage.
- **Inadequate Data Practices:** The absence of robust data collection and sharing systems limits supply chain visibility, hindering PI's ability to optimize processes and predict disruptions.
- **Collaboration Challenges:** Demonstrating PI's global benefits (e.g., higher profits) to individual companies and developing minimal-data-sharing methods to encourage participation remain critical hurdles.

4. Infrastructure Limitations

- **Underdeveloped Logistics Hubs:** Ethiopian Commodity Exchange (ECX) hubs, serving multiple roles (grading, storage, auctions), are bottlenecks due to limited facilities, requiring upgrades for PI's modular, efficient operations.
- **Lack of PI-Compatible Systems:** Current infrastructure, like 60-kg sacks and manual tracking, doesn't support PI's standardized containers, truck-trailer coupling, or real-time logistics planning.
- **Energy and Sustainability Gaps:** Unreliable energy supply constrains PI's sensor and communication arrays, while unstudied energy-coffee process relationships and unquantified CO₂ costs complicate justifying sustainable PI investments.

In various time horizons, several types of interventions are required to realize PI in the coffee supply chain. In the short term, we see the feasibility of pilot interventions including modernizing the transportation, handling, and warehousing of coffee; optimal design of facilities and processes, routing protocols and human resource management tools that minimize delays.

Setting up a national data platform for research, development and business endeavors can have a significant effect in the medium term. Another area is the incremental alignment of governance structure to reflect a shift to PI. This alignment involves the training of personnel across different government departments (e.g., customs, transport-related authorities, agriculture-related authorities, etc.), and supply chain actors.

Several long-term interventions are required to successfully embed the Physical Internet in the coffee supply chain. These include:

- strong investment into rural electrification and communications infrastructure while scaling digital literacy programs and wireless sensor networks to achieve seamless technological integration.
- improving the national data platform and strengthening trust through demonstration of business models that promote equitable profits for farmers, exporters, and international buyers, leveraging global partnerships for shared gains.
- establishing a national PI authority to formulate a robust legal framework that is locally relevant and globally compatible at the same time. A robust legal framework, led by a national PI authority, can enforce global-compatible standards and cybersecurity, resolving policy gaps.

6 Conclusion and Future Work

Through meticulous interviews and literature review, the key problems in the Ethiopian coffee supply chain have been identified. These are inefficiency and underdevelopment of

infrastructure, lack of data and a low-trust environment where data isn't shared among supply chain actors, uncertainties of policies which are often not evidence-based and technological barriers.

The consideration of PI to solve these problems in the context of the coffee supply chain in developing countries is an originality. In this regard PI shows significant promise as a solution framework, as demonstrated in the volume of research work reviewed.

The full implementation of PI, however, is a formidable challenge as of now. In this regard, we have proposed an incremental approach over a long-time horizon to overcome the challenge.

Once fully realized, Ethiopia can leverage PI to rip the benefits of a sustainable coffee supply chain. Hence, future research work is essential in areas of the short, medium and long-term interventions indicated in the previous section. Some quick wins could be harvested in pilots for modeling and optimization of facilities, scheduling and transportation protocols. Locally made sustainable packaging and the supply chain of the packaging material itself is also an interesting research avenue filled with interesting questions. Urban logistics of locally sold coffee also has room for research on collaborative logistics involving farmers, retail stores, coffee shops and artisan cafes.

The authors seek to explore several optimization techniques and simulation models to tackle a selection of problems in the aforementioned areas in the future.

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Reconfigurable Physical Internet Driven Urban Distribution Network

Masoud Kahalimoghadam¹, Russell Thompson¹, Lele Zhang², and Michael Kirley³

1. University of Melbourne, Department of Infrastructure Engineering, Melbourne, Australia
2. School of Mathematics and Statistics, The University of Melbourne, Australia
3. School of Computing and Information Systems, The University of Melbourne, Melbourne, Australia

Corresponding author: Masoud.kahalimoghadam@unimelb.edu.au

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Conference Domain Fitness: *Compose a paragraph positioning your contribution within the IPIC 2025 contribution domain as outlined in the call for contributions, using as directly as possible the provided text and cutting, assembling, and extending it as best fitting. Maximum of 10 lines.*

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

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Abstract

The Physical Internet (PI) revolutionizes freight logistics through modular standardization, open networks, and intermodal interoperability. By treating shipments as dynamically routed π -containers, PI improves transport capacity utilization and freight distribution efficiency. However, its reliance on predefined corridors limits its adaptability to real-time disruptions and demand fluctuations. A reconfigurable urban distribution network (RUDN) addresses these challenges by offering a decentralized and adaptive logistics framework that continuously adjusts based on capacity, disruptions, and market dynamics. In an RUDN, nodes do not have fixed roles but dynamically adapt their functions in response to logistics demand, considering factors such as volume, location, and delivery time.

Digital twin (DT) technology supports this adaptability by creating real-time virtual representations of freight movement, enabling predictive analytics and autonomous logistics optimization. By integrating IoT-driven data, DT enhances visibility, supports disruption management, and facilitates real-time freight flow reconfiguration. Despite its advantages, challenges remain in global scalability, computational efficiency, decentralized coordination, and secure data-sharing.

Combining PI, RUDN, and DT, urban freight can support self-optimizing ecosystems with dynamic logistics routing and enhanced resilience. However, realizing this vision requires

overcoming technological, regulatory, and operational barriers through empirical research, case studies, and cross-sector collaboration.

Introduction

Traditional urban freight relies on isolated carrier-owned storage and distribution, lacking shared infrastructure, consolidation, and transshipment. This results in inefficiencies, higher vehicle kilometers traveled (VKT), and limited modal integration.

The Physical Internet (PI) represents a transformative approach to freight transportation, enhancing efficiency, sustainability, and interoperability through standardized modular logistics, open networks, and seamless intermodal transport (Montreuil, 2011). By conceptualizing shipments as PI-containers, dynamically routed through interconnected logistics hubs akin to data packets in digital networks, PI seeks to minimize empty transport capacity and optimize freight flows. However, its reliance on standardized corridors and predefined routes limits adaptability in volatile environments, making it less responsive to real-time disruptions and demand fluctuations.

To address these limitations, the reconfigurable urban distribution network (RUDN) introduces a decentralized and adaptive approach to urban freight, enabling real-time reconfiguration of transport modes, storage locations, and distribution hubs. Unlike static logistics networks where nodes have fixed roles, the RUDN dynamically adjusts based on capacity constraints, disruptions, and market conditions. By allowing transport hubs to flexibly serve as storage, transshipment, or distribution centers as needed, the RUDN enhances the resilience and responsiveness of PI-based logistics. However, this flexibility increases the complexity of synchronization, coordination, and multi-agent decision-making, requiring advanced computational tools for real-time optimization.

Digital twin (DT) technology provides a computational framework to integrate PI and RUDN, offering real-time virtual representations of logistics networks for predictive analytics, artificial intelligence (AI)-driven decision-making, and autonomous freight optimization (Liu et al., 2023). By synthesizing live data from Internet of Things (IoT)-enabled assets, transport hubs, and urban freight stakeholders, DT technology enables simulation-based scenario analysis, disruption forecasting, and adaptive logistics flows. In the event of a bottleneck in a PI corridor, a DT-driven logistics system can autonomously assess alternative routing strategies, optimize cost-efficiency trade-offs, and dynamically reconfigure freight flows. Furthermore, DT enhances freight visibility and coordination, enabling decentralized logistics operations to function cohesively while maintaining logistics efficiency and adaptability.

Despite its potential, integrating PI, RUDN, and DT presents challenges related to scalability, standardization, computational complexity, and governance. Widespread adoption of PI requires harmonized logistics protocols while accommodating regional differences. Governance models must support interoperability across varying regulatory environments. Real-time optimization of large logistics networks demands AI-driven decision-making that balances computational efficiency with adaptive freight management. Additionally, effective coordination in RUDN requires decentralized decision-making without creating bottlenecks, relying on advanced methods that ensure flexibility and stability in dynamic settings.

Data governance and cybersecurity risk further complicate implementation, as seamless information-sharing is essential for PI and RUDN success. However, balancing collaboration with data security and competitive interests remains a critical challenge. Ensuring secure, efficient data exchange across IoT-enabled logistics networks is crucial for fostering trust among stakeholders.

Integrating PI, RUDN, and DT enables self-optimizing, adaptive freight systems with real-time reconfiguration and predictive decision-making. This fosters multimodal transport

interoperability, dynamic logistics routing, and resilience against disruptions, shaping intelligent and sustainable logistics networks. However, achieving this vision requires overcoming technological, regulatory, and operational barriers. Future research should focus on simulations, case studies, and cross-sector collaboration to bridge the gap between theoretical models and real-world applications.

Literature review

In well-established freight transportation problems, such as vehicle routing and hub location models, nodes are typically assigned fixed roles, functioning as warehouses, depots, or consolidation centers (CCs). The concept of reconfigurable nodes is widely discussed in public transportation, particularly as a resilience measure during disruptions. Du et al. (2022) emphasize that dynamic changes in node roles, supported by cyber physical systems, enhance adaptability and support rapid recovery in multimodal networks. However, a reconfigurable distribution network can address not only uncertainties in goods movement (Kahalimoghadam et al., 2024a) but also enhance operational efficiency during disruptive events such as pandemics (Kahalimoghadam et al., 2021; Thompson et al., 2024).

Among the limited applications of RUDNs, Liu et al. (2025) developed a two-stage strategy to enhance the resilience of urban transport networks during disasters through dynamic reconfiguration. In Stage I, intersections are selectively blocked to contain the spread of faults and minimize immediate disruption. In Stage II, road directions are reversed using contraflow techniques to optimize traffic flow and restore network functionality. Additionally, autonomous electric vehicles are centrally dispatched to fulfill transport demands and support power grid recovery via vehicle-to-grid operations, contributing to a faster and more coordinated system restoration. In another study, Hodson et al. (2024) investigated the reconfiguration of urban transport networks via digital mobility platforms. They identified two modes: modular platformization, which adds loosely connected services like bike-sharing, and systemic platformization, which integrates multiple modes through unified digital systems. These approaches convert traditionally fixed transport nodes into flexible, multi-functional components shaped by evolving public-private coalitions, aligning with emerging logistics paradigms such as the PI, which advocate for adaptable and interoperable distribution networks.

PI principles redefine freight transportation through standardized, modular, and interoperable logistics systems. Drawing inspiration from digital data routing, this approach enables open, shared, and dynamically reconfigurable hubs and vehicles that enhance routing efficiency, consolidation, and service adaptability. Nodes can flexibly function as temporary storage points, cross-docking sites, or last-mile dispatch centers based on real-time demand. Research by Montreuil et al. (2013) and Pan et al. (2017) highlights improved resilience, resource use, and environmental performance, though implementing such systems demands sophisticated, data-intensive orchestration technologies.

Yet, both platformization and PI frameworks often lack real-time coordination and system-wide situational awareness, limiting their responsiveness to dynamic urban freight demands. DT technology addresses this gap by enabling continuous, data-driven modeling and control of complex logistics systems. In urban freight networks aligned with PI principles, DTs enhance the dynamic reconfigurability of modular hubs and vehicles by providing real-time visibility into system states, simulating disruption scenarios, and supporting adaptive decision-making. For example, Wu et al. (2023) demonstrate the integration of the Internet of Everything and DTs to improve service platforms for cold chain logistics, enabling better traceability and decision-making. Similarly, Le and Fan (2024) present a conceptual framework where DTs enhance logistics visibility and responsiveness.

Despite their individual contributions, the true potential of these concepts emerges when they are integrated. The modularity of the PI provides the structural foundation, RUDN introduces

operational flexibility, and DT offers the intelligence and real-time coordination layer needed to harmonize both in dynamic urban settings.

Model formulation

The RUDN model is formulated to optimize the dynamic configuration and operation of an urban logistics network across multiple time periods. It determines the functional role of each node as either a transshipment hub (TH) or a CC and computes the quantity of goods transported between nodes over time. Node roles may change between time periods, subject to technical feasibility and suitability constraints. Role switching costs discourage unnecessary changes and promote network stability.

The model simultaneously determines transportation flows along predefined arcs, where the transport mode, either truck or van, is inferred from the roles of the origin and destination nodes. Flow conservation is enforced at each node for each time period. All flows are constrained by mode-specific vehicle capacities and node handling limits. The objective is to minimize total system costs, including transportation expenses, node role assignment costs, and reconfiguration penalties. Table 1 represents the notation used in this research.

Table 1. Notations of the RUDN model

Notation	Description	Value
N	Set of all nodes in the urban logistics network	
N_C	Set of customer nodes	
N_{CC}	Set of candidate CCs	
N_{TR}	Set of candidate transshipment hubs	
N_W	Set of warehouse nodes	
R	Set of possible node roles: [Transshipment, Consolidation]	
M	Set of transportation modes: [Truck, Van]	
A	Set of directed arcs between nodes	
T	Set of discrete time periods	
Ω_i	Set of roles that can be feasibly assigned to node i , where $i \in N_{CC} \cup N_{TR}$	
c_m	Unit cost of transportation from node i to node j via mode m	Truck: \$1.2/km, Van: \$0.8/km ^a
$f_{i,r}$	Fixed cost of activating role r at node i at any time period	\$750,000/year ^b
$\gamma_{i,r}$	Cost of switching role r at node i between two consecutive time periods	\$25,000/event ^c
$cap_{i,r}^{max}$	Maximum physical or operational capacity of node i under role r	Varies by node type
cap_m	Maximum transportation capacity for mode m	Van: 1.5 tones, Truck: 20 tones ^d
d_i^t	Net demand variable at node i at time t	
$\theta_{i,r}$	Maximum number of transitions (entries or exits) for role r for node i , where $i \in N_{CC} \cup N_{TR}$	1 per week
$S_{i,r}$	Suitability score of node i for role r ; used to enforce soft constraints via minimum threshold S_r^{min}	[0,1]
S_r^{min}	Minimum suitability score required for role r	0.5
d_{ij}	Distance between nodes i and j	
$x_{i,r,t}$	Binary variable equal to 1 if role r is assigned to node i , where $i \in N_{CC} \cup N_{TR}$, at time t ; 0 otherwise. A node may be assigned multiple roles simultaneously.	
y_{ijt}	A continuous variable that determines the quantity of goods transported from node i to node j at time t	
$s_{i,r,t}$	Binary variable equal to 1 if node i , where $i \in N_{CC} \cup N_{TR}$, either enters or exits role r between times $t - 1$ and t ; 0 otherwise. Nodes may hold multiple roles simultaneously; switching is tracked per role.	
δ_{ijmt}	A binary variable equal to 1 if arc (i, j) is traversed using mode m at time t ; 0 otherwise. Mode selection is restricted based on the roles assigned to nodes i and j .	

^a: (Wu et al., 2020), ^b: (Aljohani & Thompson, 2018), ^c: (Cleophas et al., 2019), ^d: (Taniguchi et al., 2001)

$$\min \sum_{t \in T} \left[\sum_{i,j \in A} \sum_{m \in M} c_m * d_{ij} * \delta_{ijmt} * y_{ijt} + \sum_{i \in N_{CC} \cup N_{TR}} \sum_{r \in R} (f_{i,r} * x_{i,r,t} + \gamma_{i,r} * s_{i,r,t}) \right] \quad (1)$$

$$\sum_r x_{i,r,t} \leq 1 \quad \forall i \in N, \forall t \in T \quad (2)$$

$$\sum_j y_{ji}^t - \sum_j y_{ij}^t = d_i^t \quad \forall i \in N, \forall t \in T \quad (3)$$

$$\sum_{t \in T} s_{i,r,t} \leq \theta_{i,r} \quad \forall i \in N, \forall r \in R \quad (4)$$

$$\sum_j y_{ij}^t \leq cap_{i,r}^{max} \quad \forall i \in N_{CC} \cup N_{TR}, \forall t \in T \quad (5)$$

$$x_{i,r,t} = 0 \quad \forall i \in N, \forall r \notin \Omega_i, \forall t \in T \quad (6)$$

$$d_i^t > 0 \quad \forall i \in N_W, \forall t \in T \quad (7)$$

$$s_{i,r,t} \geq x_{i,r,t} - x_{i,r,t-1} \quad \forall i \in N, \forall r \in R, \forall t > 1 \quad (8)$$

$$s_{i,r,t} \geq x_{i,r,t-1} - x_{i,r,t} \quad \forall i \in N, \forall r \in R, \forall t > 1 \quad (9)$$

$$y_{ij}^t \leq cap_m \times \delta_{ijmt} \quad \forall (i,j) \in A, \forall m \in M, \forall t \in T \quad (10)$$

The objective function in equation (1) seeks to minimize the total cost associated with the operation of the urban logistics network across all time periods. This is achieved by summing the transportation costs, which are determined by the mode specific unit cost, inter node distance, mode assignment, and quantity of goods transported, and the role related costs, which include the fixed cost of activating a specific role at a node and the switching cost incurred when changing roles over time. Constraint (2) guarantees that each node is assigned at most one role per time period, thereby preventing simultaneous designation as both a consolidation and a transshipment hub. Constraint (3) imposes flow balance by equating the net inflow and outflow of goods at each node to its respective net demand in every time period. Constraint (4) limits the number of permissible role changes for each node and role combination throughout the planning horizon, thereby enforcing a cap on reconfiguration frequency. Constraint (5) ensures that the total outbound flow from any node does not exceed its maximum operational or physical capacity at any given time. Constraint (6) constrains role assignments to those explicitly allowed for each node, ensuring that role allocation respects the node's predefined functional eligibility. Constraint (7) enforces that only warehouse nodes can have positive supply if $d_i^t > 0$, then $i \in N_W$. Constraints (8) and (9) define the activation of role switching indicators, $s_{i,r,t}$, by detecting changes of role r at node i between consecutive time periods. Nodes may hold multiple roles simultaneously; switching is tracked per role. Constraint (10) restricts the quantity of goods transported on each arc to remain within the capacity limit of the assigned transportation mode and allows such flow only if the corresponding arc mode assignment is active.

Data Collection

Melbourne, Australia's second-most populous city, serves as a major hub for freight logistics. Its expansive metropolitan area, marked by rapid population growth and urban sprawl, has significant implications for the spatial configuration of freight facilities and distribution networks. The locations of major warehouses and CCs were extracted from OpenStreetMap, which provided the geographical data for all identified warehouse facilities. Based on the availability of attribute information, 39 warehouses associated with major retailers such as Amazon and Woolworths were selected for inclusion in this study. The majority of these warehouses are located in the west of Melbourne while few of them are in the north and east as illustrated in Figure 1. These warehouses are primarily located in the outer metropolitan zone, where they are relatively distant from residential areas and land prices are more affordable for major retailers. However, due to significant population growth in recent decades, some of these

facilities, such as the warehouse in Altona, are now situated within or adjacent to residential zones.

Due to the unavailability of precise data regarding the locations of THs and CCs in metropolitan Melbourne, a hub covering problem (HCP) analysis developed by Kahalimoghdam et al. (2024b) was employed to determine their spatial configuration. Initially, industrial lands were extracted from government-provided spatial datasets. A proximity constraint was subsequently imposed to limit candidate sites to those within a 13-kilometer radius of the Melbourne Central Business District (CBD). This threshold was selected because existing warehouses are typically situated approximately 17 kilometers from the CBD, and THs, which function as intermediate nodes where freight is sorted or transferred between modes, should ideally be positioned between the outer warehouses and the dense urban core to enhance the efficiency of last mile distribution.

From the resulting filtered locations, only parcels ranging in size from 5,000 to 10,000 square meters were retained. This size range was chosen based on the recommendation by Aljohani and Thompson (2021), who proposed a benchmark area of approximately 2,000 square meters for CCs designed for parcel delivery. However, given that this study encompasses a broader spectrum of freight types, including larger and heavier goods, a more inclusive and expansive size range was adopted. Following the application of all criteria, forty-three candidate locations were identified. Figure 1 illustrates the selected transshipment hubs derived from solving a hub location problem to optimize freight flows between warehouse sites and urban destinations.

Conversely, CCs are expected to be located in closer proximity to high-density residential and commercial areas, as these facilities dispatch goods to end customers using smaller and more environmentally sustainable vehicles such as vans. This approach enhances both economic and environmental performance, as evidenced in Kahalimoghdam et al. (2024c) analysis. To identify optimal CC locations, a hub covering problem was applied to the refined set of inner industrial land parcels. This methodology ensures that all urban customer zones fall within the service coverage of at least one consolidation facility. The analysis identified five suitable locations, which are also presented in Figure 1.

The candidate locations of industrial land used for applying the HCP algorithm to identify the most suitable sites for THs and CCs are also presented in Figure 2 (a) and (b), respectively.

Implementation of the RUDN

Modeling a RUDN involves structuring nodes into warehouses, THs, and CCs, as established in the previous section. Warehouse nodes manage inventory, transshipment nodes facilitate modal shifts between trucks and vans, and consolidation nodes reallocate goods to enhance the efficiency of delivery vehicles while also supporting final stage distribution through micromobility and vans. In this study, to streamline the analysis, Constraints 4 and 10 have been relaxed. Rather than minimizing the cost defined in the objective function in Equation 1, a scenario based analysis is conducted, and the establishment cost of transportation hubs is excluded, as it is assumed that all hubs are part of the network and only their functional roles may change.

To estimate daily freight demand in Melbourne, container throughput at the Port of Melbourne serves as a practical and data-informed reference. As the busiest maritime freight hub in Australia, the port handled approximately 3.2 million twenty-foot equivalent units (TEUs) during the 2022–2023 financial year, according to the Port of Melbourne Annual Report 2022–2023 (Port of Melbourne, 2023). This translates to an average daily throughput of approximately 8,770 containers. Assuming an average weight of 14 tons per loaded container, this equates to an estimated 122,700 tons of containerized freight per day. These containers carry a diverse range of goods distributed across Melbourne and its surrounding regions, supporting key sectors such as retail, manufacturing, and construction. Although not all

containers are destined for urban delivery, a significant portion is transported into the metropolitan logistics network via road and rail, making this figure a reliable proxy for estimating daily freight flows in the region.

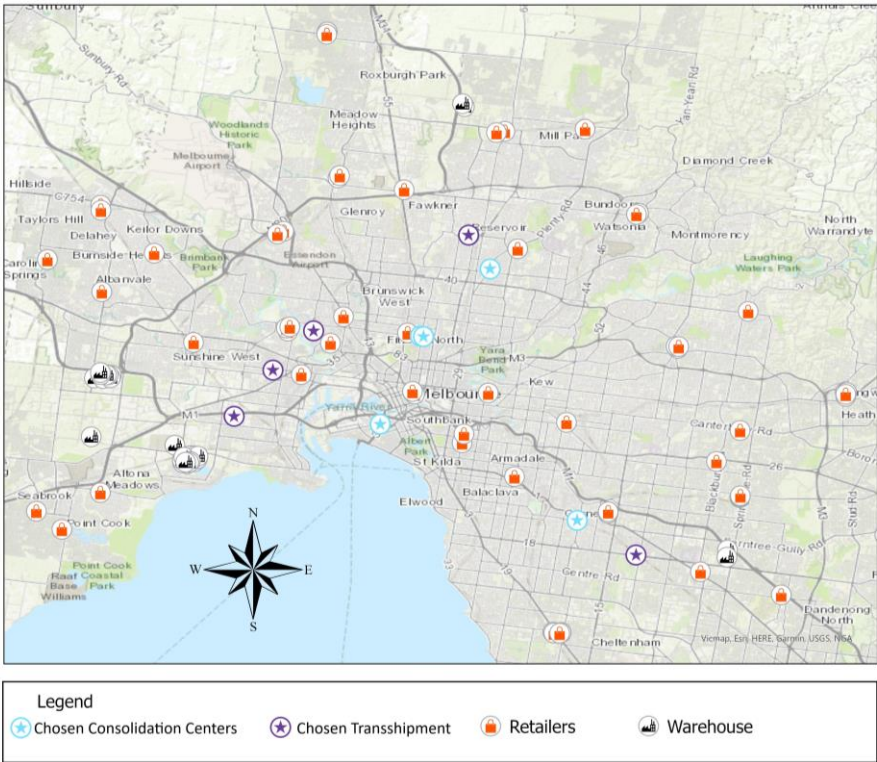


Figure 1. The geographical locations of the nodes in the Melbourne case study.



Figure 2. Candidate industrial lands for (a) THs and (b) CCs using the HCP algorithm.

Given the spatial distribution of warehouses, which are mostly located in the western part of Melbourne, the majority of freight demand is allocated to transshipment hubs situated in the west. Specifically, 25 percent of the daily demand is assigned to each of the transshipment hubs T1, T2, and T3, as shown in Figure 2(a). In comparison, the eastern region shows greater freight demand than the northern region; accordingly, 15 percent of the demand is allocated to T5 in the east, and the remaining 10 percent to T4 in the north.

The distribution network in this study is structured into three echelons: from warehouses to THs, from THs to CCs, and from CCs to customers. Initially, the total cost was calculated based on the most suitable locations for THs and CCs. Subsequently, dual roles were assigned to selected nodes in accordance with the scenarios outlined in Table 2. The evaluation of role

changes is restricted to the THs located in the western region, due to the higher freight demand in this area and the positioning of THs in the outer layer of the metropolitan area compared to CCs. Across all scenarios, the total number of facilities remains constant.

Results

The developed model was executed over a one-month period, during which each scenario involved a single role change at a selected node. Table 2 presents the total transportation and reconfiguration costs across four scenarios, evaluating the impact of assigning dual roles, transshipment and consolidation, to selected nodes within the RUDN. The scenarios are designed to evaluate the impact of assigning combined transshipment and consolidation roles to selected nodes within an urban freight network. Beginning with a baseline scenario that excludes intermediate facilities, each subsequent scenario introduces a controlled change in node function to assess variations in total cost under different spatial configurations. Although the model simplifies some real-world conditions, such as fixed demand distribution and isolated role changes, it effectively captures key operational tradeoffs and offers a structured representation of decision-making in urban distribution planning. The cost components include transportation from warehouses to transshipment hubs ($C_{W \rightarrow T}$), from transshipment to CCs ($C_{T \rightarrow C}$), and from CCs to retailers ($C_{C \rightarrow R}$), along with the cost associated with switching node roles (C_{Switch}). The sum of these components constitutes the total system cost (C_{Total}).

In the baseline scenario (S_0), the distribution network is evaluated without the inclusion of any THs or CCs, representing a one-echelon structure. In this configuration, the only cost considered is the transportation cost incurred by vans delivering goods directly from warehouses to retailers and it is calculated as 32,598 thousand dollars. In the subsequent scenario (S_1), the influence of incorporating THs and CCs is assessed under the condition that no node is assigned a dual role. The total transportation cost in this scenario amounts to 14,362 thousand dollars. In scenario S_2 , node T_1 functions as both a transshipment and CC, with 75 percent of demand routed to CCs and the remaining 25 percent consolidated on site. This configuration results in an increased total cost of 14,592 thousand dollars. The rise is primarily attributed to a significant escalation in the $C_{T \rightarrow C}$ component, from 2,508 to 3,266 thousand dollars, indicating that node T_1 is likely suboptimal for consolidation activities due to extended travel distances or inefficiencies in routing between transshipment and consolidation stages.

In contrast, scenarios S_3 and S_4 , where nodes T_2 and T_3 respectively adopt dual roles, show considerable reductions in cost compared to the baseline. The total transportation costs decreased to 13,757 and 13,807 thousand dollars, respectively. These improvements are driven by reductions in both $C_{T \rightarrow C}$ and $C_{C \rightarrow R}$ components, suggesting that nodes T_2 and T_3 are more favorably positioned to perform dual functions, thereby reducing travel distances across multiple stages of the logistics network.

These results highlight the importance of spatial suitability in the selection of dual role facilities. Although integrating transshipment and consolidation functions may yield cost savings, its effectiveness is highly contingent upon the geographic placement of the selected nodes within the network.

Table 2. Evaluated scenarios for RUDN (costs are in \$1,000 units).

Scenario	Node with dual roles	Demand allocation: forwarded to CC / consolidated	$C_{W \rightarrow T}$	$C_{T \rightarrow C}$	$C_{C \rightarrow R}$	C_{Switch}	C_{Total}
S_0	NA	NA	0	0	0	0	32,598
S_1	NA	NA	3,076	2,508	8,777	0	14,362
S_2	T_1	75% / 25%	3,076	3,266	8,223	25	14,592
S_3	T_2	75% / 25%	3,076	2,435	8,220	25	13,757
S_4	T_3	75% / 25%	3,076	2,532	8,174	25	13,807

Conclusion

This study introduced and evaluated the Reconfigurable Urban Distribution Network as a novel framework for enhancing adaptability, efficiency, and resilience in urban freight systems. By integrating PI principles with DT technologies, the framework enables dynamic reconfiguration of node functionalities, specifically the capacity of logistics hubs to alternate between transshipment and consolidation roles in response to real time demand patterns and operational conditions. This flexibility allows for more responsive freight distribution and improved infrastructure utilization in complex urban environments.

The scenario-based analysis revealed that reconfiguring node roles within the proposed network does not uniformly lead to cost reduction. Instead, the effectiveness of role reassignment is highly dependent on the spatial suitability of the facility and the volume of freight demand it accommodates. For instance, assigning dual roles to nodes situated in spatially suboptimal locations or areas with insufficient surrounding demand resulted in increased transportation costs, as demonstrated in specific test cases. These outcomes highlight the necessity of informed spatial planning and demand analysis when implementing reconfigurable logistics strategies. Compared to the baseline scenario (S_0) with a total transportation cost of 32,598 thousand dollars, the introduction of THs and CCs in scenarios S_1 – S_4 results in substantial cost reductions. The lowest total cost is observed in scenario S_3 , with a 58% decrease relative to the baseline, followed closely by S_4 and S_1 . These improvements highlight the effectiveness of integrating transshipment and consolidation processes, particularly when dual roles are strategically assigned to selected nodes. Overall, the proposed framework offers a promising pathway for developing intelligent, modular, and adaptive urban logistics systems. Its effective deployment requires access to accurate spatial datasets, coordinated governance structures, and computational tools capable of supporting real time decision making.

While recent studies, including the work by Kahalimoghdam et al. (2025), have showcased the potential of advanced technologies such as reinforcement learning-powered intelligent multi-agent system to enable intelligent, adaptive control in last-mile logistics, their application in broader, fully reconfigurable urban freight systems remains underexplored. Building on this foundation, future research will extend the current model into a multi-period location-routing framework that reflects the temporal dynamics of node role changes. This evolution will support joint optimization of facility placement, routing strategies, and role transitions, while incorporating key operational costs. Achieving such complexity will require the seamless integration of PI concepts, the flexibility of RUDN structures, and the real-time analytics of DTs, which together can support the development of truly adaptive, efficient, and resilient logistics networks.

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Securing the Food Supply Chain Resilience – The SecureFood Project

Sofia Kokonezi¹, Dr. Angelos Amditis¹, Giannis Kanellopoulos¹, Konstantinos Touloumis², Apostolos Kapetanios³, Dr. Dimitris Drakoulis⁴ and Dr. Georgios Kolionis⁵

1. ISENSE Group-Institute of Communication and Computer Systems (ICCS), Athens, Greece

2. European Dynamics SA, Athens, Greece

3. European Dynamics Luxembourg SA, Luxembourg, Luxembourg

4. InnovActs, Nicosia, Cyprus

5. EXUS, Athens, Greece

Corresponding author: sofia.kokonezi@iccs.gr

Abstract: *The increasing complexity and vulnerability of food supply chains demand integrated, data-driven solutions to ensure resilience and adaptability. In response, the EU-funded SecureFood project introduces a digital ecosystem composed of interoperable tools designed to enhance logistics, transparency, and proactive decision-making across all stages of the food system. This paper presents the SecureFood architecture and the functionalities of its five key tools: the Observatory Dashboard for real-time monitoring of essential metrics and access to system components; an AI-powered Early Warning System for risk prediction; the Digital Twin for scenario simulation and vulnerability assessment; the RESILOG tool for resilient route planning; and a blockchain-based Information Exchange Platform for secure data sharing.*

These tools are built to operate collaboratively, under a common authentication system, and support modular, scalable deployment in line with the Physical Internet paradigm. Tool interactions and functionalities will be demonstrated through four case studies—covering grain, dairy, aquaculture, and fruit and vegetable supply chains—highlighting their value in enhancing situational awareness, stakeholder coordination, and operational continuity. The findings underscore the potential of SecureFood to drive the transition toward hyperconnected, intelligent, and sustainable food logistics systems.

Keywords: *Supply Chain Resilience, Digital Twin technology, Physical Internet, Predictive Analytics, Block-chain-Based Information Exchange, Resilient Route Planning, Early Warning System, Data Visualisation.*

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

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

1 Introduction

The global food supply chain is a highly complex and interconnected system that ensures the movement of food from production to consumption. However, it faces numerous challenges

that threaten its efficiency, resilience, and sustainability. One of the most critical issues is logistics inefficiencies, which lead to delays, increased costs, and food waste. The food supply chain requires well-coordinated transportation and storage systems, yet disruptions caused by climate change, geopolitical instability, and labour shortages frequently hinder operations (Rasshyvalov et al., 2024). In addition, the COVID-19 pandemic further exposed vulnerabilities in food supply chains by causing massive disruptions in logistics, trade restrictions and labour availability. Lockdowns and border closures disrupted transportation networks, leading to bottlenecks in food distribution and shortages of essential goods (Li et al., 2023). The pandemic also highlighted the need for more flexible and adaptive supply chain models that can withstand sudden shocks and disruptions (Ivanov and Dolgui, 2020; Aday S. and Aday M. 2020). Inadequate route planning and inefficient distribution networks further exacerbate these problems, causing significant losses, particularly in perishable goods (Fatorachian et al., 2025).

Another major challenge is fragmented information exchange across stakeholders. Food supply chains involve multiple actors -farmers, producers, processors, distributors, and retailers- each operating with different systems and data sources. The lack of real-time, standardized data-sharing mechanisms creates inefficiencies and impede collaboration (Akinbamini et al., 2025). Blockchain and digital platforms offer promising solutions (Abideen et al., 2021; Li et al., 2021), yet significant challenges that need to be overcome still exist, with the most prominent being interoperability issues and concerns about data security (Li et al., 2021). Early warning systems (EWS) are also critical in mitigating risks associated with food supply chain disruptions, such as food contamination, extreme weather events, and logistics bottlenecks. However, data-driven decision-making in food logistics remains underutilized. Many organizations still rely on reactive rather than proactive strategies, missing opportunities to optimise supply chain visibility and performance through predictive analytics and artificial intelligence (Adewale and Ahsan, 2025).

Addressing these challenges requires innovative digital solutions that optimise logistics, enhance information transparency, and enable proactive, data-driven decision-making. In response, the EU-funded SecureFood project has developed a comprehensive ecosystem designed to strengthen the resilience and sustainability of food supply networks. At its core, this ecosystem integrates cutting-edge digital tools, including the Digital Twin for smart supply chains, an Early Warning System for risk detection, the Resilient Route Planning tool for optimising transport logistics, a blockchain-based Information Exchange Platform to ensure secure and transparent data sharing and the Observatory Dashboard, which serves as the system's central access point and provides monitoring and visualization of key resilience metrics. Together, these technologies streamline operations, mitigate disruptions, and enhance the overall efficiency of food supply chain management.

2 System Layers

The reference architecture of the SecureFood project is structured across four main layers: Business, Process, Technology, and Data. Together, these layers create a resilient, interoperable, and adaptive digital ecosystem that supports food supply chain stability. While SecureFood includes a range of innovative digital tools, this paper focuses on those most directly aligned with the Physical Internet vision - namely the Observatory Dashboard (OD), Early Warning System (EWS), Digital Twin (DT), Information Exchange Platform (IEP), and the Resilient Route Planning tool (RESILOG).

The **Business Layer** defines the overarching strategic objectives, priorities, and governance mechanisms that shape resilient food systems. This layer brings together key stakeholders -

including producers, processors, logistics operators, and policymakers - to coordinate responses to food security risks and align with EU goals such as sustainability, decarbonization, and supply chain transparency. Decision-making at this level is supported by the risk assessment model embedded within the Digital Twin for Smart Supply Chain, which enables strategic scenario planning and vulnerability evaluation across different stages of the food supply network.

The **Process Layer** encapsulates the workflow and operations necessary to implement resilience strategies. Key SecureFood tools such as RESILOG, the DT, the EWS, and the OD, enable predictive and proactive action. RESILOG and the DT allow route optimisation, scenario-based planning and vulnerability analysis. The EWS provides AI-driven early detection of risks, and the OD ensures real-time monitoring and visualization of risk indicators. These tools are especially relevant to the Physical Internet paradigm, promoting hyperconnected, decentralized logistics decision-making.

The **Technology Layer** provides the enabling infrastructure for secure, scalable, and interoperable deployment of digital tools. Cloud-native architectures, containerised microservices, and secure APIs allow for real-time integration across internal modules and with external datasets. The IEP, built on blockchain, exemplifies trust-by-design infrastructure by ensuring traceability and immutability of shared data. Secure authentication systems (e.g., Keycloak, DIDs) ensure controlled data access. Together, these technologies underpin Physical Internet principles such as modularity, decentralization, and transparency.

This foundational **Data layer** manages the collection, processing, and storage of supply chain data. It integrates real-time feeds (e.g., weather, transport delays, stock levels), historical performance data, and open-access datasets from publicly available sources like Copernicus and FAO. Advanced analytics and machine learning models transform raw data into predictive insights, supporting tools such as the EWS and DT. The IEP and OD further ensure structured data exchange and visualization, empowering stakeholders to act on a shared understanding of risks and conditions. In the context of the Physical Internet, this data backbone is essential for synchronised, data-driven logistics optimisation across a distributed network.

By integrating these four layers, SecureFood delivers a comprehensive digital architecture to enhance food supply chain resilience. The tools emphasized in this paper provide practical, PI-aligned solutions to today's pressing logistics challenges - ensuring that food flows remain efficient, adaptive, and secure in an increasingly complex global environment.

3 Digital Tools

3.1 Observatory Dashboard

The Observatory Dashboard (OD) is a unified digital platform that facilitates the monitoring, analysis, and visualization of essential metrics pertaining to food system resilience and security. By aggregating and visualizing data from diverse sources, including weather forecasts, food commodity prices, demand fluctuations, and production data, the OD enhances situational awareness and supports evidence-based decision-making. Through its secure API integration and in cooperation with blockchain-supported information exchange and the EWS, it fosters an interconnected network, aligning with the Physical Internet's vision of open and efficient logistics.

The OD incorporates cutting-edge web technologies to provide an intuitive and responsive interface for users. Developed using React and TypeScript, the system ensures scalability, maintainability, and high-performance rendering of real-time data. Interactive features such as

dynamic charts and historical trend analysis allow stakeholders to track disruptions and adjust their operations proactively. Secure access is managed via Keycloak authentication, ensuring compliance with industry standards and safeguarding sensitive data. Additionally, React Query and Zustand optimise state management, while WebSockets or Server-Sent Events (SSE) enable real-time updates, a crucial feature for logistics coordination in Physical Internet-enabled networks.

Beyond its technical framework, the OD is designed to facilitate collaboration across food supply chain actors. By standardizing and sharing key indicators, it promotes transparency in food markets, improves risk assessment, and enhances supply chain interoperability - a core principle of the Physical Internet. Its ability to provide clear, analytical tables and dashboards empowers food supply chain actors such as transport operators and wholesalers to optimise routing and inventory management based on real-time conditions. As global food systems become increasingly interconnected and digitalized, the Observatory Dashboard serves as a critical enabler of resilient, data-driven, and hyperconnected logistics, paving the way for a more efficient and sustainable food supply chain ecosystem.

3.2 Early Warning System

The Early Warning System (EWS) is an advanced module which suggests and predicts risks relating to different food supply chain stages, to increase risk awareness, issue prevention and support decision making for stakeholders. The EWS receives input from both internal sources (other SecureFood components, e.g. the IEP) and external data sources (e.g. Copernicus, Eurostat) and uses AI risk identification and prioritization techniques along with real-time data analytics in conjunction with user evaluation to predict possible risks along with a criticality level personalized to each user according to their risk profiles. The estimated risks are transferred as alerting messages to other SecureFood components (e.g. the DT to perform simulations) and displayed in the EWS Graphical User Interface (GUI) with their details. The GUI also assists users in monitoring and managing the estimated risks during their entire lifespan. The EWS architecture comprises of several key components and is depicted in the figure below:

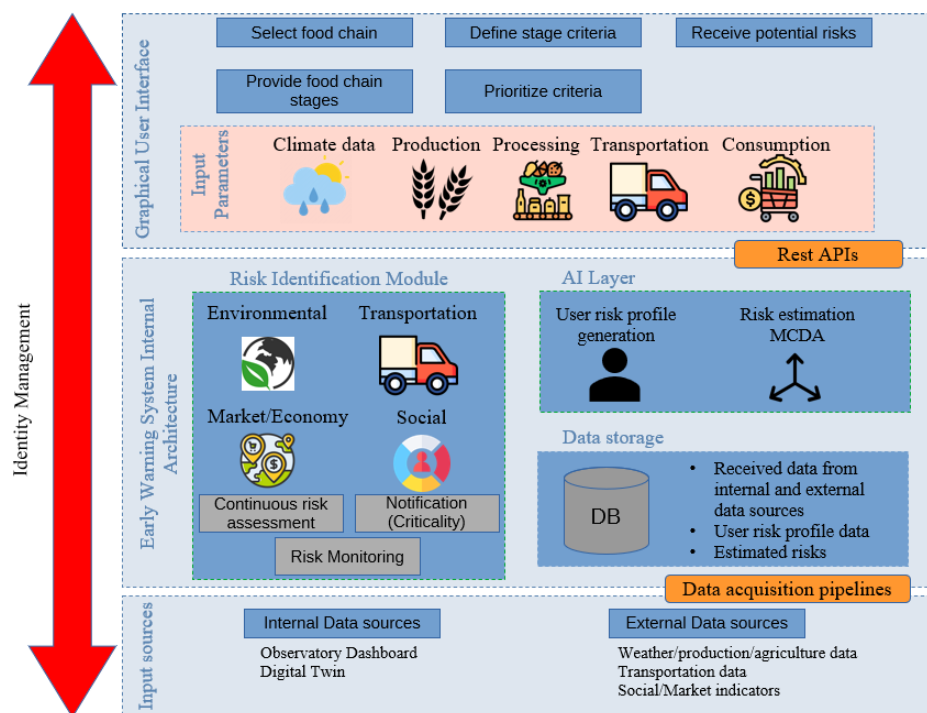


Figure 1: EWS Architecture

- Graphical User Interface (GUI): Enables users (transport operators, producers, wholesalers, policy makers) to input food supply chain parameters, define their risk thresholds, and receive automated alerts.
- AI Layer: Uses AI and Multiple Criteria Decision Analysis (MCDA) techniques to estimate risks based on user-defined profiles.
- REST APIs: Establish endpoints for secure interactions of external systems with the EWS.
- Risk Identification Module: Identifies risks according to user risk profiles, each risk is followed with a criticality message depicting the urgency of actions needed to be taken by the user.
- Data Acquisition Pipelines: Automates the collection, processing, and storage of real-time data from diverse sources.
- Data Storage: Maintains structured datasets, including user-defined parameters, external and internal data sources, and risk estimations.
- Identify Access Management Layer (vertical): Ensures secure and role-based access to system resources and risk profiles. It authenticates users and services, manages credentials, and enforces permissions across all system layers.

By implementing this modular and interoperable architecture, the EWS enhances the predictive capabilities of food supply chain actors, allowing them to:

- Predict extreme weather conditions droughts/snowstorms (based on temperature, windspeed, precipitation).
- Predict extreme sea water conditions (temperature, chlorophyll-phytoplankton, oxygen)
- Identify processing risks (increased energy costs, prices).
- Generate warnings for transportation disruptions (e.g. accidents).

The EWS is deployed using a Windows/Ubuntu Virtual Machine (VM) infrastructure with Docker containers, ensuring scalability, security, and seamless integration within existing digital ecosystems. It utilizes:

- Frontend (GUI): Angular-Ionic for a responsive user experience.
- Risk Estimation APIs: Java Spring Boot, ensuring efficient risk computation.
- Data Storage: PostgreSQL, offering high-performance risk data management.

In alignment with Physical Internet principles, the EWS functions as a decentralized, interconnected risk prediction platform and alerting system. It enables food supply chain actors to share real-time alerts and optimise logistics and resource allocation dynamically. By embedding data-driven intelligence into supply chain processes, it contributes to hyperconnected, autonomous decision-making, strengthening food security and resilience in an increasingly volatile global landscape.

3.3 Digital twin-driven smart supply chain

The Digital Twin-driven Smart Supply Chain (DT) is a virtual replica regarding production quantities and disruptions in food supply chain, designed to enhance situational awareness, improve decision-making, and ensure food supply chain resilience. By integrating historical and real-time data with predictive analytics, simulation and risk assessment models, the tool enables stakeholders to anticipate disruptions, explore what-if scenarios, and optimise supply chain performance dynamically. It serves as a strategic solution to improve operational visibility, test potential impact of disruptions and response strategies, and assess vulnerabilities

across different stages of the food supply chain - while aligning with SecureFood's overarching objectives for food security and sustainability.

This web-based tool is designed to act as both a monitoring tool and a predictive engine for identifying turnaround scenarios in the face of potential disruptions. It incorporates supervised machine learning algorithms - such as Random Forest and Decision Trees - to forecast disruption probabilities across the supply chain, as well as advanced mathematical models to assess risk exposure and vulnerabilities. These models process a combination of historical and real-time data to simulate system behaviour under stress, helping stakeholders anticipate disruptions and formulate optimal intervention strategies. By modeling both internal operational factors and external influences, the tool delivers a comprehensive view of supply chain stability. Through techniques like Mixed-Integer Linear Programming, the system supports data-driven decision-making aimed at strengthening the core pillars of food security: availability, access, utilization, and stability. Embedded within a broader suite of SecureFood components - including the Early Warning System, the Information Exchange Platform, and RESILOG - the Digital Twin facilitates dynamic data sharing and coordinated risk management.

From a technological perspective, the system architecture includes containerized back-end and front-end layers, utilizing scalable, cloud-based infrastructure. A modular design supports simulation engines, rendering modules, and a data orchestration service, enabling input collection, execution of AI and mathematical models, and visualization through a user-friendly interface. Alerts and reports are generated in standardized formats, facilitating quick dissemination of actionable insights.

The Digital Twin aligns with the principles of the Physical Internet by enabling modular, interoperable, and real-time orchestration of food logistics networks. It promotes standardized data exchange, decentralized decision support, and dynamic reconfiguration of assets and flows in response to changing conditions - key enablers of hyper-connected, efficient, and resilient supply chain ecosystems.

3.4 Information Exchange Platform

The Information Exchange Platform (IEP) is a digital tool designed to enhance communication, transparency, and trust among stakeholders across the food supply chain - from producers and retailers to logistics actors and public authorities at national and European levels. Its core purpose is to enable secure, structured, and timely information sharing through a decentralised architecture, ensuring all participants can access and act on reliable data. By leveraging blockchain technology, the platform guarantees data integrity, traceability, and trust across the ecosystem - key enablers of transparency and accountability.

IEP is composed of three key modules:

- **General Information Exchange Module:** Facilitates collaborative knowledge sharing by enabling end-users (food actors, transport operators, retailers and authorities) to exchange general updates, circulate best practices, and engage in structured communication. This promotes openness and cooperation throughout the food supply chain system.
- **Stock Reporting Module:** Provides food actors with a secure mechanism to notify authorities of available commodity stocks using standardized forms. This ensures an accurate, real-time view of food availability, which is essential for informed policy-making and rapid response during crises.

- **Incident Reporting Module:** Enables the structured and timely reporting of incidents, alerting both authorities and other interdependent actors within the supply chain. This supports early detection, response coordination, and mitigation of cascading effects.

Each module collects input directly from users through predefined forms that ensure consistency, completeness, and harmonization of data. The submitted information is visible to other authorized users and can also be shared with other SecureFood tools through a dedicated API - fostering interoperability and integration across the broader digital ecosystem.

The architecture of the IEP is designed around a decentralized application (D-App) model, structured into six functional layers. Three of these form the blockchain core, while the remaining layers ensure seamless interaction with users and other systems.

The diagram below shows the Information Exchange Platform's architecture which consists of:

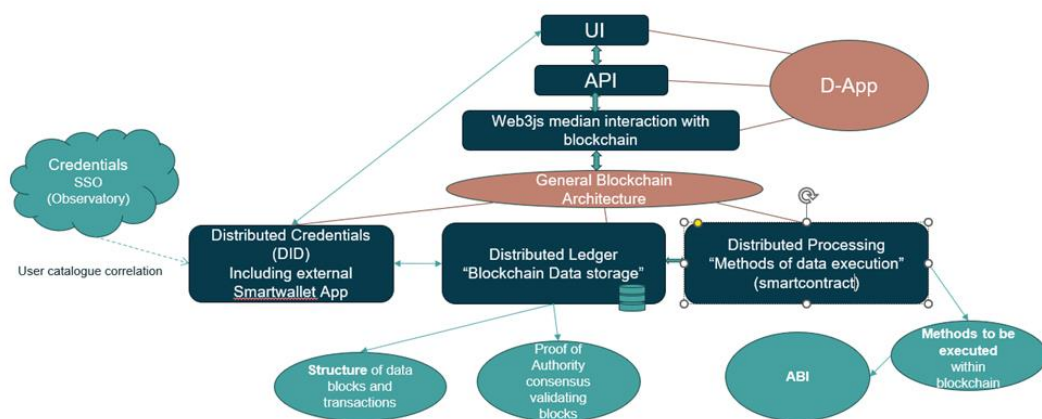


Figure 2: IEP architecture

- **Distributed Network & Credentials:** Defines user identities using a combination of centralized credentials and Distributed Identifiers (DIDs), ensuring secure access and user authentication. It includes public and private keys in order for users to submit a transaction in the blockchain. An external smart wallet application (e.g., Metamask) manages user keys and enables secure blockchain transactions.
- **Distributed Ledger:** Serves as the immutable data repository and transaction engine, operating on Ethereum blockchain technology with a Proof-of-Authority (PoA) consensus mechanism to validate and secure entries.
- **Distributed Processing:** Defines the methods of data execution to be performed within the general blockchain distributed network. These methods are imprinted in a smart contract and define all actions performed by the Application Binary Interface (ABI), while corresponding with the ledger to successfully submit the transaction. For IEP, the smart contract will imprint all methods of data execution needed for the three modules to be properly performed by the users.

To provide a user-friendly experience, the blockchain back-end is connected to:

- **Web3 Library Layer:** Bridges smart contracts with the application layer, abstracting complexity and enabling secure interactions.
- **Backend API:** Enables communication between the blockchain and front-end applications, while also providing endpoints for other SecureFood tools—such as the

Early Warning System or the Observatory Dashboard - to retrieve alerts or stock updates.

- **Graphical User Interface (GUI):** Offers a clean, intuitive interface for end-users to submit information, report incidents or commodities stocks, and interact with other actors in the platform. Access can be initiated through the SecureFood Observatory Dashboard, provided identity mapping with DIDs is in place.

The Information Exchange Platform acts as a digital enabler of trust and collaboration, providing the infrastructure needed for synchronized, adaptive, and efficient food supply chain operations—precisely the type of integration envisioned by the Physical Internet paradigm.

3.5 Resilient Route Planning tool

The RESILOG is a cloud-based, data-driven platform designed to foster digital and horizontal collaboration between shippers, carriers, and other multimodal logistics stakeholders. Its core function is the identification of the best available transport options, considering both single-mode and multimodal alternatives. Acting as a collaborative digital marketplace, RESILOG facilitates synchromodal transport planning, by intelligently matching transport demand and supply. It also uncovers opportunities for cargo consolidation and bundling opportunities across different shippers and logistics service providers, enhancing efficiency and flexibility across the supply chain.

RESILOG offers key functionalities such as:

- **Mapping commercially viable transport routes** between two points, incorporating mode combinations and logistics constraints
- **Forecasting route performance** based on historical and disruption-related data
- **Increasing load factors** for transport vehicles and standardized modular units
- **Reducing empty returns** and overall transport costs

While RESILOG can function independently, it also includes an API integration layer for seamless data exchange with other tools in the SecureFood ecosystem - such as the Digital Twin, the Information Exchange Platform and Early Warning System - enabling coordinated responses and improved situational awareness. Its flexible design allows it to operate in both federated and standalone modes:

- As part of a federation, using the authentication and authorisation controls defined by the federation, encouraging data sharing and interoperability.
- As a standalone platform, using its own user authentication and authorisation controls to meet varying user needs.

More specifically, to effectively support decision-making in both long-term transport planning and ad-hoc rerouting after disruptions, RESILOG offers a user-centric interface that enables logistics stakeholders to input key parameters and execute scenario-based route planning. Complementing this, an Application Programming Interface (API) facilitates seamless bulk data exchange with users' back-office systems, allowing the import of operational data and the provision of up-to-date transport schedules and available capacities. The API also supports real-time updates, ensuring the tool reflects the most current network conditions. At its core, RESILOG leverages advanced graph-based technology to dynamically explore all feasible multimodal transport routes between two locations, breaking them down by leg and providing key indicators such as turnaround time, estimated CO₂ emissions, and cost. Enhancing this capability, a predictive algorithm utilizes historical data and disruption-related parameters to

assess and forecast route availability, delivering proactive insights that strengthen transport resilience and continuity in the face of evolving supply chain risks.

RESILOG embodies the principles of the Physical Internet (PI) by enabling open, modular, and intelligent logistics planning. It encourages collaboration across traditionally siloed stakeholders, standardises data sharing, and supports interconnected routing strategies that mirror PI's vision of seamlessly moving goods through a shared, responsive network. By facilitating the real-time reconfiguration of logistics flows based on disruptions, RESILOG contributes to a more adaptive, transparent, and sustainable food transport system, aligning logistics infrastructure with Physical Internet values.

4 SecureFood System: Tools' Interactions and Case Study Applications

4.1 Tool Interactions

The SecureFood system is built upon the safe and seamless integration of multiple digital tools, working together to support food system resilience and security. Central to this architecture is a common authentication mechanism, which ensures secure and role-based access across all SecureFood tools.

At the core of the user experience is the Observatory Dashboard (OD), which serves as the main entry point to the SecureFood system. Through the OD, users can visualize key metrics related to food system resilience and disruptions. It also provides direct links to access the graphical user interfaces (GUIs) of the other SecureFood tools, enabling smooth navigation and operational efficiency.

The Information Exchange Platform (IEP) functions as a coordination hub for incident reporting and communication. It sends confirmed incidents to the EWS to be used as input for the EWS's multi-criteria analysis and end-user notification system. Simultaneously, the IEP also communicates with the Digital Twin (DT) by transmitting identified disruptions, enriching the DT's data sources. Additionally, it provides the EWS with production level information, triggering incident alerts when thresholds defined by user profiles are exceeded.

RESILOG, the resilient route logistics optimisation tool, can be accessed either independently or through the Observatory Dashboard, giving flexibility to transport stakeholders in identifying optimal routes and managing disruptions in delivery.

Through this interconnected framework, SecureFood enables data-driven, anticipatory decision-making, ensuring that stakeholders can act swiftly and effectively to maintain food system stability.

4.2 Case Studies

The SecureFood system and its integrated digital tools will be demonstrated and validated through four distinct case studies, each reflecting different food supply chains, regional contexts, and resilience challenges across Europe. These scenarios are selected to ensure a comprehensive evaluation of the system's capabilities in diverse settings, highlighting how SecureFood supports risk-informed decisions, operational coordination, and supply chain resilience.

- Grain Case Study – Ukraine
- Fruits and Vegetables – Portugal
- Fish and Aquaculture – Greece and Belgium
- Milk and Dairy Products – Greece and Finland

5 Conclusion

The SecureFood project presents a comprehensive and modular digital ecosystem designed to address the pressing challenges facing modern food supply chains - ranging from climate-related disruptions to fragmented information exchange and logistics inefficiencies. By integrating advanced technologies such as Digital Twins, blockchain, predictive analytics, and AI-driven early warning systems, SecureFood enables stakeholders to move from reactive to proactive risk management. The interaction between tools like the Observatory Dashboard, Early Warning System, Digital Twin, Information Exchange Platform, and RESILOG exemplifies the synergy required for real-time coordination, transparency, and resilience across all stages of the supply chain. Fundamentally, the system's architecture and operational design directly support the core principles of the Physical Internet, including modularity, interoperability, real-time data exchange, and decentralisation. SecureFood aims to demonstrate the value of an integrated, scalable digital infrastructure that empowers stakeholders to anticipate disruptions, optimise logistics, and ensure continuous food availability even under volatile conditions. SecureFood solutions are going to be evaluated through four diverse case studies across Europe, nonetheless, realizing the full potential of the SecureFood system requires further progress in several areas. These include fostering stakeholder collaboration and trust for data sharing, improving interoperability with existing systems, and establishing unified data provision mechanisms. Additionally, aligning digital tools' deployment with clear incentives for end-users remains critical to encouraging adoption across a diverse and often fragmented supply chain landscape.

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A novel approach to describe transshipment processes with consolidation within nodes: The Column-First Data Model

Tadashi Mizutani¹ and Yuzo Ishida²

1. Nomura Research Institute, Tokyo, Japan

2. Nomura Research Institute, Tokyo, Japan

Corresponding author: t-mizutani@nri.co.jp

Abstract: *This paper proposes a column-first data model as a novel approach to describe transshipment with consolidation for implementing the Physical Internet. The strength of this approach lies in its ability to represent complex existing logistics structures, such as variable container hierarchies and multiple transshipments, and in its flexibility to support the future addition of new data elements. These attributes are essential for constructing a logistics digital twin. As the system infrastructure and applications underpinning the Physical Internet are expected to evolve incrementally, the approach proposed in this study is well positioned to make a meaningful contribution to that progressive development.*

Keywords: *digital twin, data model, normalization, common language*

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

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

1. Introduction

1.1 Research objective and scope

This paper introduces a novel Column-First Data Model designed to accurately represent “transshipment with consolidation,” essential for realizing the Physical Internet. This research aligns with the Solution Design phase, the third of four phases in the Physical Internet research.

Solution design studies are conducted to build systems. Various system-building techniques exist. First, it is important to clarify the differences between the topics addressed in this paper and existing system-building techniques. Table 1 classifies and compares system building techniques along two axes. One axis is whether or not to allow data updates and deletions, and the other axis is row-oriented or column-first. Using these classification axes, system construction techniques can be classified into four categories.

First, positioned at the upper left is the traditional system construction technique, which uses a row-oriented data model. Row-oriented data has many columns, and data updates and deletions are allowed. The same data is redundantly stored in multiple purpose-specific tables. Normalization, if any, is performed up to the third normal form. Traditional centralized systems are characterized by low scalability and low real-time performance due to batch processing (i.e., Extract-Transform-Load) among multiple databases.

Table 1: Comparative Table of System Construction Techniques

SQL Database centric or Application centric		Scalability (Commutative Property)	
		Mutable Database (UPDATE/DELETE Allowed)	Immutable Database (INSERT ONLY)
Data Integrity (Single Source of Truth)	Row- oriented (Batch)	Row-Oriented Data Model ($< 3NF$) applied for different workload (OLTP + OLAP with ETL)	Block Chain (a falsification at one place can be identifiable by others)
	Column-first (HTAP)	In-Memory Columnar Database (ex. SAP S/4 HANA)	Column-First Data Model (7NF) applied for both scalability and data integrity with type safety

In contrast, positioned in the lower right-hand corner is the technique proposed in this paper that uses a column-first data model. Data is stored across multiple tables with a small number of columns. Data updates and deletions are not allowed, and only raw data is kept in columnar tables without redundant purpose-specific tables at all. It has the advantage of high scalability and real-time performance. This is an appropriate technique for building a digital twin of logistics because the number of stakeholders involved is likely to increase as the logistics network expands, and it is necessary to immediately analyze problems from integrated data and propose alternatives of transportation means to irregular phenomena that occur in logistics.

For reference, the remaining two cells are explained below. The first, positioned in the upper right corner, is the blockchain. The most important feature of the blockchain is that if data is tampered with in any one place, it can be detected by others. Data is not allowed to be updated or deleted, but the same data is held in multiple locations. Data is stored in a row-oriented manner. The next technique, positioned at the bottom left, is the use of in-memory columnar databases. Its typical example is SAP S4/HANA. This in-memory columnar database is a relational database management system that provides an SQL interface to the applications and has the ability to map between row-oriented tables in memory and columnar storage in the database. Data updates and deletions are allowed, but the same data is kept in only one place in a column-first manner in handling both transactional and analytical processing workloads.

The proposed technique in this paper, using a column-first data model, differs from both blockchain and in-memory columnar databases. As shown in Table 1, the key difference is that how data is held in a company database. More concisely, data can be stored in either row or column format.

1.2 Motivation

Logistics operations within the Physical Internet are inherently complex, as illustrated by the involvement of multiple carriers instead of a single entity. Furthermore, transshipment can occur even within a single carrier's transportation process, and multi-stage consolidation is frequently implemented to enhance truck fill rates. Despite this complexity, existing digital twins often fall short in adequately representing these nuanced operations.

Among various logistics processes, mixed load and transshipment operations present particular challenges. Designing and implementing such operations is not the final step; continuous improvement is required after the system becomes operational. This improvement depends on a clear understanding of actual phenomena such as the utilization rate of transportation capacity for each transport section and the dwell time of cargo at transshipment location.

Closely related to the digital twin is the project to build a logistics data sharing and exchange platform. There have been many projects related to the construction of data exchange and sharing platforms in Europe. However, challenges have been pointed out in the handling of data models [1]. These projects are often based on a use case approach, as commonly observed.

However, data models covering end-to-end logistics processes were not adopted, and situations where functional or use case silos formed between different projects were observed.

In international air cargo, which may form part of the Physical Internet, a data model framework called ONE Record has been under development by the International Air Transport Association since 2017 [2]. The goal is to improve air cargo efficiency. ONE Record is set for partial implementation in 2026, with plans to gradually expand its functions thereafter.

As seen above, there is a growing movement to reconsider data models in the field of logistics. This paper aims to contribute to the development of digital twins for complex logistics operations handled within the Physical Internet.

1.3 A new approach to modeling data for digital twin realization

Implementing the Physical Internet necessitates the use of digital twins. Generally, a digital twin serves two primary functions: first, to understand past events; and second, to analyze opportunities for improvement based on this historical data, potentially leading to feedback mechanisms such as the revision of operational rules.

Japan is facing the “2024 logistics problem.” The shortage of truck drivers is worsening, reducing transportation capacity and making truck efficiency a challenge. One solution is “transshipment with consolidation,” but there may be no digital twin to express this concept.

The lack of a digital twin stems from the difficulty of recording “transshipment with consolidation” and storing it in a database for flexible analysis. Handling variable numbers, such as nested logistics containers and the number of transshipment locations from origin to destination, is challenging since event frequency cannot be fixed.

The concept of variable numbers is defined as follows. Many readers may be familiar with bills of materials (BOM) used in the manufacturing industry. The BOM deals with variable numbers. The maximum number of nests varies from product to product, and the number of nests of components varies even within the same product.

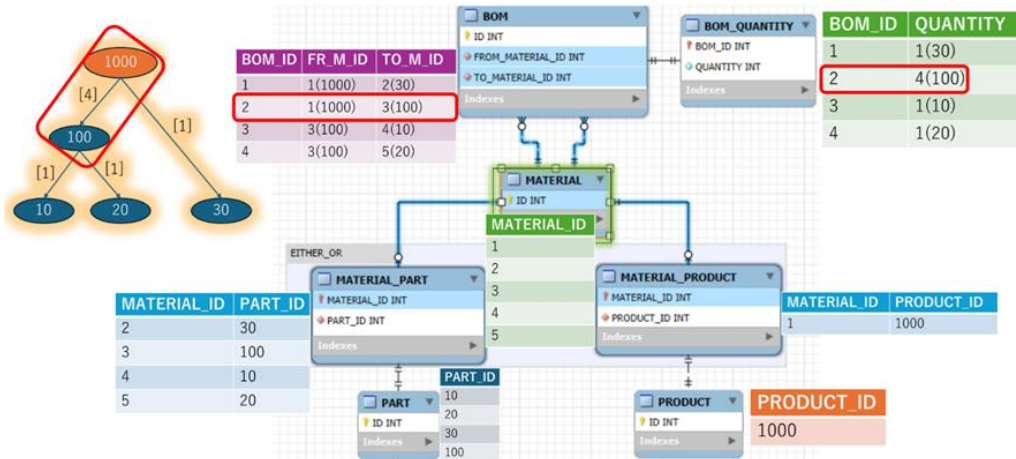


Figure 1: Bill of Materials in algebraic diagram with abstract concept accompanied by real numbers

Here, by setting up a table named “MATERIAL” to identify (i.e., abstract) products and parts, variable numbers can be managed by combining the relationship between upper and lower MATERIALs (see Figure 1). That is called a recursive structure.

These innovations are common in the software implementation phase. Cooperation between domain experts and system engineers is essential for building a digital twin. When experts from different backgrounds share abstract concepts, it is necessary to give appropriate names to abstract concepts and to use visual diagrams in leading the design of implementations directly.

2. Communicating across professional backgrounds

2.1 Potential problems

Generally, when building a software system, the division of roles is such that the business process designer defines the requirements and the system engineer writes the programming based on those requirements. In such cases, it is rare for the business process designers to consider “how to hold data in the database” when they study the requirements. Such responsibilities are often considered solely within the domain of system engineers, which leads to significant challenges during implementation.

2.2 Use a common language for digital twin implementation

The increasing complexity of business operations, coupled with the fragmentation of specialties, makes it increasingly challenging to ensure system integrity and comprehend the holistic view of data utilization. For successful digital twin implementation, seamless communication through a common language among logistics experts and system engineers (including programmers and architects) is paramount. A lack of shared understanding can lead to significant rework and delays in system implementation, thereby diminishing development efficiency and jeopardizing the long-term sustainability of system evolution.

An effective common language for digital twin implementation is the use of visualized diagrams that allow stakeholders to reference and verify information collaboratively. The diagram is a data model that expresses the relationship between items. Normalization is the method used to eliminate data duplication and improve data integrity.

In this paper, the data model based on normalization is referred to as the column-first data model. By adopting the column-first data model, business process designers and system engineers can discuss the essence of business in a common language without being conscious of technical issues such as null and complex table structures. This prevents the design of business processes that cannot be implemented and enables more realistic and efficient system development based on clearly visualized foundation of requirements with right terms.

3. Structural principles of the column-first data model

Note to the reader: This chapter discusses technical aspects of database design. If your primary interest lies in practical applications or case studies, feel free to proceed directly to Chapter 4 without losing the logical flow of the paper.

Database system development involves programming logic on defined tables. This process typically uses a standard language called SQL. There are two issues here.

First, while SQL is an easy way to manipulate data, it has the danger of not being compile-checked. For example, if an instruction is given to join two tables that are logically impossible, the response will follow the instruction.

Second, table design standards on the database side and coding conventions for applications are independent, making it difficult to define the standardized way of adapting requirement changes. Careful development and testing are essential when modifying a system for every change, leading to a system that is hard to understand due to accumulated ad-hoc maintenance.

If future changes are assumed to be unpredictable, it becomes necessary to return to the principle of “Divide and Conquer”, which is to decompose both data and logic into elements that cannot be further divided. A new approach, the column-first data model, is introduced based on the design concept of “normalization as much as possible.” This approach will be described in the following sections to clarify how it differs from traditional models.

3.1 Column-based normalization of matrix structures using Binary Relation

Normalization reduces duplication and improves integrity. This concept can be illustrated with an address book. Imagine a person's name stored in multiple spreadsheet files. If the name changes, all related files must be updated to maintain data integrity. Consider that a person has both a name and an address. Changes to the name and address are independent, and the number of changes varies for each item. Managing history without duplication, null, or waste reveals the limitations of a row-oriented representation. Therefore, focus on “columns,” the components of rows. The sheet should be divided by attribute, adding only changed items. This separation necessitates establishing links between them. In this example, the key item identifying a person and the attribute items (name and address) need to be related (called “Binary Relation”). Once the values of the name and address are determined, it uniquely identifies whose attributes they are, a property known as “Functional Dependency.” [3]

3.2 Manage column update history for logical updates and deletions: 6th Normalization (6NF)

CRUD refers to the four basic data manipulation functions: Create, Read, Update, and Delete. The column-first model intentionally avoids updates and deletions, managing changes through timestamped inserts and logical cancellations. Updates and deletions are handled logically by breaking down the dataset by individual items, managing dependencies on key items, retrieving the latest timestamped values, and combining item values. This approach allows full traceability of historical states without compromising data integrity. Dividing a table for each item and maintaining a history of changes aligns with the sixth normalization, which highlights the need for a temporal feature to manage the validity period of each item, such as tax rates [4].

Unpacking the definition of the sixth normalization reveals that it states: NO NONTRIVIAL JOIN DEPENDENCIES AT ALL. This indicates that the data model is fully normalized, ensuring complete unambiguity at the time of join operations.

In addition, the column-first data model has a flexible structure. If a row-oriented data model is used, adding columns later requires altering an existing table. However, if a column-first data model is used, no table modification is required at all; a new table is simply added.

3.3 Manage transactions by canonical table design: 7th Normalization (7NF)

When normalization is pursued, the total number of tables increases, leading to two problems. First, querying the database (usually with SQL) becomes more complex as the number of join conditions rises. Second, transaction management becomes more complicated due to the increased number of tables and the presence of foreign key columns across many tables.

One of the responsibilities of the database is to maintain transactional consistency. To this end, there is a function called rollback, which restores the database state to the point at which the process started if a database state change procedure fails in the middle of a transaction. When normalization is pursued, the processing load related to rollback increases.

To address this issue, a method was developed to eliminate the need for rollback. Transaction management should move from the database to the application, with a focus on canonicalizing the table design on the application side. One author named this the seventh normalization, which includes the sixth normalized set of tables and additional tables for transaction management. For more details, please refer to the references [5].

The following simple example demonstrates this concept. The key idea of the seventh normalization is to reverse the usual order of INSERT operations in transaction management.

In traditional models, parent records are inserted first, followed by child records. In 7NF, this order is reversed to enhance concurrency in completing children's transactions individually.

If “parent first, children last” is the normal case, the reverse is “children first, parent last.” Children records are considered logically invalid without a corresponding parent, with the parent table serving as the commit point. The order in which the child tables are written to the database is not questioned, and the INSERT process is performed concurrently, facilitating database distribution. Thus, rollback functionality is logically implemented in application level.

3.4 Type safe system based on Binary Relation as a unified language

In a typical architecture, transaction processing (OLTP) and analytics processing (OLAP) are built separately to protect the core system that underpins the business. The database is divided to manage the processing load of the analysis system. The tables are row-oriented and moderately denormalized (<3NF, indicating a state below the third normal form) for easier SQL operations. Reducing the number of table joins shortens the SQL embedded in the application. Additionally, preparing denormalized tables for various purposes in advance reduces the join processing load and improves response performance.

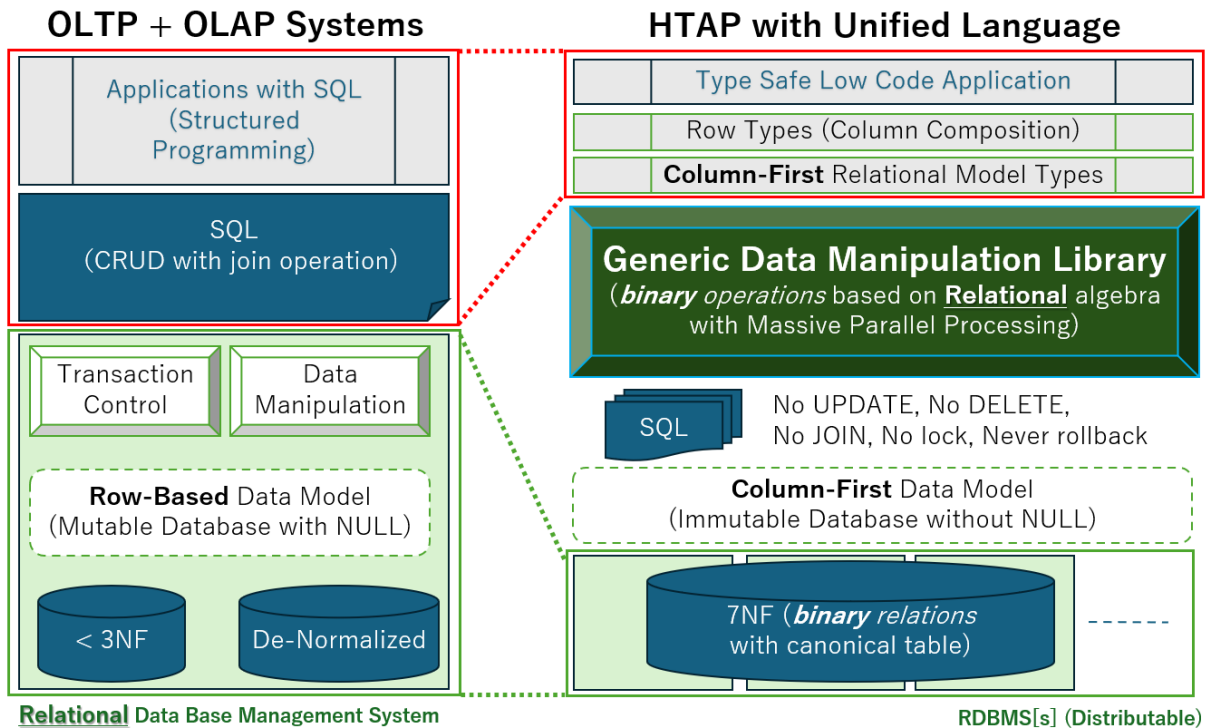


Figure 2: Architectural differences created by the degree of database normalization

On the other hand, data integrity and real-time performance are compromised when databases are separated. Hybrid Transactional Analytical Processing (HTAP) attempts to solve this problem. Figure 2 compares the typical architecture with the HTAP-enabled architecture.

The role of the database is rethought to increase scalability and flexibility to accommodate the digital twin in the application design. In the column-first data model, data design and logic design are expressed in a common language (Unified Language). This common language is called “Binary Relation” and is visualized in Entity-Relation diagram in reflecting the right terms of the physical world into the source code of the cyber world as static types.

The following sections will focus on the four characteristics and explain the mechanism of HTAP with Binary Relation at its core.

3.4.1 Definition of Binary Relation

A Binary Relation is a relationship between two elements. For example, from the point of view of a table, it means that it has at most only two foreign keys. This allows the table to be finely divided and the dependencies to be clearly defined. Giving each an appropriate name, shared with domain experts, provides a foundation for data management.

3.4.2 Join operations implemented into a generic library

By decomposing the data model down to Binary Relation, the data join process is simplified. Specifically, by repeating the operation of joining two tables, complex programming logic in the application can be simplified as a collection of binary operations. This allows efficient development by consolidating the data manipulation implementation logic into a generic library.

3.4.3 Application of type theory

This column-first data model is based on Set Theory, which eliminates null (no value present). Furthermore, by applying Type Theory, logical inconsistencies can be automatically detected during compile-time, enabling early error prevention, when applications are developed and the data model changed. This allows the system to evolve flexibly while maintaining data integrity.

3.4.4 Handling of null

Data integrity is improved because column-first tables neither have null nor contain duplicated records. However, it is important to clearly distinguish between mandatory and optional attributes in defining row types, as these must be handled differently. By eliminating null from the data model and clearly distinguishing between mandatory and optional attributes at the type level, the system achieves safer and more efficient data management and processing.

4. Case study of a column-first data model in the logistics domain

The following sections explain the column-first data model, with a simple logistics case.

4.1 Case description of “transshipment with consolidation”

Figure 3 illustrates a case in which a total of five consignment orders are generated from two purchase orders. The following is a description of the case.

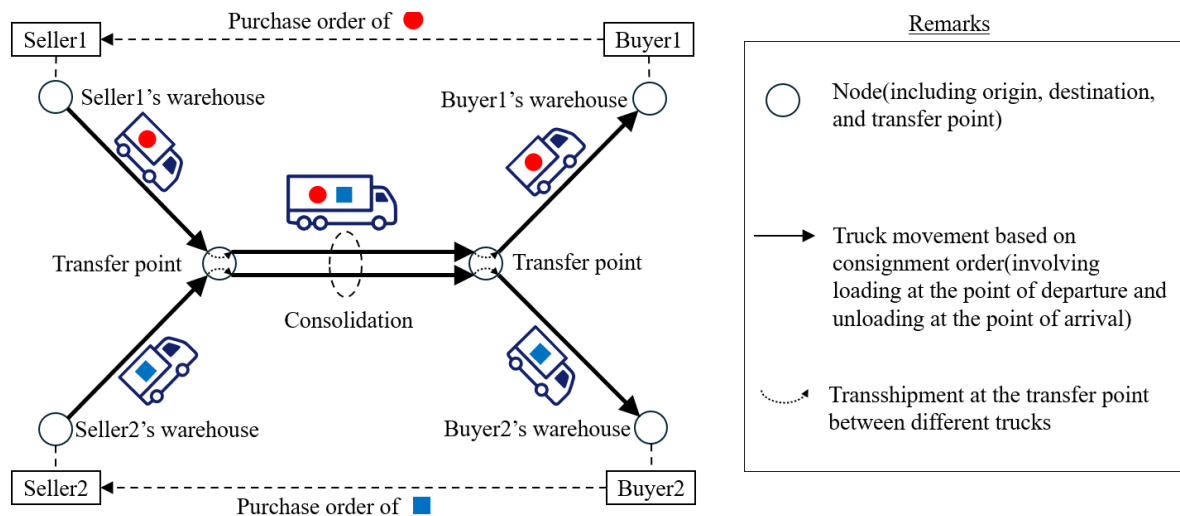


Figure 3: A case describing five consignment orders generated from two purchase orders

4.2 Normalized representation of “transshipment with consolidation

Figure 4 is derived by representing logistics operations depicted in Figure 3 with the column-first data model with some degree of normalization. The following text explains the data model shown in Figure 4.

- Upon receiving a purchase order from the buyer, the seller issues a G SIN and ships the goods. The seller then commissions an LSP to handle the consignment, and the LSP issues a CONSIGNMENT ORDER. Since transportation for the purchase order is divided into three segments, the CONSIGNMENT ORDER generates three CONSIGNMENT ORDER ELEMENTs, each assigned a GINC. Each element involves one loading and one unloading operation. Loading occurs at the departure node, while unloading occurs at the arrival node.
- There are two types of nodes: Warehouse and Transfer Point. A node is classified as a Warehouse if it corresponds to the seller’s or buyer’s warehouse.
- DEPARTURE, shown by the red box in Figure 4, is an abstract concept: the departure node, or starting point of the truck, is either the origin warehouse or the transfer point. Similarly, ARRIVAL, shown by the blue box in Figure 4, is also an abstract concept.

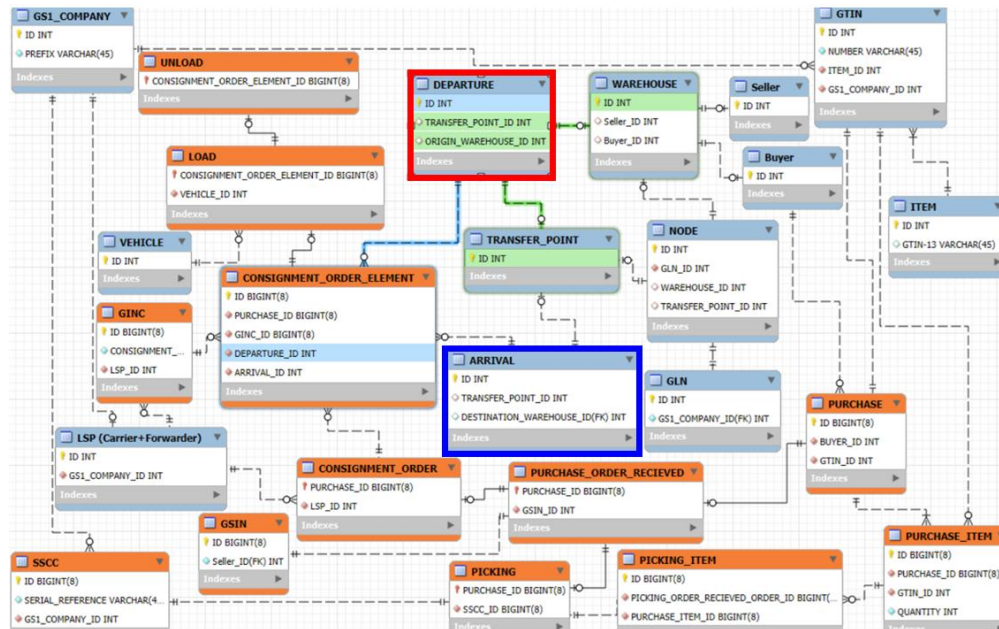


Figure 4: Example of column-first data model (first step)

The DEPARTURE table has two columns besides the DEPARTURE ID. Therefore, it is row-oriented. Only one of the two is selected. The selected column (e.g., origin warehouse) is populated, while the other (e.g., transfer point) remains null. Normalization has been advanced to a certain extent.

4.3 Advancing normalization to its full extent

Figure 5 shows a further decomposition of the DEPARTURE and ARRIVAL tables, including the NODE and WAREHOUSE tables, as well as the DEPARTURE ORIGIN and DEPARTURE TRANSFER POINT tables. DEPARTURE is decomposed into DEPARTURE ORIGIN and DEPARTURE TRANSFER POINT, and the two are related by DEPARTURE ID with “EITHER OR” assignment rule in decomposing a logical row. Here null does not occur.

Using the column-first data model, it will be possible to determine facts such as the actual occurrence of transport capacity surplus in each transport section and the dwell time of cargo at transship locations, which will allow for continuous improvements. Readers will understand that this approach is essential for the implementation of the Physical Internet.

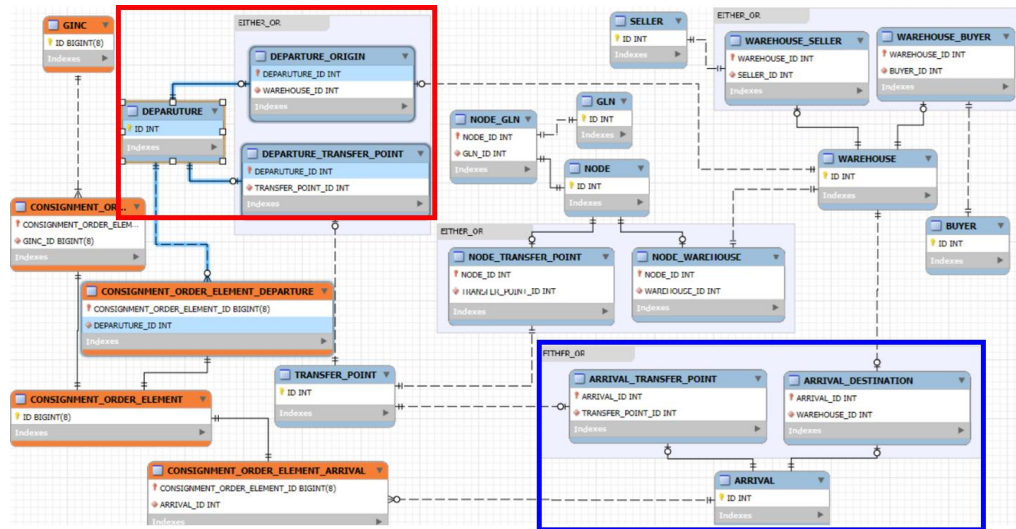


Figure 5: Example of column-first data model (second step)

5. Examples of column-first data models in non-logistics domains

The effectiveness of the column-first data model is not limited to the logistics domain. Examples from domains other than logistics are presented to demonstrate its versatility.

5.1. A Japanese die manufacturer (Tada Seiki)

5.1.1 Observed problems

In Make-to-Order manufacturing, production planning has a significant impact on productivity. When handling multiple orders simultaneously, schedule adjustments are necessary, but as the number of orders increases, the required response can exceed human capabilities. Although production plans are frequently revised, there was a problem in that the reasons for these changes could not be traced.

5.1.2 Solution

In corporate information systems, it is necessary to build interfaces that connect various systems such as ERP and MES. At Tada Seiki, the existing planning and management system, which was built for each process, was not changed. The row-oriented data exported from various systems is converted into a column-first format in the Data Hub. When necessary, the Data Hub then reconverts it into a row-oriented format to meet the input requirements of existing systems.

Furthermore, within the newly created data hub system, there is no “data updates and deletions” and inserted data continues to be saved. The data hub enables multi-dimensional analysis to identify the reason for the changes in production plans based on the facts, and better production plans can be developed that contribute to improving factory productivity.

5.2 A tangible fixed assets management package software (ProPlus by Pro-Ship)

5.2.1 Observed problems

The operation to calculate the residual value of tangible fixed assets involved maintaining intermediate tables, often leading to time-consuming data retrospectives due to issues like program bugs and changes in depreciation rules. These tables were kept for performance, but if a software bug caused data irregularities, simply replacing the software was insufficient. Introducing a bug-fixed version to other companies could create logical inconsistencies among intermediate tables, resulting in a dilemma where the package software company, Pro-Ship, could not apply the bug-fixed version to all ProPlus users immediately.

5.2.2 Solution

By transitioning from a row-oriented to a column-first table structure, the need to retain intermediate tables was eliminated. Consequently, the residual value of tangible fixed assets can now be calculated on the fly using the original data (i.e., the raw data without any modification), which enables flexible single version of Software as a Service for multiple tenants without any customization.

5.3 Implications in logistics

Inventory quantities and transportation empty capacity are “derived item values” that change over time and are calculated by combining multiple data sets. Timely understanding of these values is crucial for improving business efficiency, requiring both accuracy and freshness of data. Column-first fact management allows immediate access to derived values from raw data without intermediate tables, facilitating easier software version upgrades.

Without intermediate tables, there’s no need to address incorrect data, simplifying decisions when upgrading software used by many. If an intermediate table exists, backtracking data can be time-consuming, complicating bug fixes and extending system downtime.

6. Conclusion

This study addresses database structure issues related to implementing the Physical Internet and proposes a column-first data model as a solution. Through case studies, it is shown that this model effectively describes complex logistics operations, such as “transshipment with consolidation,” which traditional data modeling struggles to capture. The paper discusses limitations and breakthroughs in description capabilities in database structures, a topic rarely explored in IPIC. As the Physical Internet becomes more feasible, increased interest among researchers and practitioners in data management and adaptation is anticipated. This study is expected to stimulate further discussion and facilitate the early exchange of ideas.

The system infrastructure and applications for the Physical Internet is expected to evolve gradually. This design philosophy that normalizes data structures is crucial to develop effectively while leveraging existing system assets and to share data across the Physical Internet nodes as well. The column-first data model, which allows for structural descriptions of abstract concepts without natural language, is scalable in both complexity and progressive change, making it a promising foundation for future challenges toward Ultra-Large-Scale Systems.

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Dynamic Freight Routing and Dispatch Protocols for the Physical Internet

Sahrish Jaleel Shaikh, Praveen Muthukrishnan, Benoit Montreuil
Physical Internet Center, Supply Chain & Logistics Institute,
H. Milton Stewart School of Industrial & Systems Engineering,
Georgia Institute of Technology, Atlanta, United States
sshaikh34@gatech.edu

Abstract: *The Physical Internet (PI) promises to transform freight movement by enabling standardized modular containers to be dynamically routed and dispatched through interconnected hubs. A key challenge in such networks is determining the optimal dispatch timing that balances consolidation opportunities, service reliability, and efficient asset utilization. In this paper, we propose an integrated framework that simultaneously addresses three interrelated decisions at each hub: which containers to dispatch, where to send them next, and when to dispatch them. We compare combinations of two routing protocols, destinational routing (DER) and directional routing (DIR), and three dispatch protocols, Fixed Threshold Dispatch (FTD); Flow-Adaptive Dispatch (FAD); and Dynamic Adaptive Consolidation (DAC). Our simulation experiments, conducted using real-world network data, demonstrate that integrating DIR routing and DAC dispatch protocols significantly improves consolidation, reduces empty mileage, and maintains high on-time delivery performance.*

Keywords: *Physical Internet, Dynamic Directional Routing, Dispatch Deadline Protocols, Dwell Time Optimization, Maximum Latency, Freight Consolidation, Logistics Network Optimization, Adaptive Routing, Directional Freight Movement, Hyperconnected Logistics*

Physical Internet (PI) Roadmap Fitness: ☒ PI Networks, ☒ System of Logistics Networks.

Targeted Delivery Mode-s: ☒ Paper, ☒ In-Person presentation

1 Introduction

The Physical Internet envisions an open, globally interconnected logistics system in which standardized modular containers are routed through a network of multimodal hubs (Montreuil, 2011). Unlike current traditional logistics practices, where fixed dispatch schedules and static routing decisions often lead to underutilized truck capacity and suboptimal consolidation, the Physical Internet envisions dynamic operations. When dynamically operating hubs in such a system, three critical challenges must repeatedly be resolved concurrently at each hub considering all containers arriving or already at the hub: determining which containers to dispatch together (consolidation), selecting the optimal next hub (freight routing) for each container, and deciding when to dispatch (timing) each multi-container shipment.

Previously proposed methods for inter-hub freight routing each container from origin to destination essentially are based on finding and adopting a travel-time-based shortest path across the hub network, while those for containerized shipment dispatch decisions have relied on fixed schedules or simple volume thresholds. This is simple yet does not consider and leverage the interdependencies between these decisions. In this paper, we propose an integrated framework that combines dynamic freight routing with adaptive dispatch protocols. In

particular, our framework dynamically assigns the next hub for each container while also evaluating the current load, projected arrivals, and available slack time to determine the optimal dispatch moment for each shipment.

2 Literature Review

The Physical Internet (PI) has attracted significant attention as a means to revolutionize logistics operations through standardization, modularity, and decentralization (Montreuil et al., 2013). Early studies primarily focused on static routing approaches, employing traditional shortest-path algorithms. While effective under stable conditions, these methods fail to adapt to real-time network fluctuations such as congestion or dynamic demand patterns. To address this, more recent work has explored dynamic routing protocols, including directional routing methods that identify candidate next hubs based on their geographic bearing relative to the destination (Shaikh and Montreuil, 2024; Shaikh et al., 2025).

Separately, research on dispatch protocols has traditionally relied on fixed schedules or simple capacity-based triggers to initiate dispatch decisions (Venkatadri et al., 2016; Chargui et al., 2019). Shaikh and Montreuil (2023) introduced the Maximum Latency Time (MLT) concept to enable containers to wait strategically for improved consolidation along fixed predetermined paths. All these prior protocols did not account for the uncertainty and variability introduced by dynamic routing environments.

Our contribution advances the field by integrating dynamic routing with adaptive dispatch protocols within a decentralized framework. Specifically, we systematically analyze the interplay between routing and dispatch decisions by evaluating combinations of destinational and directional routing protocols with three levels of dispatch sophistication: fixed-threshold, flow-aware, and dynamically adaptive consolidation protocols. This integration enables more responsive and resilient hyperconnected logistics network capable of maintaining high performance under fluctuating demand and congestion conditions.

3 Methodology

In this section, we describe the theoretical foundation of our integrated framework. We begin by defining routing protocols, then detailing dispatch protocols, and finally explain how they are combined into our operational framework.

3.1 Freight Routing Protocols

We consider two freight routing protocols: Destinational Routing (DER) and Directional Routing (DIR).

In the destinational approach, the network is modeled as a directed graph with hubs as nodes and travel times as edge weights. For container c at hub h , the shortest path from h to $dest(c)$ is computed by minimizing the total delivery time:

$$\text{shortest_path}_{(c)} = \arg \min_p \left\{ \sum_{(i,j) \in p} \text{travel_time}(i,j) + \sum_{k \in p'} \text{dwell_time}(k) \right\} \quad (1)$$

where p' represents the set of intermediate hubs in path p , and $\text{dwell_time}(k)$ is the estimated processing time at hub k .

This shortest path, computed at hub entry in the network is adopted through its journey across the network. Thus the next hub for c at any hub along its journey is then the next hub along this shortest path. This method is simple but does not adapt to real-time conditions.

Directional routing dynamically selects the next hub based on geographic alignment, service level constraints, and dynamic conditions. The process comprises several steps:

Bearing Calculation: For container c at hub h with destination d , we calculate the bearing from h to d .

Directional Neighbor Filtering: For each neighboring hub n , we compute the bearing $b_{h,n}$ from h to n . A neighbor is considered aligned if

$$|b_{h,n} - b_{h,d}| \leq \theta \text{ or } |b_{h,n} - b_{h,d}| \geq 360 - \theta \quad (2)$$

where θ is a threshold (e.g., 50°). The set of directional neighbors is:

$$DN(h, d) = \{n \in H: (h, n) \text{ is an edge, } |b_{h,n} - b_{h,d}| \leq \theta \text{ or } |b_{h,n} - b_{h,d}| \geq 360 - \theta\} \quad (3)$$

Service Level Feasibility: For each neighbor $n \in DN(h, d)$, we calculate the remaining time for container c as:

$$\text{remaining_time}(c) = \text{due}(c) - t \quad (4)$$

Neighbor n is deemed service-feasible if:

$$\text{traveltime}_{(h,n)} + \text{traveltime}_{(n,d)} + (\text{handling_time}(n) \times n_{est}(n, d)) \leq \text{remaining_time}(c) \quad (5)$$

where $n_{est}(n, d)$ represents the estimated number of hubs between n and the destination d

Next Hub Selection: For each feasible neighbor $n \in FN(c)$, a tri-criteria score is computed that balances consolidation opportunities, travel efficiency, and network congestion:

$$\text{score}(c, n) = \alpha \times \text{cons_factor}(h, n) - \beta \times \text{traveltime}_{(h,n)} - \gamma \times \text{congestion}(n) \quad (6)$$

where:

- α, β , and γ are weighting parameters in the range $[0, 1]$ with $\alpha + \beta + \gamma = 1$
- $\text{cons_factor}(h, n)$ quantifies the number of containers at h for which n is also feasible
- $\text{travel_time}(h, n)$ is the transit time from hub h to neighbor n
- $\text{congestion}(n)$ is the ratio of containers at or en route to n relative to its capacity

The next hub is chosen as:

$$\text{next_hub}(c) = \arg \max_{n \in FN(c)} \text{score}(c, n) \quad (7)$$

If $FN(c)$ is empty, a fallback strategy selects the neighbor closest to d .

In essence, directional routing computes the bearing from the current hub to the destination, filters neighbors based on directional alignment and then evaluates service feasibility. Finally, it selects the next hub using a scoring function that accounts for consolidation potential, travel time, and congestion.

3.2 Dispatch Protocols

Efficient dispatch decisions are critical to achieving enhanced consolidation and high on-time delivery performance within Physical Internet (PI) networks. In our framework, once a container's next hub is determined via the routing protocol, containers are grouped based on their common next hub. We evaluate three dispatch protocols that represent a progression in sophistication:

- **Fixed Threshold Dispatch Protocol (FTD)**
- **Flow-Aware Dispatch Protocol (FAD)**
- **Dynamic Adaptive Consolidation Dispatch Protocol (DAC)**

Each protocol builds upon the previous level by incorporating additional adaptive criteria that reflect real-time network conditions, service requirements, and consolidation opportunities.

3.2.1 Fixed Threshold Dispatch Protocol (FTD)

FTD Protocol serves as the baseline approach. In FTD, containers at a hub are grouped based on their computed next hub, and a dispatch is initiated when either of the following triggers is activated:

- **Capacity Trigger:** The group of containers reaches the full capacity of the truck.
- **Time Trigger:** Any container in the group has been waiting longer than a threshold.

FTD relies solely on static thresholds that are invariant with respect to real-time flow patterns, service deadlines, or projected arrivals. Its simplicity establishes a reference point for assessing more adaptive approaches.

3.2.2 Flow-Aware Dispatch Protocol (FAD)

FAD Protocol extends FTD by incorporating service-based waiting times, which are derived from slack time calculations, and by taking into account containers that are already en route to the current hub. The key components of FAD are as follows:

1. Slack Time Calculation

For a container c at hub h , the overall slack is computed as:

$$\text{slack}(c, h) = \max\{0, \text{due}(c) - t - \text{est_tt}_{(h, \text{dest}(c))} - \text{handling_time}(h) \times n_{\text{est}}\} \quad (8)$$

where t is the current time, est_tt is the estimated travel time and n_{est} is the estimated number of hubs remaining.

2. Equal Slack Distribution

The overall slack is allocated equally across the estimated remaining hubs:

$$\text{AsnDwellTime}_{c,h} = \frac{\text{slack}(c)}{\text{estimated_remaining_hubs}} \quad (9)$$

3. Latest Departure Time (LDT)

Rather than applying a uniform fixed waiting time, FAD computes a container-specific Latest Departure Time at the current hub:

$$\text{LDT}(c, h) = \text{arrival_time}(c) + \text{handling_time}(h) + \text{AsnDwellTime}_{c,h} \quad (10)$$

4. En-route Container Consideration

FAD monitors containers that are en route to the current hub. If additional containers, sharing the same computed next hub, are expected to arrive before the calculated LDT, dispatch is deferred to improve consolidation.

By adapting waiting times based on computed slack and near-term arrivals, FAD is more responsive than FTD, yet it does not consider network congestion or allow dynamic reallocation of slack beyond the current hub.

DAC Protocol further refines FAD by explicitly integrating the concept of Maximum Latency Time (MLT) to facilitate additional waiting time when consolidation opportunities justify a delay. In previous work (Shaikh et al., 2021), the concept of Maximum Latency Time (MLT) was introduced for scenarios with predetermined paths, where the number of remaining hubs was fixed. In our current framework, container paths are dynamically estimated, so the total available slack must be apportioned among the estimated remaining hubs. DAC allows a

container's Latest Departure Time at the current hub to be extended by "borrowing" slack allocated to subsequent hubs, provided that such delay does not compromise the overall delivery deadline or induce network bottlenecks defined as hubs operating above 90% capacity for extended periods, which can cause cascading delays throughout the network.

Let $LDT_{c,n}$ denote the baseline Latest Departure Time for container c at the current hub n computed as in FAD, and let $AsnDwellTime_{c,i}$ be the anticipated dwell time for container c at future hub i (with $i = n + 1, \dots, n_{\text{remaining}}$). DAC defines Maximum Latency Time $MLT_{c,n}$ as:

$$MLT_{c,n} = LDT_{c,n} + m \left(\sum_{i=n+1}^{n_{\text{remaining}}} AsnDwellTime_{c,i} \right),$$

where m (with $0 \leq m \leq 1$) is a flexibility parameter that dictates the fraction of future dwell time that may be reallocated to the current hub.

DAC works according to the following operational mechanism:

1. Dynamic Decision-Making

DAC first calculates the available slack at the current hub as in FAD. Then it evaluates whether extending the waiting period-up to $MLT_{c,n}$ will likely result in better consolidation. This decision is informed by the expected arrivals (through flow prediction) and real-time monitoring of en-route containers.

2. Bottleneck Prevention

To preclude congestion, DAC continuously monitors hub congestion defined by:

$$\text{congestion}(h) = \frac{\text{containers_at_}h + \text{containers_en_route_to_}h}{\text{capacity}(h)}.$$

If the congestion metric exceeds a predefined threshold, DAC curtails any additional waiting, thereby ensuring that extended dwell times do not translate into bottlenecks.

3. Flow Prediction

By incorporating real time estimation of future container arrival times, DAC assesses the potential gains from waiting. If enroute arrivals indicate significant consolidation benefits, DAC allows the container to remain until nearing $MLT_{c,n}$; otherwise, dispatch occurs sooner.

DAC effectively permits containers to "borrow" time from future hubs by extending the Latest Departure Time under favorable consolidation circumstances. This dynamic adjustment is balanced by congestion monitoring and urgency measures, ensuring that the extended dwell time does not compromise overall service levels while enhancing consolidation opportunities. This extends the MLT concept from predetermined paths (Shaikh et al., 2021) to a fully dynamic routing context and incorporates new congestion-aware features, representing a significant contribution of our current work.

4 Performance Evaluation and Simulation Results

We evaluate our integrated framework through an extensive simulation study that compares both routing protocols (DER and DIR) across all three dispatch protocols (FTD, FAD, and DAC). Our simulation environment models a transportation network in the Southeastern United States, with ten origin hubs and two destination hubs. Each shipment has an associated service level (1, 2, or 3), translating into delivery deadlines of 24, 48, or 72 hours, respectively.

To ensure realistic freight flow patterns, container demands are gradually introduced into the system rather than simultaneously. The origin, destination, service level, and creation time for each container demand are randomly generated to reflect heterogeneous traffic patterns. Our simulator explicitly models both vehicle-level processes (routing, scheduling) and freight-level processes (loading, unloading, consolidation), distinguishing between truck operations and the handling of consolidated loads (sets of containers grouped together at hubs for transport on a single vehicle). Following digital freight matching principles, we assume trucks perform single hub-to-hub movements rather than multi-hub routing.

4.1 Simulation Setup

Using destinational routing, each container demand follows the precomputed minimum travel-time path from origin to destination through the hub network, with hub-to-hub edges designed to respect driver hour limitations. Using directional routing, upon arrival at a hub, the system dynamically identifies candidate next hubs within $\pm 50^\circ$ of the bearing toward the destination, selecting based on travel time, consolidation opportunities, and current congestion levels. Each truck has a capacity of 40 containers, and dispatch decisions are implemented using three distinct protocols FTD, FAD, and DAC that vary in sophistication as described previously.

We conducted simulations for five daily demand levels (500, 600, 1000, 2000, and 3000 shipments) across all six combinations of routing and dispatch protocols. All simulations were run on the same network with identical service level distributions and time windows, ensuring that observed differences can be attributed to the routing and dispatch protocols.

4.2 Simulation Results and Analysis

Our simulation experiments yielded comprehensive data comparing the routing protocols and dispatch protocols across five demand levels. The next sections present the results, focusing on key performance metrics: on-time delivery, resource utilization, and consolidation efficiency.

Table 1: On-time Delivery Performance (%)

Demand Level	Shipments	Routing Protocol	FTD	FAD	DAC
Very Low	500	Destinational	100	100	100
		Directional	100	100	100
Low	600	Destinational	100	100	100
		Directional	100	100	100
Moderate	1000	Destinational	100	100	100
		Directional	100	100	100
High	2000	Destinational	99.8	100	100
		Directional	99.9	100	100
Very High	3000	Destinational	97.2	98.1	99.2
		Directional	98.1	98.6	99.9

4.2.1 On-time Delivery Performance

Table 1 presents the on-time delivery performance across demand levels. At low to moderate demand levels, both routing protocols maintain perfect on-time delivery across all protocols. However, as demand increases to high and very high levels, performance begins to diverge. The service degradation becomes particularly evident with the FTD protocol, where destinational routing experiences a drop to 97.2% on-time delivery at very high demand, while directional routing maintains 98.1% performance.

Most notably, the combination of directional routing with the DAC protocol demonstrates remarkable resilience, maintaining 99.9% on-time delivery even at very high demand levels.

This suggests that the adaptive nature of directional routing, when combined with intelligent slack time management, creates a system that remains stable even under challenging conditions.

4.2.2 Resource Utilization

Resource efficiency was measured through trucks dispatched and total miles traveled illustrated in Figure 1. The truck utilization data reveals several important patterns. First, across both routing protocols, the progression from FTD to FAD to DAC results in substantial reductions in required vehicles. Second, directional routing consistently requires fewer trucks than destinational routing for the same protocol, with the difference becoming more pronounced at higher demand levels. For example, at very high demand, DIR+FTD requires 16.3% fewer trucks than DER+FTD.

The most efficient combination is directional routing with DAC, which at very high demand requires only 480 trucks compared to 1198 for destinational routing with FTD—a 59.9% reduction. This dramatic improvement illustrates the compounding benefits of combining intelligent routing with adaptive dispatch timing. Interestingly, while both routing protocols show similar total miles at low demand levels (with directional routing occasionally requiring slightly more miles), directional routing demonstrates increasing advantage as demand rises. At very high demand, directional routing with DAC achieves a 7.9% reduction in total miles compared to destinational with DAC.

This pattern suggests that at lower demand levels, pure distance minimization through destinational routing performs well, but as network complexity increases with higher demand, directional routing's ability to distribute traffic and avoid congested areas becomes more valuable, resulting in overall distance savings despite not explicitly optimizing for minimum distance.

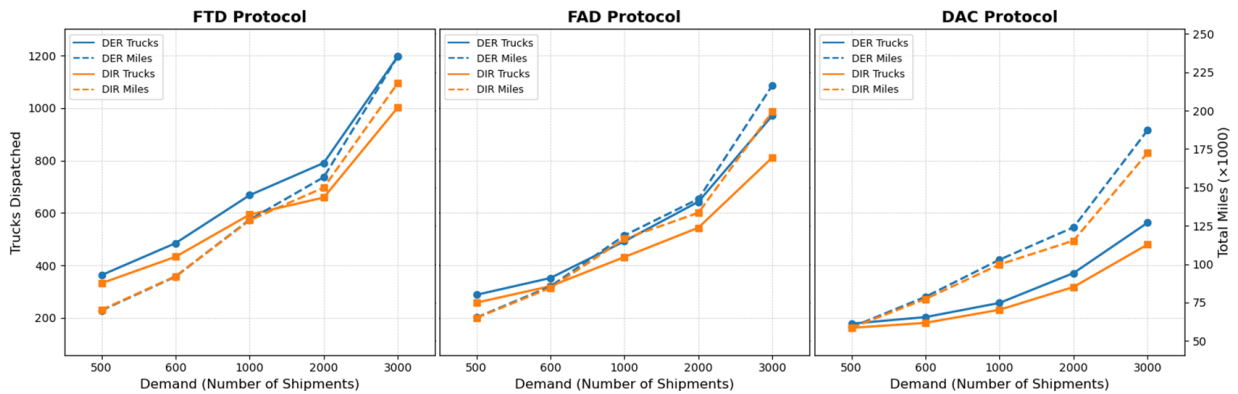


Figure 1: Comparison across three dispatch protocols showing how Destinational routing (blue circles) and Directional routing (orange squares) perform over five demand levels (500–3000 shipments). Solid lines plot **Trucks Dispatched** (left y-axis), while dashed lines plot **Total Miles Traveled** ($\times 1000$, right y-axis).

4.2.3 Consolidation Efficiency

The fill rate metric directly measures consolidation efficiency—the percentage of truck capacity utilized when dispatched. The fill rate data in Table 1 reveals several notable patterns. The DAC protocol dramatically outperforms both FTD and FAD across all demand levels and for both routing protocols. Directional routing consistently achieves higher fill rates than destinational routing for the same protocol, with an absolute improvement of 6-7 percentage points across most scenarios.

Table 2: Average Fill Rate (%) by Demand Level and Protocol

Dispatch Protocol	Routing Protocol	Demand Level				
		Very Low	Low	Moderate	High	Very High
DESTINATIONAL	FTD	29.5%	28.3%	30.0%	31.0%	30.5%
	FAD	39.5%	38.8%	40.5%	42.3%	40.7%
	DAC	65.0%	66.5%	69.0%	73.0%	74.3%
DIRECTIONAL	FTD	35.8%	34.5%	36.4%	37.5%	37.0%
	FAD	46.2%	45.4%	47.0%	48.8%	47.2%
	DAC	71.4%	73.9%	75.7%	79.8%	81.0%

The most striking observation is again the combined effect of DAC protocol with directional routing, which achieves fill rates of up to 81% at very high demand—an improvement of 50.5 percentage points over the traditional approach (DER+FTD). This represents a transformative improvement in vehicle utilization that would have significant economic and environmental benefits in practical implementation.

4.2.4 Network Stability and Resilience

To better understand the mechanisms behind the observed performance differences, we analyzed the formation of bottlenecks—defined as hubs operating above 90% capacity for extended periods—across demand levels. Figure 3 shows the number of critical bottlenecks observed during simulation.

The bottleneck analysis reveals a critical insight: while destinational routing creates an increasing number of bottlenecks as demand grows (reaching 17 at very high demand), directional routing dramatically reduces bottleneck formation (only 2 at very high demand). This reduction in bottlenecks directly correlates with the improved on-time delivery performance observed earlier. The mechanism behind this improvement is directional routing's ability to distribute traffic more evenly across the network. By considering alternatives to the shortest path when making routing decisions, directional routing prevents the concentration of traffic that leads to bottlenecks in the destinational approach. This, in turn, reduces the cascading delays that bottlenecks introduce into the system.

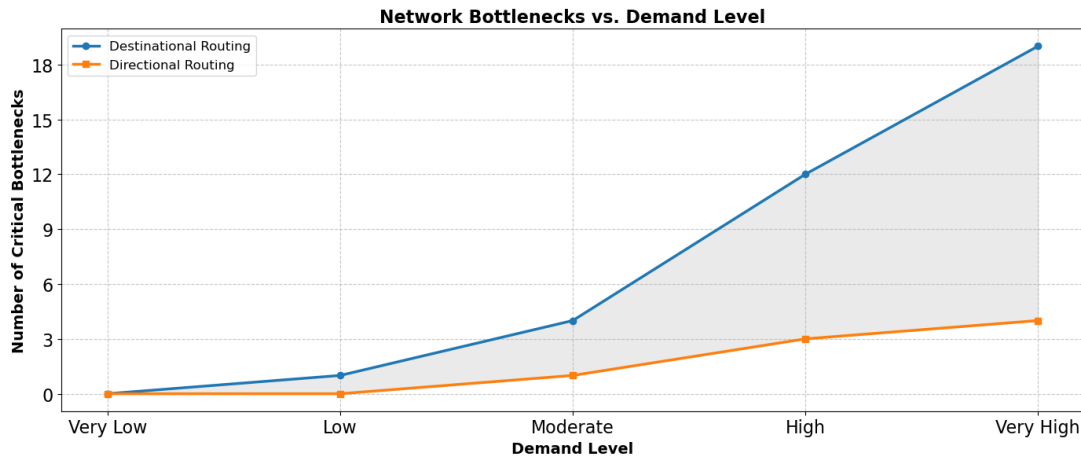


Figure 2: Number of Critical Bottlenecks (>90% Capacity) by Demand Level with DAC

The simulation results demonstrate that path diversity increases with directional routing and advanced dispatch protocols. While the destinational approach consistently routes shipments through predetermined minimum-time corridors, the directional approach explores alternate feasible routes as shown in Figures 4. This diversity becomes particularly valuable in high-demand scenarios where traditional corridors experience congestion.

Figure 4 illustrates this effect by visualizing sample shipment paths between common origin-destination pairs. With directional routing and DAC, shipments between the same origin-destination pairs often follow diverse paths, distributing flow more evenly across the network and avoiding congestion bottlenecks.

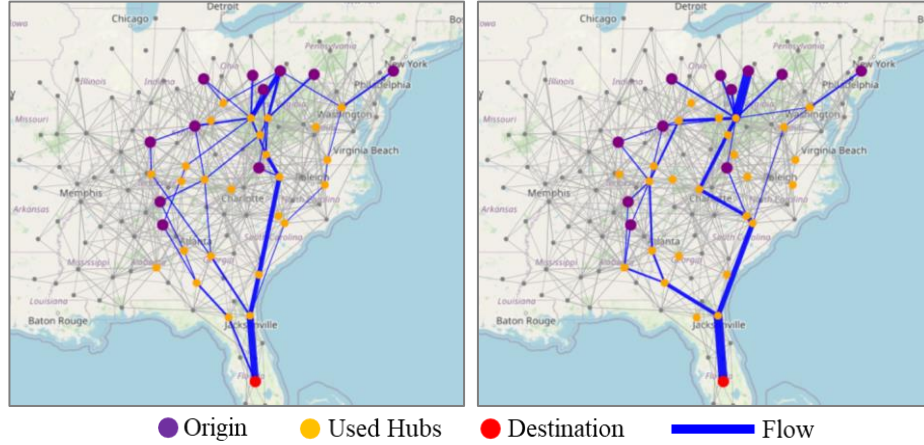


Figure 3: Path Selection and Consolidation Efficiency: Destinational Routing (Left) and Directional Routing (Right)

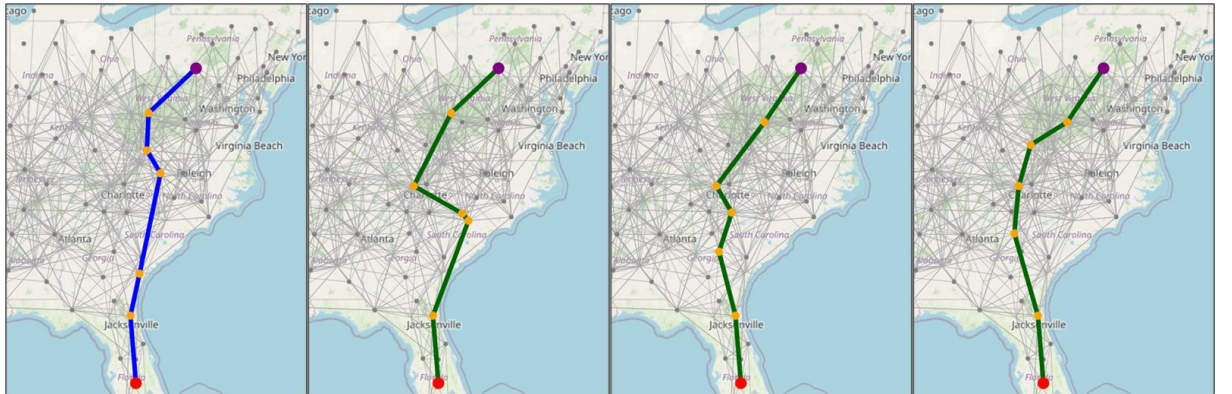


Figure 4: Visualizing Routing of Containers with the same Origin and Destination (Destinational: Blue, Directional: Green)

5. Conclusion

Our simulation experiments demonstrate that both routing and dispatch protocols selection significantly impact Physical Internet performance, with their effects becoming increasingly pronounced at higher demand levels. The most significant finding is the remarkable synergy achieved when combining directional routing with adaptive dispatch protocols. While each component individually improves performance, their integration creates multiplicative benefits through network load balancing, responsive consolidation, and reduced network oscillation.

The performance gap between the baseline DER + FTD protocols and the proposed DIR+DAC protocols widens as demand increases. At very high demand, the DAC protocol achieves a 59.9% reduction in trucks dispatched compared to FTD, while maintaining higher service levels. This demonstrates superior resilience under stress conditions, as directional routing

maintains 99.9% on-time delivery with the DAC protocol at the highest demand level, compared to 99.2% for destinational routing.

Beyond improving service levels, our proposed combination of DIR+DAC protocols offers substantial operational and environmental benefits. The dramatic improvement in fill rates—from 30.5% with the baseline DER+FTD protocols to 81.0% with our proposed DIR+DAC protocols represents a transformative change in asset utilization. The 26.8% reduction in total miles traveled, combined with higher fill rates, would significantly reduce carbon emissions, fuel consumption, and road congestion, aligning with growing sustainability imperatives in the logistics industry.

Implementing our proposed approach in real-world PI networks requires consideration of computational requirements, data integration needs, and parameter tuning. Directional routing requires more computational resources than destinational routing, particularly for real-time bearing calculations and scoring potential next hubs. The DAC protocol relies on accurate data about container locations, hub capacities, and predicted arrivals, highlighting the importance of standardized information exchange protocols across PI participants.

6 Future Research

Our findings strongly support the potential of the Physical Internet to transform logistics operations through standardization, modularity, and intelligent coordination. Our research indicates that the traditional focus on minimizing direct travel time may be suboptimal in hyperconnected PI networks, where consolidation opportunities and network-wide traffic distribution become increasingly important considerations.

Future research should explore the integration of time-dependent traffic data to enhance responsiveness to real-world dynamics, including rush hour congestion, weather disruptions, and infrastructure bottlenecks. Extending directional routing models to incorporate multi-objective optimization balancing transit time, consolidation, congestion avoidance, and environmental impact could further elevate network efficiency. Additionally, enhancing dispatch decisions through predictive analytics, leveraging not only en-route containers but also broader traffic forecasts, holds promise for improving the Dynamic Adaptive Consolidation Dispatch Protocol (DAC).

Research should also investigate network design implications, multimodal integration strategies, and collaborative decision-making frameworks among multiple stakeholders. Real-world pilot studies will be essential to validate simulation findings, assess computational scalability, and identify practical barriers to adoption. Finally, developing structured approaches for the incremental transition from traditional logistics operations to fully realized Physical Internet networks remains a critical area for future exploration.

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Redefining Port Call Processes: The Role of Automation and Emerging Technologies

Dr Anastasia Roukouni¹, Giannis Kanellopoulos¹, Konstantinos Louzis², Alexandros Koimtzoglou², Dr Nikolaos P. Ventikos² and Dr Angelos Amditis¹

1. I-SENSE Group/Institute of Communication and Computer Systems (ICCS), Athens, Greece

2. Laboratory for Maritime Transport, School of Naval Architecture and Marine Engineering, NTUA, Athens, Greece

Corresponding author: anastasia.roukouni@iccs.gr

Abstract: *The present paper explores the automation of vessel port call processes as a critical advancement in maritime logistics, within the framework of the EU-funded AutoMoTIF project. It presents a comprehensive simulation-based use case that incorporates autonomous tugboats and Automated Mooring Systems (AMS) to enhance the berthing and unberthing of freight vessels. Key technologies, operational frameworks, and coordination protocols are analyzed, while a Key Performance Indicator (KPI) evaluation framework is proposed to assess the operational, safety, environmental, economic, and societal impacts of automation. Moreover, the research introduces an Open Reference Architecture for Digital Twins (DTs), offering a modular and interoperable design tailored to smart port operations. This work contributes to the broader digital transformation of maritime logistics, promoting efficiency, resilience, and sustainability within multimodal supply chains.*

Keywords: *Maritime automation, port call optimization, Digital Twins (DT), Physical Internet (PI), autonomous tugboats, hyperconnected freight transport, smart logistics*

Physical Internet (PI) Roadmap Fitness: ☒ PI Networks, ☒ System of Logistics Networks

Targeted Delivery Mode-s: ☒ Paper, ☒ In-Person presentation

1 Introduction

Automation has brought drastic changes in many different disciplines during the last decades, with freight transportation being one of them. While this evolution has opened new prospects, a number of new challenges (De Alvis and Nam, 2024) and uncertainties (Dekhne et al., 2019) associated with it made their appearance as well. Advanced technologies have been adapted across all stages of the supply chain to address the growing demand for faster and more efficient product delivery (Yang et al., 2021). As a key component of the freight industry, maritime transport is also undergoing significant transformations, driven by the increasing use of technological innovations and digitalization introduced to enhance safety, efficiency and sustainability (Andrei and Scarlat, 2024).

The paper is part of the on-going research conducted in the context of the EU-funded AutoMoTIF project. In this project, different use cases are employed to extract relevant user needs and understand technological gaps which lead to the development of technical specifications, different scenarios and concepts of operations, capturing different parts of the freight transport and logistics chain. One of these use cases focuses on investigating the potential advantages of utilizing automation across all phases of the port call process. The

overarching objective is to identify the basic requirements for a seamless automated port call process - this initially includes the vessel's arrival at the port, entailing the initial announcement, allocation of berth windows as well as the tugboats assignment, and continues with the vessel's manoeuvring and docking processes, both performed by the assigned tugboats. This is followed by the stevedoring operations that secure the vessel on the quay to initiate the cargo loading and unloading processes.

The relevance of this research to the Physical Internet (PI) concept lies in its alignment with the PI's vision of hyperconnected, interoperable logistics networks (Montreuil, 2011). (REF) By introducing automation and standardized digital systems into the port call process, this study supports the seamless integration of maritime operations into larger, intermodal logistics ecosystems. Moreover, the AutoMoTIF open architecture framework proposed for Digital Twins promotes modularity and data transparency—key principles of the Physical Internet—which can ultimately enable real-time coordination between sea, rail, and land-based logistics, reducing fragmentation and maximizing resource efficiency

The remainder of the paper is structured as follows: Initially, a state-of-the-art analysis of automated vessel calls is presented, followed by the description of the automated call process as approached by the use case of AutoMoTIF. After that, the key performance indicators that will be used to evaluate the results of the use case are outlined. Finally, the adaptation of the proposed a new AutoMoTIF open reference architecture framework to the specific use case is discussed and some general conclusions are drawn.

2 State-of-the-art analysis of automated vessel calls

The automation of vessel port call processes is a critical part of automating freight transport in general, as they can be found in the intersection of maritime vessels with land-based logistics networks. The calls comprise well-coordinated procedures that facilitate the seamless movement of goods across borders and supply chains. Port call optimization needs to be integrated with inbound and outbound logistics. Port operations are complex as they are intended to serve sea and land transport simultaneously and consist of multiple actors who must act cooperatively for the port to be an effective hub. The actors and systems involved in the automated port call process concept are the following: Berth Allocation System (BAS), tugboat personnel, autonomous tugboats, vessel, Automated Mooring System (AMS), Shore Control Centre (SCC) operator, Vessel Traffic System (VTS) operator.

Current research on vessel automation is primarily focused on enhancing vessel autonomy through the development of sophisticated navigation and control systems, addressing communication and connectivity challenges, improving situational awareness for collision avoidance and safety, and exploring commercial viability and necessary regulatory frameworks. However, there are significant gaps related to the automated operation of vessels when calling ports. Research that investigates parts of this process has been conducted in the context of EC-funded projects such as MOSES, AEGIS, AUTOSHIP and SEAMLESS focusing mainly on autonomous ship navigation, automated loading and unloading, automated manoeuvring and docking and shore control stations that deal with the exchange of data required for the technical integration rather than the business one (Segura et al., 2025).

The exchange of crucial information such as stowage plans, loading/discharging plans, berthing place, etc. are often ignored thus making the adoption of automated vessel operations for commercial exploitation practically impossible. The vessel calls phases involve a complex interplay of activities implemented by different technologies, as presented in the following

diagram (Figure 1). The differentiation in colour demonstrates that cargo operations (in orange) is a phase that is out of scope of the use case discussed herein.



Figure 1: The different stages of a port call process

Planning for arrival: The logistical planning for a port operation typically encompasses the scheduling of berths and quay cranes, the planning of vessel routes, and the accurate prediction of vessel arrival times. However, a significant challenge arises from the frequent deviations of ships from their anticipated arrival times, which can lead to disruptions in the plan. The technologies involved in the planning for arrival stage are described in the following table (Table 1).

Table 1: Planning for arrival technologies

Planning for arrival	
Port Management System (PMS) / Terminal Operating Systems (TOS)	Description: Integrated software solutions are developed to manage internal port operations efficiently. Port authorities and terminal operators have the responsibility for managing port facilities and operations. Over recent decades, these systems have undergone significant advancements, integrating cutting-edge technologies to enhance their functionality and effectiveness (Hernandez et al., 2024).
	Current Applications: PMS/TOS is currently integrated in large ports, which have a high volume of traffic and arrival.
Port Collaborative Decision Making (PortCDM)	Description: PortCDM facilitates the exchange of operational information among key stakeholders involved in port call processes. By centralizing all port call-related events in a single platform, the system provides a unified view of operations, enabling better coordination and optimized planning for all parties. (Lind et al., 2019).
	Current Applications: PortCDM meets the demands from shipping companies to adjust just-in-time arrivals and departures.
Port Community Systems (PCS)	Description: PCS are digital collaborative platforms that enable seamless exchange of information among a port's many stakeholders. By integrating the various systems, the PCS reduces duplication of effort, saves time, and improves communication among all stakeholders. (Prasad et al., 2023).
	Current Applications: fourth wave of PCS, since 2018. PCS are based on multimodal service offerings, offered on the cloud and linked to other external digital logistics platforms, adopting Industry 4.0 technologies.
Vessel Traffic System (VTS)	Description: VTS is a maritime traffic monitoring system operated by port authorities to ensure safe and efficient vessel movements in the port area. The system uses radars, Automatic Identification System (AIS), and CCTV to track vessels in real time (Vessel Traffic Services, n.d.).
	Current Applications: Operators provide real-time guidance and instructions to the vessel, coordinating traffic and preventing collisions with other ships.
Radio Frequency Identification (RFID)	Description: RFID is a technology that uses radio waves to identify and track container movements within the port, from arrival to loading/unloading. They consist of RFID tags (small electronic devices) and RFID readers that transmit and receive radio signals (Shi, et al., 2011). They are also used in Automated Gate Operations, allowing the entry and exit of trucks and containers, and for automated data collection and paperless transactions.

	<u>Current Applications:</u> largely implemented in operational procedures in port-based container logistics. (Shi et al., 2011)
Satellite communication systems	<u>Description:</u> Low-Earth Orbit (LEO) Satellite Connectivity, MEO Satellite (GNSS) and GEO Satellites (SATCOM) provides reliable and high-speed internet access to ships operating, telecommunications, broadcasting and weather forecasting (IEC Telecom, 2023).
	<u>Current Applications:</u> While MEO and GEO are mature technologies, LEO satellites are considered relatively mature.

Berthing and unberthing: Proper berthing is crucial for ensuring safety, efficiency, and the smooth operation of maritime activities. It requires coordination between the vessel's crew and port authorities, as well as consideration of factors such as tide, weather, and vessel size. By incorporating the technologies presented in Table 2, ports can improve the efficiency and safety of berthing operations, ultimately enhancing the overall effectiveness of maritime transport. Unberthing and departure are the concluding phases of a vessel's stay in port, marking the beginning of its voyage. These processes require careful coordination, precision, and adherence to safety protocols.

Table 2: Berthing/Unberthing technologies

Berthing / Unberthing	
Berth Allocation System (BAS)	<u>Description:</u> The Berth Allocation Systems optimizes the allocation of berths to vessels, providing a solution to the Berth Allocation Problem (BAP), a logistical challenge that arises in ports when determining how to optimally allocate available berths to incoming vessels to minimize waiting times. Existing different categories of BAP: discrete (for berthing and unberthing), continuous, and hybrid. Many studies have focused on single quay, and few for the Multi-Quay BAP (Aslam et al. 2023)
	<u>Current Applications:</u> The single quay is the most used (Port of Limassol in Cyprus, has seven continuous berthing quays) while the implementation of the multiple quays is currently underway.
Dynamic Positioning Systems (DPS)	<u>Description:</u> DPS is an advanced technology used to maintain a vessel's position and heading without the use of anchors making it easier to control their movements during berthing and unberthing operations. The implementation of DPS requires the vessel to be equipped with azimuth type propulsion, instead of the conventional rudder-propeller arrangement.
	<u>Current Applications:</u> DPS is currently used in special purpose vessels, such as Offshore Support Vessels, tugboats, small cargo ships.
Automated Berthing System (ABS)	<u>Description:</u> ABS focuses on the physical process of docking a ship by using advanced algorithms and sensors (e.g. LIDAR) onboard to help ships dock safely and efficiently using their own propulsion means.
	<u>Current Applications:</u> ABS is currently in the research and development phase with some successful pilot demonstrations of vessels berthing automatically in Europe and Japan ^{1,2} .
Terminal Logic Control Interface (TLC)	<u>Description:</u> Refers to a system or interface used to manage and control terminal activities effectively. TLC can automate several processes, such as gate operations, cargo tracking, and billing, reducing manual intervention and increasing accuracy.
	<u>Current Applications:</u> currently used in automatic stacking and automated cranes and vehicles, integrated with TOS and PCS for better coordination with stakeholders.
Terrestrial digital communications	<u>Description:</u> Terrestrial digital communications enable connectivity and real-time data exchange for IoT devices, machine-to-machine (M2M) communications, and user group alerting services.

¹ <https://www.nippon.com/en/japan-topics/g02047/>

² <https://maritime-executive.com/article/european-space-agency-sponsors-grimaldi-project-for-automated-berthing>

	<p>Low-Power Wide-Area Network:</p> <ul style="list-style-type: none"> -LoRaWAN and 0G Network technology: Used to connect low-power sensors over long distances using low energy. It enables low-bandwidth, low-power communication. Ideal for IoT sensor communication that does not require high data rates, such as container location and environmental condition monitoring. -Cellular networks: 4G LTE and 5G connects mobile devices and sensors in real-time providing low latency and higher data speeds, ideal for more complex applications. In ports, they give access to remote control of cranes, autonomous vehicles, and real-time logistics management in the port. <p><u>Current applications:</u> Terrestrial digital communication technologies are increasingly essential in the context of ships equipped with intelligent technologies.</p>
Automated Mooring Systems (AMS)	<p><u>Description:</u> AMS are advanced technologies used in ports to securely and efficiently moor vessels. They are essentially robotic systems that can automatically handle the process of attaching and detaching mooring lines to a vessel, or that eliminate the need for using mooring lines completely by using vacuum-based attachment methods. These systems reduce the need for manual labour and minimize the risks associated with handling mooring lines both onboard the vessel by the Deck team and onshore and by the port stevedores.</p> <p><u>Current Applications:</u> Examples of existing AMS include Trelleborg's³ AutoMoor™ and Cavotec's⁴ Moormaster™ vacuum-based systems, Mampaey's Intelligent Dock Locking System⁵ magnetic mooring system, and MacGregor's⁶ robotic system for handling mooring lines.</p>
Information Systems	<p><u>Description:</u> Ports are increasingly implementing systems that exploit real-time information from sensors (e.g. weather, air quality etc.) in order to facilitate decision-making in port operations.</p> <p><u>Current Applications:</u> An example application is the Port of Rotterdam that has implemented a smart mooring solution as part of their digitalisation strategy to predict the impact that storms and adverse weather will have on moored vessels, providing users in the port with the much-needed time to prepare and avoid incidents in the port. (Port Technology International, 2021).</p>
Autonomous Tugboats	<p><u>Description:</u> Autonomous tugboats are highly automated vessels equipped with advanced technology, incl. sensors, computers, and propulsion systems that enable them to navigate and manoeuvre with minimal or no human intervention.</p> <p><u>Current Applications:</u> Automated tugboats are not a fully mature technology, and they are not widely implemented, although significant advancements are being made. Several industry-led projects have explored the capabilities of autonomous tugboats, including the following (Hensen, 2021):</p> <p>2017: remote control demonstration of the Svitzer Hermod in the port of Copenhagen (Rolls-Royce and Svitzer).</p> <p>2018: remote control demonstration of the Kotug RT Bocum in the port of Rotterdam from a control station in Marseille.</p> <p>2020: Intellitug project that aims to retrofit a harbour tug for enabling autonomous navigation (Wärtsilä, PSA Marine, Lloyd's Register, the Technology Centre for Offshore and Marine Singapore (TCOMS), and co-funded by Maritime and Port Authority of Singapore's Maritime Innovation and Technology Fund).</p> <p>2021: RECOTUG project aimed at developing a remotely controlled tugboat capable of conducting a full towage operation (Svitzer A/S, Kongsberg Maritime and ABS).</p> <p>2021: Damen designed and built tugboat Nellie Bly, outfitted with the Sea Machines Robotics autonomy system SM300, which conducted 342 collision avoidance manoeuvres during a 1000 nm voyage around Denmark while being remotely controlled from the US⁷.</p>

³ <https://www.trelleborg.com/en/marine-and-infrastructure/products-solutions-and-services/marine/docking-and-mooring/automated-mooring-systems/automoor>

⁴ <https://www.cavotec.com/en/your-applications/ports-maritime/automated-mooring>

⁵ <https://twd.nl/projects/structural-design-for-mampaey-intelligent-docklocking-system/>

⁶ <https://www.macgregor.com/intelligent-solutions/automated-mooring-system/>

⁷ <https://www.rivieramm.com/news-content-hub/news-content-hub/halfway-mark-reached-for-the-autonomous-machine-odyssey-67916>

Furthermore, the EU-funded research project MOSES developed a concept for an autonomous tugboat swarm that is monitored through a remote-control station. The project developed a machine-learning based algorithm for controlling the swarm and demonstrated the concept in a Pilot demonstration in Denmark.
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The automation of the port call process relates to the governance, operational, and digital dimensions of the Physical Internet, which have been identified by Fahim et al. (2021a) with respect to port development. In terms of governance, rules and protocols will need to be developed to facilitate interconnectivity between the different actors and autonomous systems involved in the process. In the operational dimension, automation will change how the manoeuvring and mooring operations are conducted by integrating the tugboats and mooring systems as autonomous agents. In the digital dimension, the various information systems that need to be integrated will facilitate information flow through the different parts of the transport network and support decision-making.

Specifically, the automated port call process will contribute to the following port performance criteria, which have been identified by Fahim et al. (2021b) and are expected to play a role in port selection in the Physical Internet paradigm. The quality of the port's Level of Service (LoS) will be increased by minimizing the time to berth to which an increase in availability of port tugboat services will also contribute. Automating tugboat and mooring services are expected to improve safety as less humans will be involved in hazardous tasks, as well as improving the level of the port's automation. Furthermore, the automation and the level of network interconnectivity, which will be required to acquire the necessary information from the supply chain (i.e. calling vessel characteristics, type of cargo) and the port (i.e. berth availability), will increase the port's "smartness" with respect to optimizing the manoeuvring and the berth allocation processes.

3 The automated port call process in AutoMoTIF

In AutoMoTIF, the entire process of berthing and unberthing will be simulated at a generic port (i.e. container terminal), to replicate the complex interactions among the process key players under the assumption that the operation will be performed by fully autonomous tugboats (i.e., without a master onboard) and that an Automated Mooring System (AMS) is installed at the quay. The simulation will incorporate various key parameters for the process, such as weather conditions, size of the vessel, number of tugboats, significant wave etc. The outcome of the simulation, together with the results of the rest of AutoMoTIF use cases that will simulate automated port operations, automated shunting as a service-oriented platform and automated multimodal terminal operations, will then be used to validate a new proposed open reference architecture framework for Digital Twins (DT), one of the most prominent emerging technologies in the field.

During the planning of arrival phase, the vessel provides the port the ship-specific data as required by the Maritime Single Window (e.g. length, draught, type of cargo, Estimated Time of Arrival, EDI files, etc). Using this information combined with the maritime traffic at the port,

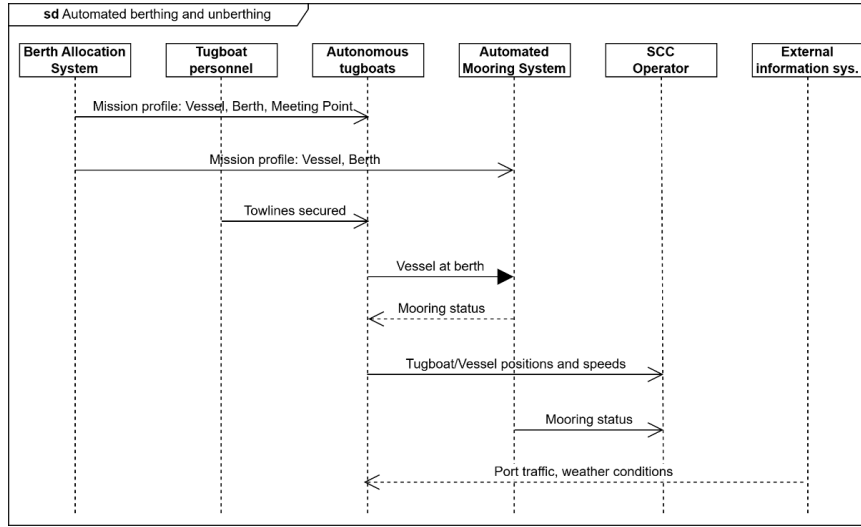


Figure 2: Diagram of interactions between components in the automation framework

the BAS assigns the vessel to a berth. When the vessel reaches the anchorage, the autonomous tugboats receive a mission profile from the BAS, which includes the vessel characteristics, the location where they will meet the vessel, and the location of the allocated berth (Figure 2). The mission profile is also sent to the AMS that is positioned at the allocated berth. The autonomous tugboats

navigate towards the designated meeting point and the tow lines are secured by the onboard personnel.

During the autonomous manoeuvring process, the autonomous tugboats receive information from external information systems, such as the VTS and AIS regarding the maritime traffic within the port limits, and port weather stations regarding the environmental conditions. The operation is also remotely monitored by a shore-based operator in-the-loop based on operational data, such as the positions and speeds of the vessels involved, received from the autonomous tugboats and the AMS. The autonomous tugboats manoeuvre the vessel close to the designated berth in a predefined position and then the AMS is triggered by receiving the data from the autonomous tugboats that the vessel is in the berthing position. The AMS then secures the vessel at the berth and notifies the autonomous tugboats to disengage and also notifies the port that the berthing process has been successfully concluded.

4 Key Performance Indicators

An important part of the introduction of automation of any kind in the transport and logistics field is undoubtedly the evaluation of its potential impact. For this reason, this section presents and discusses the Key Performance Indicators (KPIs) identified in AutoMoTIF for the use case of automated berthing and unberthing of freight vessels. The outlined KPIs cover several impact areas, i.e., operational efficiency, safety, environment, economy, and society (Hadjidimitriou, 2025).

The KPI framework for the use case is designed to assess various aspects of the automated system, ensuring a holistic evaluation that covers technical performance, environmental sustainability, economic viability, and societal impact. By leveraging both time-sensitive and resource-specific data, the framework aims to provide actionable insights into the performance of berthing and unberthing processes under varying conditions (Hadjidimitriou, 2025).

KPIs in **Operational Efficiency** measure the speed and smoothness of vessel maneuvering and docking. The following list of seven KPIs is critical for understanding how effectively the automated system reduces turnaround times and minimizes disruptions.

Manoeuvring and Docking Duration: This KPI measures the time required for a vessel to berth and unberth within the port area. Specifically, it captures the duration of the entire berthing process (i.e., from the anchorage point to being moored at the quay) and the unberthing process (i.e., from the quay to the sailing point). It provides a clear indication of the system's efficiency in reducing turnaround time and streamlining the port call process. Data collection will focus on the duration of operations across different weather conditions, ensuring a comprehensive performance assessment.

Number of Tugboat Movements: By tracking the number of directional changes or movements performed by tugboats during the berthing and unberthing processes, this indicator quantifies the operational dynamics. Monitoring these movements under varying weather conditions helps to pinpoint inefficiencies and potential areas for process improvement.

Safety-related metrics focus on the risk exposure for humans involved in berthing and unberthing processes. A key objective is to evaluate whether automation can lower the number of personnel required, thereby potentially reducing humans at risk.

Number of Humans at Risk: This safety metric assesses the number of crew members required on tugboats during port calls. The goal is to reduce human involvement in potentially hazardous operations through automation, thereby enhancing overall safety. The KPI is measured by counting the total number of personnel on board tugboats during these operations.

Environmental KPIs monitor the ecological footprint of the operation, including pollutant emissions and energy consumption. These measures help in assessing the sustainability of the automated process under different weather conditions.

Emissions: This environmental KPI quantifies the emissions produced by both the tugboats and the vessel during berthing and unberthing. Tracking the type and volume of emissions under different weather conditions allows for an assessment of the operation's environmental impact and helps identify areas for improvement.

Consumed Energy: Measuring the energy consumption of the tugboats during these operations provides another key environmental metric. The KPI focuses on total fuel consumption, highlighting the energy efficiency of the system and identifying opportunities to optimize fuel usage under various operational conditions.

Economic performance is evaluated by examining operational expenses. This KPI provides insight into the cost efficiency of running the tugboat services during berthing and unberthing, an important factor in overall project feasibility.

Operational Expenses of Tugboat Service: This metric tracks the cost associated with operating tugboats during berthing and unberthing. It is essential for evaluating the economic feasibility of the automated system. By monitoring these expenses, stakeholders can perform a detailed cost-benefit analysis to determine the financial viability of the process.

The **societal** impact is captured by assessing personnel requirements. This metric is crucial for understanding the potential workforce implications of transitioning from conventional to automated operations.

Personnel: This KPI measures the number of crew members needed to operate the tugboats. It serves as a direct indicator of the potential workforce reduction and improved operational safety

that automation might offer. The focus is on determining the optimal crewing levels required for efficient operation under the new automated system.

5 The AutoMoTIF Open Reference Architecture Framework for Digital Twins adapted to berthing and unberthing of freight vessels

One of the most prominent emerging technologies in the field of transport and logistics is the Digital Twin (DT), the rapid evolution of which has brought significant advancements, but it has also introduced new challenges that must be addressed in today's era that is characterized by an increased demand for open, modular, interoperable and scalable systems. As DTs transition to open architecture items as well, the complexity of managing diverse data sources, integrating legacy systems, and enabling advanced functionalities has grown significantly (Klar et al., 2024). Some additional challenges are ensuring security in data exchange and data governance and the required customization according to domain-specific requirements. The Open Digital Twin Reference Architecture framework that is developed in the context of the AutoMoTIF project aims to address these challenges.

The framework provides a structured and modular approach to designing DTs that meet the demands of interoperability and scalability while also offering a foundation for future advancements. By focusing on three key layers, namely, external integration, core functionality, and intermediary integration mechanisms, this architecture ensures a seamless flow of data and operations between external systems and the DTs' internal components (McKee, 2023). The Open Reference Architecture is specifically designed to overcome the limitations of traditional closed systems, which are often difficult to expand, providing a framework that is modular, interoperable, and expandable, enabling the seamless integration of external components, tools, and technologies from various providers. This openness does not imply that the system is "free" or unregulated; instead, it refers to the system's ability to interoperate with diverse external modules while maintaining a standardized core (Klar et al., 2024).

Figure 3 provides a comprehensive overview of the automated berthing and unberthing process for freight vessels at a port, adapted to the proposed framework. The process is structured across three interconnected layers: the outer, middle, and inner layers. These layers work together to create a detailed simulation of the use case, integrating real data and artificial intelligence models to optimize port operations.

The outer layer serves as the foundation, incorporating critical input parameters that influence the system's operations. These inputs include navigational data, continuous monitoring of unmanned tugboats and container ships, and the automation of mooring, berthing, and unberthing. Additionally, this layer accounts for various environmental and operational factors, such as weather conditions, vessel characteristics, tugboat specifications, predefined operating rules, and port infrastructure details. Lastly, it highlights the selected simulation platform for the deployment of the simulation of the use case, which is Unity 3D. These elements together establish the constraints and variables necessary to form the fundamental structure of our simulation.

The middle layer functions as the central processing unit of the system, managing data flows, system interactions, and communication between different components. The API Gateway ensures seamless and secure data exchange between external sources and the simulation environment, such as port data and port call information. Meanwhile, the data processing and transformation unit cleans, organizes, and structures raw input data, making it suitable for analysis and simulation. The workflow orchestrator synchronizes various tasks, ensuring the smooth execution of berthing and unberthing procedures, while the event handling and notification system enables users to select which scenario they want to execute. This includes options related to environmental conditions, port vessel traffic, and vessel size. Acting as a

bridge between the inner and outer layers, this layer ensures that all elements function in harmony to facilitate automation procedures.

The inner layer serves as the core of the simulation, integrating and coordinating all the preceding layers to execute the simulation process effectively. The Business Rules Engine ensures that all automated decisions comply with predefined operational regulations governing the berthing and unberthing of vessels. Furthermore, the Information Model structures the data flow, enabling smooth data retrieval and analysis related to the port, vessels, and tugboats. Simultaneously, the Simulation and Analysis Controller manages the execution of various user-selected scenarios, ensuring accurate and efficient simulation outcomes.

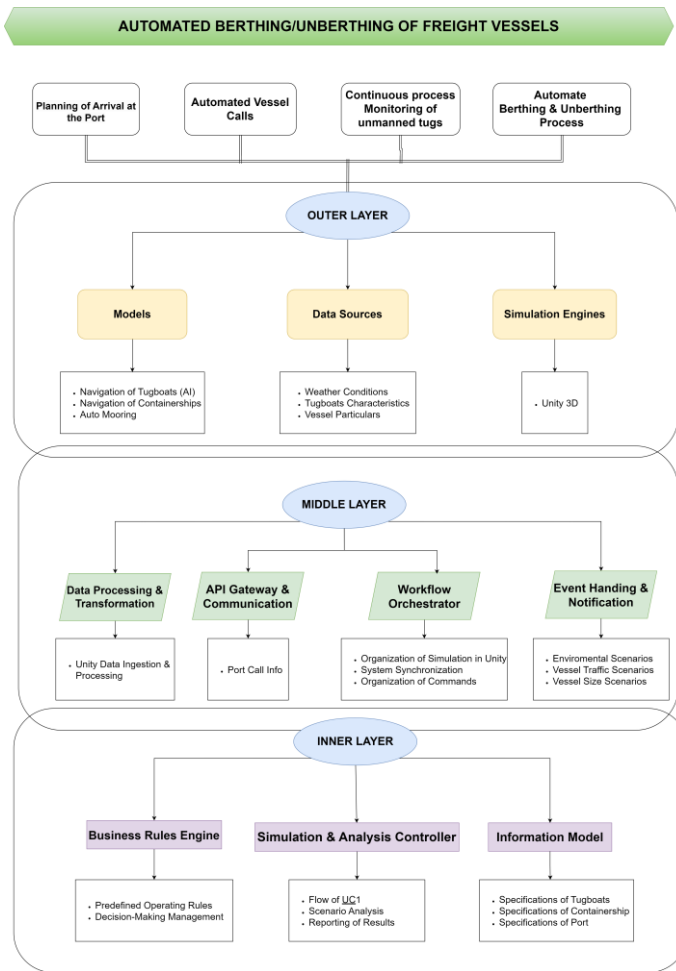


Figure 3: AutoMoTIF Open Reference Architecture diagram for the use case of automated berthing/unberthing of freight vessels

The benefits of developing the simulation for the AutoMoTIF automated port call process based on the reference architecture framework relates to the simulation itself, as well as to how the simulation can be used in future research. A standardized way to structure the simulation will support how it can be validated, while the modular architecture will provide the ability to test different models (e.g. for tugboat navigation) and efficiently integrate models through the Simulation & Analysis Controller and the Workflow orchestrator. Using the framework will also allow the simulation to be “DT-ready” and act as part of the digital twin of the automated port call process that can be used for supporting decisions in real-time.

Conclusion

This paper, which is part of the on-going research conducted in the context of the EU-funded AutoMoTIF project, contributes to the IPIC 2025 conference by exploring how automation and digitalization can enhance the efficiency, resilience, and sustainability of maritime freight transport, aligning with the broader goal of transforming supply chains through hyperconnectivity. It presents a use case which focuses on the automation of vessel port calls, a critical link between sea and land logistics. The research presented herein directly supports the large-scale implementation of Physical Internet by optimizing multimodal logistics operations, integrating emerging technologies and ensuring seamless data exchange across stakeholders. Moreover, the proposed open reference architecture for Digital Twins enables scalable, interoperable, and future-proof solutions that can contribute to the next generation of smart, hyperconnected maritime logistics ecosystems.

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Multi-stakeholder insights on integrating public transport for urban freight deliveries.

Cécile Dupouy^{1,2}, François Clautiaux², Walid Klibi¹ and Olivier Labarthe¹

1. The Center of Excellence in Supply Chain Innovation & Transportation (CESIT), Kedge Business School, Bordeaux, France.
 2. Université de Bordeaux, Institut de Mathématiques de Bordeaux, UMR CNRS 5251, Centre Inria de l'Université de Bordeaux, France
- Corresponding author: cecile.dupouy@kedgebs.com

Abstract: This paper explores the integration of public transport networks for urban freight deliveries within the framework of Hyperconnected City Logistics (HCL), focusing on multi-stakeholder perspectives. By synergizing freight and passenger networks, the study optimizes parcel consolidation and containerization in the urban middle-mile, efficiently moving parcels between access hubs during off-peak hours to reduce reliance on dedicated freight vehicles. The model is validated through computational experiments based on public transport system, evaluating various collaboration strategies among multiple logistics service providers. Specifically, it examines three consolidation policies: independent, where each provider reserves its own vehicle; partially shared, where different providers share the same vehicle, but containers remain separate; and fully integrated, where parcels from different providers are consolidated in the same container. To compare policies, a realistic case study based on the city of Bordeaux, provides insights into the operational and collaborative potential of integrating public transport into urban logistics.

Keywords: Physical Internet, Hyperconnected City Logistics, Freight transportation, Urban mobility, Public Transportation.

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

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

1 Introduction

1.1 Motivation

Traditional freight urban delivery systems rely on dedicated vehicles, infrastructures, and flows. However, with the rapid growth of e-commerce sales and the increasing demand for same-day deliveries, urban deliveries with vehicles have surged (Faugère et al., 2022). At the same time, growing urban population density has led to significant passenger flows, supported by dedicated networks of private cars, public buses, tramways, and infrastructures such as roads and rails. Urban areas benefit from diverse public transport services that provide access to pedestrian zones in city centers. While public transport networks operate at full capacity during rush hours, they often have underutilized spare capacity during off-peak periods. Leveraging this existing

infrastructure for freight transport could significantly reduce the reliance on dedicated delivery vehicles (Fatnassi et al, 2015).

Even though the freight and people mobility networks operate similarly in the same environment, the traditional practical scheme imposes a separation between them regarding flows, infrastructures, and resources. The Physical Internet (PI) concept introduced in Montreuil (2011) proposes connecting people, objects, stakeholders, and networks in a unified, open, interconnected system. When applied to urban environments, the concept of Hyperconnected City Logistics (HCL, Crainic et al., 2023) emerges. The HCL concept of integration and interconnection of passenger and freight movements in urban transit systems establishes synergies to move people and freight simultaneously.



(a) Amazon tramway, Frankfurt, Germany (2024) (b) La Poste, tramway, Strasbourg, France (sept-oct 2024) (c) GLS, metro, Madrid, Spain (sept 2024)

Figure 1: Projects integrating public transportation into urban freight delivery

Recently, several projects have tested the integration of public transportation networks into urban freight deliveries, highlighting the potential of this approach. In Frankfurt, Germany, Amazon operates the Gütertram to transport parcels (*Figure 1a*). In Strasbourg, France, La Poste, the French postal service, conducted a two-month pilot project (September-October 2024) to evaluate the feasibility of parcel deliveries inside tramways alongside passengers (*Figure 1b*). In Madrid, Spain, GLS and the metro of Madrid launched the M4G project, using one metro line for freight transportation since September 2024 (*Figure 1c*). All these projects rely on the principle of containerization, where parcels traveling in the same direction are grouped into containers before being loaded onto public transport. This approach streamlines handling, loading, and unloading operations at hubs, improving efficiency and facilitating seamless integration into an existing network (Kaboudvand et al. 2021, Montreuil et al. 2018). Furthermore, parcel consolidation provides notable environmental benefits by enabling the pooling of supply networks from different stakeholders reducing CO₂ emissions (Ballot et al. 2010).

1.2 Business context

We consider a parcels' urban delivery system where the public transportation network is appended to a traditional delivery schema to move parcels by dedicated trucks, as characterized in Labarthe et al. (2024). We structure urban logistics around three tiers as represented in *Figure 2*: the urban first-mile where Logistics Service Providers (LSP) connect local hubs; the urban middle-mile corresponding to the movement of parcels within the city and access hub, and the urban last-mile connecting pick-up or delivery points. Connections and synchronization among LSPs occur between each tier (Delle Donne et al., 2025).

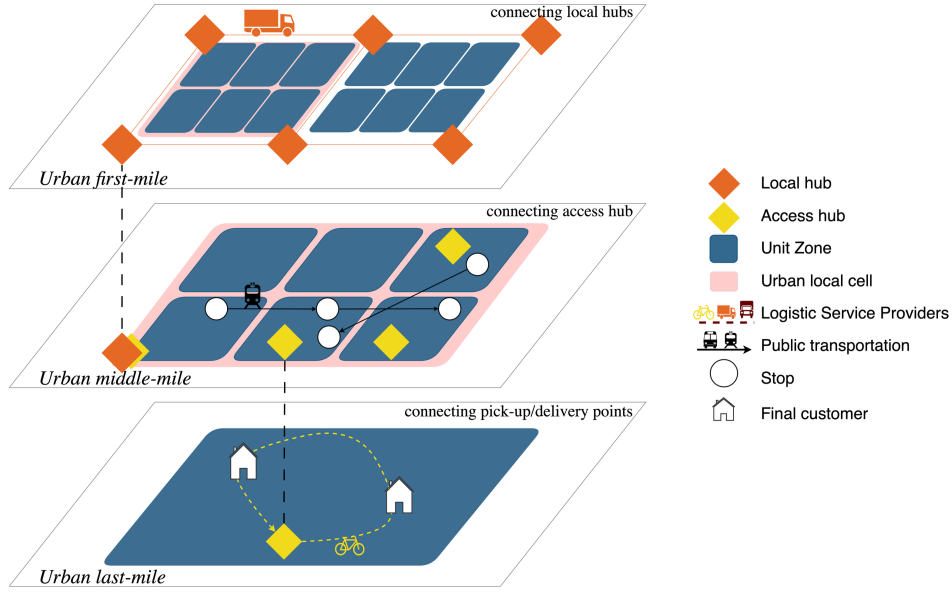


Figure 2: Three-tier urban delivery network.

The scope of the synergized network studied in this work is delimited at the urban middle-mile section corresponding to the movement of parcels between access hubs within the city. It starts at an origin access hub where parcels of various logistics service providers arrive by trucks (from a local hub) and ends at a destination access hub where the parcels need to be collected by urban operators for urban last-mile delivery by cargo bikes to their final destination. Similarly, the urban middle-mile also facilitates the upstream movement of parcels collected from customers at pickup points. In this case, last-mile operators bring the parcels to an access hub, from where they are transported through the network to another access hub, before reaching a local hub for further processing. To perform the urban middle-mile, our system offers the possibility of using public transportation services, including different modes and lines. If a demand cannot be served through the public transportation network, an alternative using private freight vehicles is allowed to ensure demand satisfaction. Workforces are deployed in unit zones to authorize the transfer of parcels between public transportation lines and to manage their entry or exit from the network. This flexible approach enables multiple transfers within the public transportation network to use all available lines and modes. Demands from multiple stakeholders are shaped by the number of parcels that need to be delivered within a city divided into predefined unit zones with designated access hubs and stops. These demands originate and terminate in specific unit zones, similarly to Faugère et al. (2022).

The proposed approach uses containerization, where parcels travelling in the same direction are grouped into urban containers to facilitate operations at transfer hubs. This strategy is particularly relevant in scenarios using multiple stakeholders as it allows the implementation of different degrees of collaboration. LSPs can operate independently, each reserving dedicated vehicles and containers or adopt consolidation and containerization strategies to share resources. As we consider multiple LSPs operating within this urban logistics network, an external orchestrator is required to ensure efficient coordination and resource allocation. This orchestrator is responsible for managing the shared infrastructure, synchronizing freight flows, and optimizing the use of transport capacity across different actors. It can be a dedicated entity, a specific LSP, an actor mandated by the city, or a public transport operator (Kwon et al., 2023, Zhang et al., 2025).

As outlined by Mohri (2024), the use of standardized containers in multi-mode delivery systems offers several operational benefits, particularly in terms of reducing fixed and operational costs at transfer access hubs. Modular vehicle concepts, when coupled with consolidation strategies, have also shown strong potential to improve the efficiency of urban logistics by reducing empty kilometers and operating costs (Hatzenbühler et al., 2023). Labarthe et al. (2024) introduced the concept of urban synchromodality, emphasizing the synergies between freight and passenger mobility, highlighting its potential to reduce the time and space consumed by containers in the network. Synchromodal systems utilizing standardized containers also contribute to a reduction in the environmental footprint (Lemmens et al., 2019). However, most of the research is focused on a single actor. In contrast, the concept of multi-stakeholders, multi-modal logistics, as discussed by Montreuil (2018), enables collaboration between multiple logistics stakeholders. Modular containerization, as proposed in this context, facilitates shared resources and maximizes space utilization across various stakeholders. At the operational level, collaboration between stakeholders is essential to optimize resource allocation and reduce empty runs and avoid duplication of services (Zhang et al. 2025).

Integration of public transport and freight logistics requires attention to operational attributes such as space allocation, reliability, and coordination between actors. Yet, few studies address how such integration can support multi-stakeholder, consolidated containerization at the short-term planning level. Focusing on the operational problem of short-term planning, this study evaluates how different consolidation strategies impact LSPs' operational performance, providing key managerial insights into the benefits of containerization in a multi-mode, multi-line integrated public transportation system.

The paper is organized as follows. In section 2, our proposed approach is presented, including levels of consolidation and modelling approach. In section 3, we present the case study and the results. Finally, section 4 concludes this paper.

2 Proposed approach

2.1 Levels of consolidation

To respond to the business context presented and assess the feasibility and efficiency of integrating freight transport within the public transit system, we explore different consolidation strategies between logistics stakeholders. Specifically, we analyze the level of collaboration among logistics service providers. In many urban settings, multiple logistics stakeholders operate independently, each reserving its own dedicated transport capacity, leading to some resource underutilization (Zhang et al. 2025). We evaluate three levels of collaboration among stakeholders in using public transport for freight movements. In the *independent policy*, each LSP reserves its own dedicated public transport vehicle to carry its dedicated containers. In the *partially shared policy*, the same public transport vehicle is shared by different LSP, but each container remains assigned to a single LSP, meaning that consolidation can only occur at the vehicle level, not at the parcel level. Finally, in the *fully consolidated policy*, parcels from different LSPs are consolidated within the same container, maximizing space utilization. *Figure 3* illustrates these three levels of consolidation using an example with two stakeholders, the approach can be extended to multiple actors.

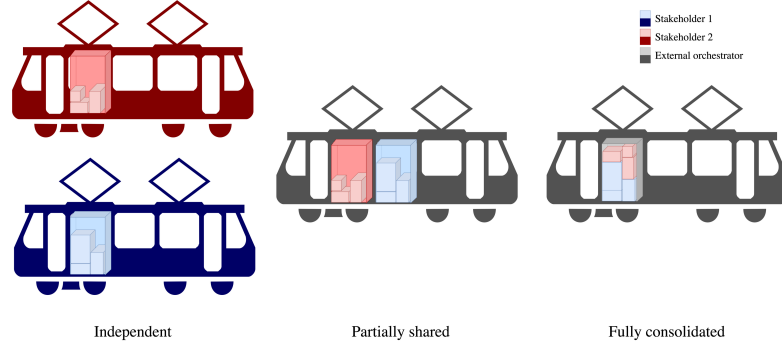


Figure 3: Levels of consolidation.

In the partially shared policy, the reserved public transport vehicle does not belong to either stakeholder 1 or stakeholder 2 but is instead managed by an external orchestrator. Similarly, in the fully consolidated policy, not only the vehicle but also the containers are managed by this orchestrator.

2.2 Modeling

To compare the level of consolidation, we developed the operational problem of short-term planning for studying the flow of parcels and their consolidation into containers within a multi-mode, multi-line, multi-stakeholder integrated public transportation system. The objective function is different for each consolidation levels, reflecting the different operational cost implications for stakeholders. The model aims to minimize the total cost including reservation costs for public vehicles (w^R), and transportation costs (w_a) based on parcel (\mathbf{y}) and container (\mathbf{x}) operational decisions.

In the *independent policy*, each stakeholder ($s \in \mathcal{S}$) operates separately, reserving its own number of dedicated public transport vehicles (\mathbf{z}_s), and using its individual containers $q \in Q^s$. The objective function (1a) minimizes the total reservation costs and the operational costs of parcels $c \in \mathcal{C}^s$ and containers $q \in Q^s$ for each stakeholder s .

$$\text{Min} \sum_{s \in \mathcal{S}} w^R \mathbf{z}_s + \sum_{s \in \mathcal{S}} \left(\sum_{q \in Q^s} \sum_{a \in \mathcal{A}^q} w_a \mathbf{x}_a^q + \sum_{c \in \mathcal{C}^s} \sum_{a \in \mathcal{A}^c} w_a \mathbf{y}_a^c \right) \quad (1a)$$

In the *partially shared policy*, stakeholders can share the same public transportation vehicle while still using separate containers $q \in Q^s$ for their respective parcels $c \in \mathcal{C}^s$. The decision variable \mathbf{z} correspond to the total number of public vehicles reserved. The objective function (1b) accounts for the shared vehicle reservation cost ($w^R \mathbf{z}$) while maintaining parcels and containers costs for each stakeholder s .

$$\text{Min} \quad w^R \mathbf{z} + \sum_{s \in \mathcal{S}} \left(\sum_{q \in Q^s} \sum_{a \in \mathcal{A}^q} w_a \mathbf{x}_a^q + \sum_{c \in \mathcal{C}^s} \sum_{a \in \mathcal{A}^c} w_a \mathbf{y}_a^c \right) \quad (1b)$$

Finally, in the *fully consolidated policy*, stakeholders consolidate their parcels into shared containers allowing vehicle and container consolidation. The objective function (1c) minimizes the reservation cost for the shared vehicle, the operational cost for shared containers $q \in Q$ and the individual parcel $c \in \mathcal{C}^s$ operational cost for each stakeholder s .

$$\text{Min} \quad w^R \mathbf{z} + \sum_{q \in Q} \sum_{a \in \mathcal{A}^q} w_a \mathbf{x}_a^q + \sum_{s \in \mathcal{S}} \sum_{c \in \mathcal{C}^s} \sum_{a \in \mathcal{A}^c} w_a \mathbf{y}_a^c \quad (1c)$$

The three policies are subject to the same set of constraints. Capacity constraints regulate the number of containers transported within public transport vehicles, the volume of parcels that can be loaded into each container, and the number of handling operations that can be performed by operators within a given zone. The operational model is formulated as an arc-flow optimization problem, ensuring flow conservation for both containers and parcels. Additionally, linking constraints enforce that parcels are transported exclusively within their assigned containers when applicable.

3 Case study

3.1 Bordeaux Case study presentation

The proposed operational model is validated through computational experiments on scenarios inspired by Bordeaux's, France, public transport network, chosen for its extensive infrastructure and availability of open data (L'atelier Opendata). This study considers two different network configurations. The first configuration represented in *Figure 4a* considers two tramway lines while in the second configuration as shown in *Figure 4b*, the network is expanded to four lines including three tramway and one bus lines. The addition of new lines enables the system to serve a larger geographical area and reach new demand zones.

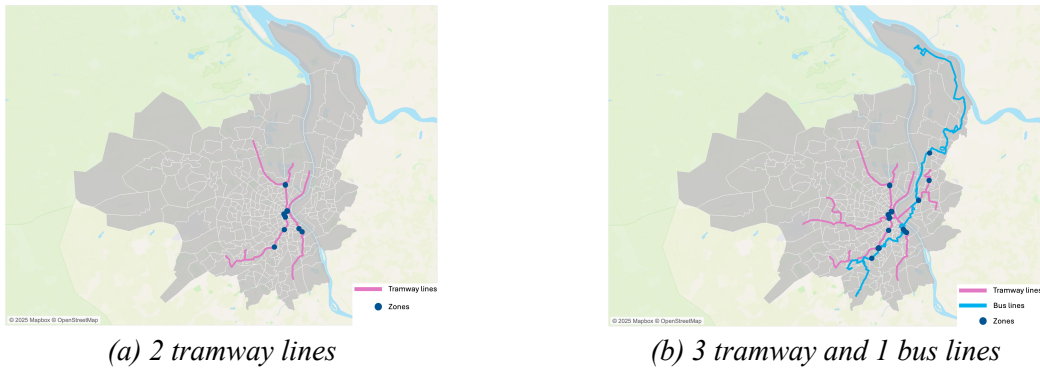


Figure 4 Public transport networks

In addition to the variation of the public transport network, the number of logistics stakeholders involved in the system is also varied. The experiments are conducted with two and three stakeholders to analyze the impact of the consolidation levels on network performance and resource utilization.

3.2 Results and discussion

By leveraging the mathematical formulation of our short-term planning model, we evaluate how different levels of consolidation impact network utilization, delivery efficiency, and cost-effectiveness for all stakeholders. Consolidation levels are assessed using key performance indicators. The first indicator is the impact of consolidation levels on public transportation use. The second indicator is the total operational cost, including both the reservation of public transport vehicles and the handling operations. Finally, we compare the container usage with their routes and their average time spent within the system. All the results presented in the following subsections are based on scenarios with 150 parcel requests distributed over a two-hour operational window.

3.2.1 Impact of consolidation levels on public transportation use

In this section, three logistics service providers operate within the system under the three previously defined levels of consolidation using 2 tramway lines.

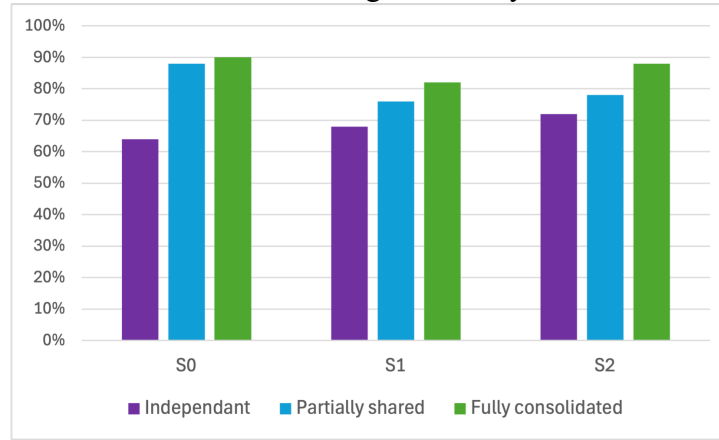
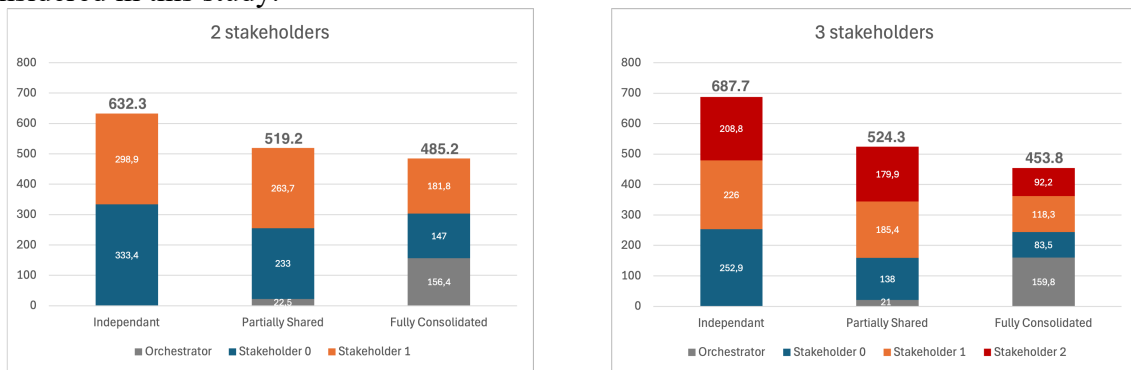


Figure 5: Demand delivered with public transport - 2 lines

Figure 5 illustrates the proportion of parcel demand delivered via public transport for each of the three stakeholders (S0, S1, S2), under the three consolidation policies. The results reveal a consistent increase in public transport utilization as the level of consolidation increases. While the independent strategy results in lower shares (64% for Stakeholder 0), the fully consolidated case reaches up to 90% of demand delivered with public transportation. This evolution highlights that greater collaboration leads to more deliveries being absorbed by the public transport network rather than relying on dedicated freight vans. This transition has the potential to reduce the number of freight vehicles circulating in dense urban areas. Notably, even partial collaboration already leads to improvements in transport efficiency and network utilization.

3.2.2 Impact of consolidation levels on operational cost.

We provide a detailed analysis of operational costs across different consolidation levels. These costs include the direct delivery cost (identical for all stakeholders), incurred when parcels cannot be delivered with public transport; the operational cost, which covers handling and movement of parcels and containers; and the reservation cost, for the reserved capacity on public transport vehicles. It is important to note that only short-term planning costs are considered in this study.



(a) Two stakeholders

(b) Three stakeholders

Figure 6: Comparison of cost repartition per stakeholder

Figure 6 confirms that consolidation significantly reduces the total system cost. Moving from the independent policy to the fully consolidated one, the total cost decreases by 23.3% in the case of two stakeholders (Figure 6a) and by 34.0% in the case of three stakeholders (Figure 6b). This highlights that the benefits of consolidation increase with the number of involved actors. Figure 6 also illustrates how the cost decreases at the stakeholder level. In the fully consolidated policy, the introduction of an orchestrator allows for a more balanced allocation of costs and significantly reduces the individual expenses incurred by each logistics service provider. For each stakeholder, direct delivery costs correspond to the dominating cost. Direct delivery costs are reduced through consolidation, reflecting the increase of resource sharing. In both the independent and partially shared policies, direct delivery represents the largest cost component, accounting for more than half of the total costs. For instance, in the case with three stakeholders, direct delivery costs decrease by 58% from the independent policy to the full consolidation. This substantial reduction illustrates the effectiveness of containerized consolidation in enabling more parcels to be delivered via public transport.

3.2.3 Impact of consolidation levels on container routes

To illustrate the operational differences induced by varying consolidation policies, we compare the container routes observed under the *independent* and *partially shared* consolidation policies. In the case with three logistics stakeholders involved and four public transport lines.

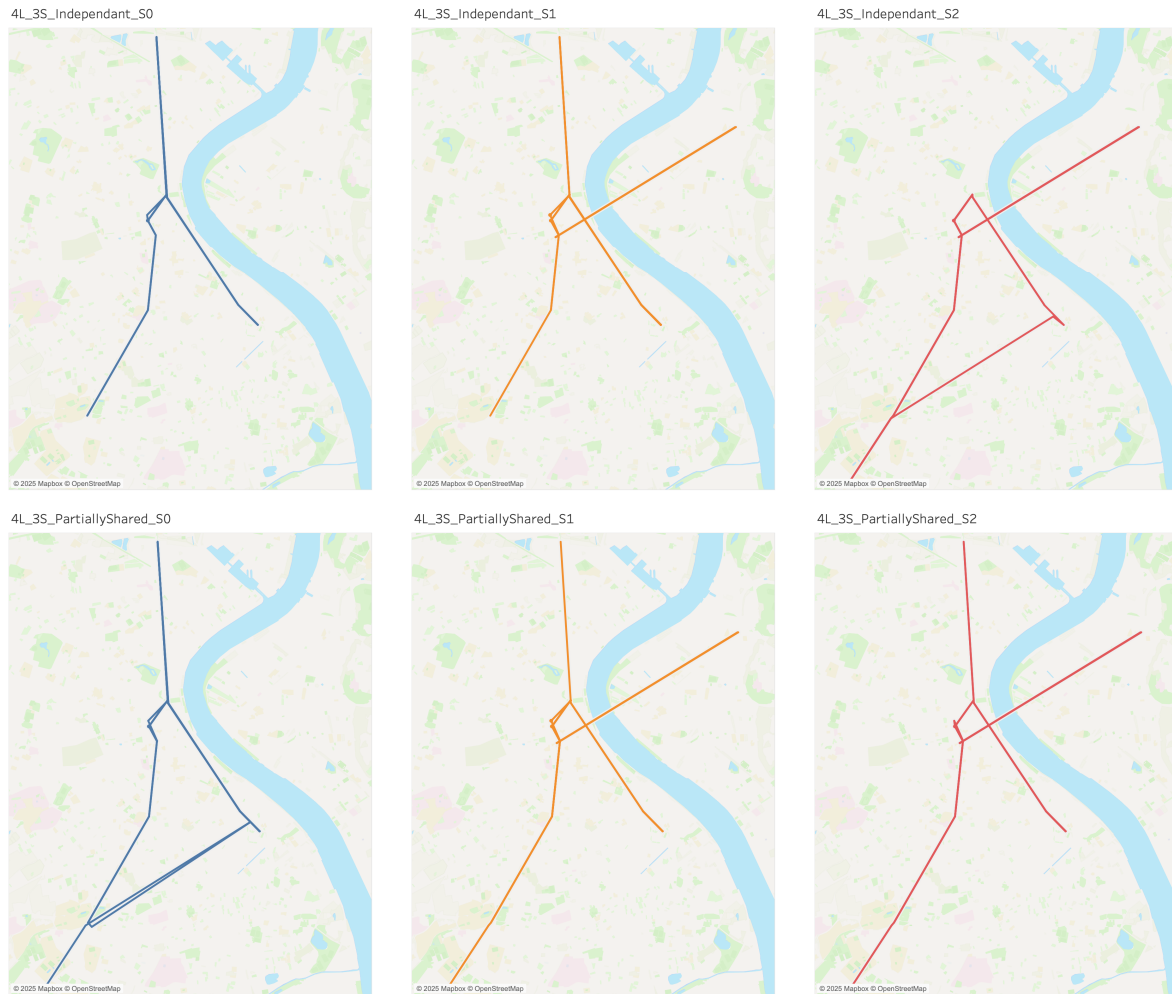


Figure 7: Container routes per stakeholder

Figure 7 illustrates the paths used by containers for each stakeholder using an *independent* or *partially shared* consolidation policy. Under the *independent* policy, each stakeholder reserves its own public transportation vehicle and container. In contrast, the *partially shared* policy allows containers from different stakeholders to share capacity on the same public transport trips, resulting in a more extensive use of the network. This is visible in the lower row of the Figure 7, where several routes not activated under the *independent* policy are now utilized. This shift in policy translates into an improvement in modal share: the proportion of parcel demand served by public transport increases from an average of 39% under the *independent* policy to 54% under the *partially shared* policy.

Table 1: Container fill rate per consolidation level and owner.

	Independent			Partially shared			Fully consolidated
Container owner	S0	S1	S2	S0	S1	S2	Orchestrator
Container used	100%	100%	100%	100%	100%	100%	100%
Average container fill rate	67.6%	67.2%	70.6%	67.1%	68.7%	78.9%	82%
Average time for containers (s)	3621	3669	3173	4093	4250	3870	4000

Table 1 illustrates the average container fill rate per stakeholder under the different consolidation policies. In the independent and partially shared policies, each stakeholder retains ownership of their 5 containers, resulting in variable fill rates. While stakeholders S0 and S1 display relatively stable averages across the two policies, stakeholder 2 achieves a notable increase from 70.6% to 78.9% when transitioning to the partially shared setting. This highlights that the opportunity to share public transport vehicles can significantly benefit stakeholders with more spatially dispersed demand. Under the fully consolidated policy, container ownership is centralized under an orchestrator who manages both routing and consolidation across all demand requests. This centralization improves the average fill rate to 82%. As a result, containers are more frequently present in the network due to higher fill rates, spending an average of more than 1h in the network across the two-hour interval of the study. In addition, the maximum time spent by a container in the network reaches up to 1 hour and 36 minutes, reflecting the extended duration that containers remain in the system when consolidation is at a higher level.

4 Conclusion

This study presents an exploration of integrating public transport networks into urban freight logistics, contributing to the concept of Hyperconnected City Logistics. We propose a short-term planning that coordinates parcel consolidation, containerization, and multimodal routing within the urban middle-mile. By focusing on multi-stakeholder perspectives, the proposed model evaluates three consolidation strategies: independent, partially shared and fully consolidated. Our computational experiments, based on Bordeaux's public transport system, confirm that consolidation within multi-stakeholder networks can significantly improve resource utilization and reduce operational costs. In particular, the fully consolidated policy, where parcels from multiple logistics service providers share containers, proves to be the most cost-effective and resource-efficient, allowing for optimal use of available transport capacity. Future research could extend this model along complementary directions. First, by incorporating environmental considerations to assess the ecological benefits of consolidation strategies. Second, by introducing tactical decisions on the number and allocation of operational resources. Third, by exploring strategic aspects such as the selection of transport lines and stops

to include in the network. Finally, a game-theory approach could be adopted to study prioritization mechanisms balancing the interests of multiple stakeholders under limited capacity.

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(De)central planning approaches for asset sharing between multiple connected fleets for airside baggage transport

Jaco van Meijeren¹, Ruben Fransen¹, Coen van Leeuwen¹ and Lola Sprenger¹

1. TNO, Netherlands Organization for Applied Scientific Research,
The Hague, The Netherlands

Corresponding author: Jaco.vanMeijeren@TNO.nl

Abstract: *The logistics sector faces big challenges in terms of ambitious sustainability targets, strong emphasis on security of supply and dealing with scarcity (in terms of physical infrastructure, energy and labor force). This requires a system change in logistics by "doing more with less" through sharing assets in the freight and transport industry in open connected logistics networks. Essential elements for this are trusted multilateral horizontal and vertical collaboration, decentral coordination and decentral data sharing. TNO developed a roadmap to develop solutions with increasing complexity in terms of requirements. This paper describes approach and results of decentral planning algorithms for a multi-fleet single party situation (full asset sharing, limited collaboration within a single company). The impact of central and decentral approaches and single fleet and multi-fleet planning are shown for a use case of airside baggage transport at Schiphol Amsterdam Airport.*

Keywords: *Asset sharing, collaborative planning, multi-fleet single party optimization, fleet management, decentral planning algorithms, Physical Internet, self organization, airside baggage transport.*

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

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

1 Introduction

1.1 Background

The logistics sector faces big challenges in terms of ambitious sustainability targets, strong emphasis on security of supply and dealing with scarcity (in terms of physical infrastructure, energy and labor force). These challenges are even further reinforced by upcoming national (e.g. road pricing) and European legislation (e.g. CSRD). To address these challenges, it is fundamental to leverage opportunities for increased logistics efficiency. The Physical Internet (PI) concept, supported by European Technology Platform (ETP) ALICE, envisions a system change in logistics by "doing more with less" through sharing assets in the freight and transport industry (Ballot et al., 2020). To realize this, the sector needs to shift from individual planning of own assets within single networks towards collaborative planning of shared assets in open connected logistics networks.

However, collaborative planning for sharing of assets between different companies requires collaboration, data sharing and control by a specific entity which are all three elements logistics companies do not like naturally. To make a solution effective and feasible, key elements are trusted multilateral horizontal and vertical collaboration, decentral coordination (to avoid central coordination) and decentral data sharing (to avoid central data sharing). Trusted decentral collaborative planning approaches where no single entity oversees everything and only the necessary data is made available under strict conditions of the data owner is needed.

1.2 Roadmap towards decentral planning approaches

TNO developed a roadmap to work on these type of solutions. Starting with solutions for situations with limited complexity and slowly increasing complexity for more difficult situations. Following this roadmap, we started with developing and testing decentral planning algorithms for a single-fleet single party situation (no asset sharing, no collaboration). In the analyses we tested and evaluated several decentral planning algorithms to build knowledge on different alternatives (Ommeren et al., 2022). Following, we developed and tested decentral planning algorithms for a multi-fleet single party situation (full asset sharing, limited collaboration within a single company). In the analyses we tested the algorithms for asset sharing and we developed a showcase to demonstrate the potential benefit of asset sharing (Fransen et al., 2025). This part is the topic of this IPIC paper. The results will be further used in the next step, decentral planning algorithms for a multi-fleet multi-party situation (full asset sharing, full collaboration between different companies). For this last step, recently a new research project for collaboration between two logistics companies with Logistics Community Brabant (see: [Project · LCB portaal](#)) and a large research program for collaboration between many companies started at TNO (Future Proof Smart Logistics, see: [Future Proof Smart Logistics | TNO](#)).

1.3 Content paper

As mentioned, this paper describes the analysis of decentral planning algorithms for multi-fleet single party situation. In the use case, we focus on the baggage handling and especially baggage transport with tugs and trailers between the baggage hall and the airplanes of KLM ground services, the largest ground handler at Schiphol Airport in the Netherlands. For this operation, two different fleets (multi-fleet) are used – for inbound and for outbound baggage transport – that currently are being planned separately by KLM ground services (single party) for operational reasons.

The analysis focusses on comparing different control methods for the different airside baggage transport fleets (incoming and outgoing); namely central planning or decentral planning combined with single fleet planning or multi-fleet planning.

After this first introduction paragraph, the multi-fleet planning problem is described in the second paragraph and the scheduling methodology is explained in the third paragraph. Following, the Schiphol use case is briefly described and the results are presented in the fourth paragraph. Finally, conclusions and considerations are given in the fifth paragraph.

2 Multi-fleet planning problem

2.1 Problem description

The goal of the research is to maximise the number of on-time delivered baggage before airplane departure at Schiphol Amsterdam Airport. This can be achieved by ensuring baggage fleets operate efficiently and by minimising the total time that it takes for the baggage to be transported from airplane to the internal baggage systems within Schiphol and vice versa. In this baggage process, there are baggage trailers and tugs that pull these trailers. To optimise the baggage process, the efficient assignment of trailer-tug combinations to trips that need to be executed, so-called jobs (transport of all baggage for one specific flight), is crucial. If the resources of trailers and tugs are non-constraining, the problem is trivial. However, there is a limited number of trailers and tugs and thus an additional goal is to maximise efficiency by maximising the delivered baggage on time with as little trailers and tugs as possible. The baggage process is separated between the incoming baggage, also called the reclaim baggage, and the outgoing baggage, which consists of transfer and departure baggage.

Each tug and each trailer can only be assigned to one job at any point in time. For every part of every journey of every job, there is a fixed time that needs to be spent. The required time for the execution of a job is the sum of the driving time and the (un)loading time of the trailers, where the latter depends on the number of bags that need to be loaded or unloaded. The problem has been formulated as a distributed constrained optimization problem (DCOP). Three main datasets have been used for the analysis: GIS data about locations airplanes and the road network, airport flight data about arriving and departing planes and baggage handling data of each airplane. For more information about the data, reference is made to the TNO research report of the project (Fransen et al., 2025).

2.2 Distributed Constraint Optimisation Problem

This section describes the DCOP formulation of this scheduling problem, with multiple cooperating agents and decision constraints. The agents (tugs) have to cooperatively decide which batch (all baggage for one specific trailer) to pick up by which tug at which point in time. In DCOPs problems are described as a tuple $T = (A, X, D, R)$. We can formulate the batch allocation problem as a DCOP by stating that each tug v is represented by an agent from $A = \{A_1, A_2, \dots, A_n\}$ and their corresponding set of batches assigned in \bar{d} are the variables that are being optimized $X = \{X_1, X_2, \dots, X_n\}$. One of the main assumptions in DCOP theory is that all variables must have finite discrete domains D , which in this case should contain every possible combination of batches to be assigned. Since there are exponentially many potential combinations, a preprocessing step is needed in which each agent selects a potential set of combinations, yielding n variable domains $D = \{D_1, D_2, \dots, D_n\}$. The DCOP minimization function is defined as

$$\operatorname{argmin}_X \sum R \tag{1}$$

in which R is the set of constraints, which map the assignment of variables to a non-negative cost: $C: D_{i_1} \times D_{i_2} \times \dots \times D_{i_k} \rightarrow R$. The constraints indicate how well an assignment is evaluated for a batch assignment, similar to the general problem formulation, only for the DCOP they will not be implemented as hard constraints, but they will be integrated as constraints in the objective functions. Their definitions in the cost function are described in the following section.

3 Scheduling methodology

This chapter will dive into the methods that have been applied to the scheduling problem. First the implementation for distributed scheduling (decentral planning) is described and secondly the benchmark heuristics (central planning) are explained.

3.1 Decentral: Cooperative Constraint Approximation

The distributed approach is based on a DCOP formulation of the baggage fleet scheduling problem. In DCOPs, agents have to find solution values for variables, which in our problem correspond to transport assignments of combinations of trailers and batches. This means that every tug is represented by an agent, who is responsible for claiming a set of batches to deliver and finding the right set of trailers to do so. The agents will have to communicate with one another to share some information about assignments. This is done to find an assignment which leads to an overall schedule that is beneficial for the whole group.

DCOPs are NP-hard and there are different algorithms available to solve DCOPs (Fransen et al., 2025). Based on a literature review Cooperative Constraint Approximation (CoCoA (Van Leeuwen and Pawelczak, 2017)) performs best for this purpose for the problem at hand in terms of computational requirements, privacy preserving characteristics and proven ability to deliver efficient schedules for transport planning (Grinshpoun et al., 2019 and Fioretti et al., 2018). CoCoA uses a non-iterative, semi-greedy approach with a one-step look ahead. It can solve DCOPs and is, in general, better (solutions closer to the optimum) and faster than other DCOP-solvers. For the implementation of CoCoA, a cost function that determines how “good” or “bad” an assignment is needs to be defined. Ideally, this cost function eventually represents the lateness of a batch of luggage and at the same time holds information about the priority of the batch, as well as the feasibility to deliver the batch. Therefore, the following cost function for an assignment x is used in our scheduler:

$$C_x = \lambda_x - n_x + \frac{s_x}{n_x+1} \quad (2)$$

Here, λ_x is a lateness penalty, indicating that an assignment with at least one batch that is delivered late will have a high cost. n_x indicates the number of trailers that is used, such that longer trains are preferred over short trains, and finally s_x is the time required to deliver all batches in the assignment. This indicates that the agents will somewhat greedily choose assignments that they can quickly complete, instead of finding the assignments that are nearly going to be too late. However, because of the lateness penalty, the agents will still try to find assignments minimising any late deliveries. This is quite a fine balance between assigning batches near their deadline versus choosing batches as quickly as possible. For a more elaborate explanation of the cost function and restrictions, reference is made to the TNO research report of the project (Fransen et al., 2025).

Besides the elements included in equation 2, other elements have been tested in development iterations, but were not added to the cost function. Examples of such elements are time remaining until batch delivery deadline, difference of batch deadlines within a train and penalising additional trailer (de)coupling.

The calibration of weight parameters has been done by evaluating scheduling results based on expert input and consequently manual tuning of results: if the resulting scheduled train lengths were relatively short with mostly one or two trailers, the weight value for train length has been

increased, and, if many batches were assigned with late delivery, then the penalty for lateness has been increased and the function for estimating has been improved.

3.2 Central: Exact and heuristic approach

3.2.1 *Branch and cut*

The problem formulation as described in section 3 has been implemented in an open source solver for MILP. Such exact MILP solvers guarantee to find an optimal solution if they are given enough computation time. The computation time, however, scales exponentially with the size of the problem. For a small problem instance with five tugs 100 trailers and 20 batches, the solver (Coin-OR branch and cut, available through PuLP in Python (Forrest et al., 2023)) already took multiple hours to find a solution. This was not entirely unexpected, as the problem has a large solution space due to the trailer and job assignment combinations. Due to this computation time challenge, we have not used this MILP-formulation in analyses on larger instances. A not explored alternative would be to use commercial solvers, which might be better suited to solving large problems. These were, however, not available for this study.

3.2.2 *Earliest deadline first*

Instead of the MILP-formulation, a more greedy approach has been implemented to have a more computation time effective benchmark method as comparison for the distributed approach. We have implemented two greedy, heuristic methods. They are both originating from the same principle: earliest deadline first. We have named this the First-in First-out (FiFo)-solver, as the first available batch is being assigned to the closest and first available tug. The algorithm consists of sorting the list of assignments to be planned based on their deadline, in which the assignment with the earliest deadline is the first on the list and the assignment with the latest deadline the last. This assignment is then coupled to the first available and nearest tug. This is followed by the search for available trailers to load the batches on. This is also done based on the first and closest available trailers. The decision to use FiFo is driven by the problem specification with time critical deadlines and the need for a computationally fast benchmark method. By sorting the available tasks on their deadline and subsequently assigning them in that order to available tugs generally leads to quite effective schedules (Pingen et al., 2022). Improving this greedy method by adding more reasoning to the trailer train formation was done to have a more-informed, alternative central approach instead of the MILP approach. We have named this improved method the FiFo'-solver (FiFoPrime).

The reasoning improvements in FiFo' are in the way the trailer trains are formed. Instead of iteratively picking the first and closest trailer for the next batch, more intelligence is added in the creation of the full combination of the required trailer train. Instead of evaluating trailer by trailer which one is the best to pick-up, a method was used that determined which n trailers to best pick-up at which location in one go. Moreover, trailers are not decoupled by default, only trailers that are no longer needed will be decoupled. This means that if a subsequent job requires four instead of the six trailers that were left over from the previous job, only two trailers will be decoupled. This trailer train formation method has also been used by the CoCoA implementation.

4 Use case Schiphol Amsterdam Airport and results

To evaluate the performance of the different scheduling approaches, a use case with real world data was setup. Flight data from Schiphol and baggage transport data from KLM Ground Services have been combined to a use case data set for the specified scheduling problem. To evaluate the quality of developed schedules a discrete simulation model was setup. The simulation setup is visualised in Figure 1, where the use case problem definition is provided to a scheduling method.

4.1 Key Performance Indicators

Four key performance indicators (KPIs) have been used to evaluate the performance of the scheduling methodologies on the baggage transport problem. The main objective of the baggage transport fleets is to ensure that as many bags as possible reach their flight in time. A more efficient scheduling method will result in the same fleet being able to deliver more bags in time. Hence, the performance of the tug fleet is evaluated on the number of on time bags that are delivered per hour. The total driving time of the tugs is reported in order to indicate the resource efficiency of the scheduling methods. Lastly, the average length of the trailer trains are reported. This is an indication of the amount of batches that can be combined into one ride and tells something about the efficiency of the rides. The KPIs that are computed are:

1. Number of on-time delivered bags
2. Total driving time of the tugs
3. Average length of trailer train

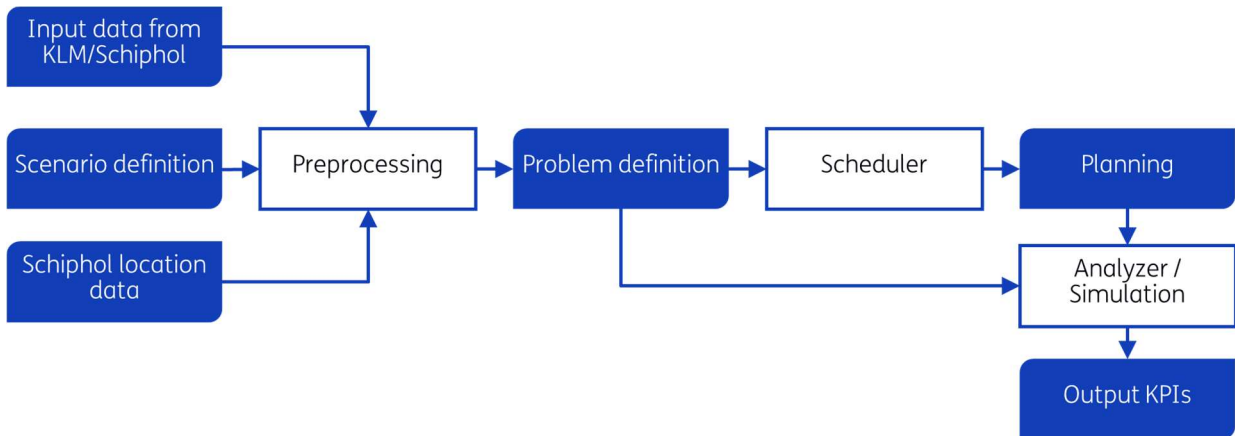


Figure 1: Schematic representation of the simulation flow

4.2 Simulation results

To evaluate the performance of the distributed scheduling method, a large problem instance with 20 tugs and 500 jobs has been simulated for the single-fleet scenario without asset sharing, and the multi-fleet scenario with asset sharing. This size of the problem instance was chosen to allow for multiple simulation runs with the distributed method, to enable evaluation of the impact of the stochasticity in CoCoA method. The stochasticity arises from the decision of which agent starts a process in case of ties. It is important to note that the created problem instance is based on the real world situation where the total tug fleet generally consists of approximately 60 tugs, which means that the 20 tugs can never deliver all bags on-time.

Providing a too large set of bags for the given fleet size is done on purpose: to analyse the impact of different schedulers on the tug fleet efficiency. In other words, this is done to

investigate how many bags can be delivered on time when applying the different scheduling methods. The analysis focusses on getting insights in the efficiency of the scheduling methods, not on determining the minimal number of required tugs or assigning all baggage to tugs and trailers.

4.2.1 Fleet Performance under different scheduling methods

The exact results are provided in Table 1 and an overview of results is given in Figure 2. On the left side of this table and figure the results for the single fleet schedule are shown and on the right side the results of the multi-fleet asset sharing schedule are shown. It shows the main indicator baggage delivered on time and the total driving time required to do this. It is emphasised again that in the results of this research we focus on the efficiency of the scheduling methods analysing the number of bags that can be transported by a limited number of tugs (not trying to deliver all baggage on time).

Figure 2 shows the average result over 100 simulation runs for the DCOP-scheduler. The spread over outcomes is plotted with the error bars. The spread is fairly small and all visualised simulation runs show an improvement compared to the FiFo-heuristics. These heuristics are fully deterministic and therefore only a single run is enough to evaluate the average performance.

These results show that the FiFo'-method outperforms the FiFo-method, as expected. This is apparent in the number of bags delivered on time, the total driving time and the average train length. The total driving time sub-KPIs of total driving time with empty/loaded trailers are higher for the FiFoPrime-schedules than for the FiFo-schedules. Combined with the drastic decrease in number of trailers used for the FiFoPrime-method, this can be explained by the decoupling/coupling-strategy for the FiFoPrime-method. The KPI for average train length is similar for the FiFo- and FiFoPrime-schedules in the single- and multi-fleet scenarios.

Table 1: Results of the single fleet and multi-fleet scheduling

	FiFo		FiFoPrime		DCOP	
	Single	Multi	Single	Multi	Single	Multi
Bags delivered on time [#]	14248	22414	16920	27380	25042	38838
Total driving time [h]	64.97	82.47	62.76	82.29	73.51	79.29
Total driving time empty trailers [h]	32.86	37.91	32.37	40.84	35.37	36.82
Total driving time loaded trailers [h]	27.98	34.50	30.39	41.46	38.13	42.46
Average train length [#]	1.49	1.57	1.52	1.60	3.75	3.39

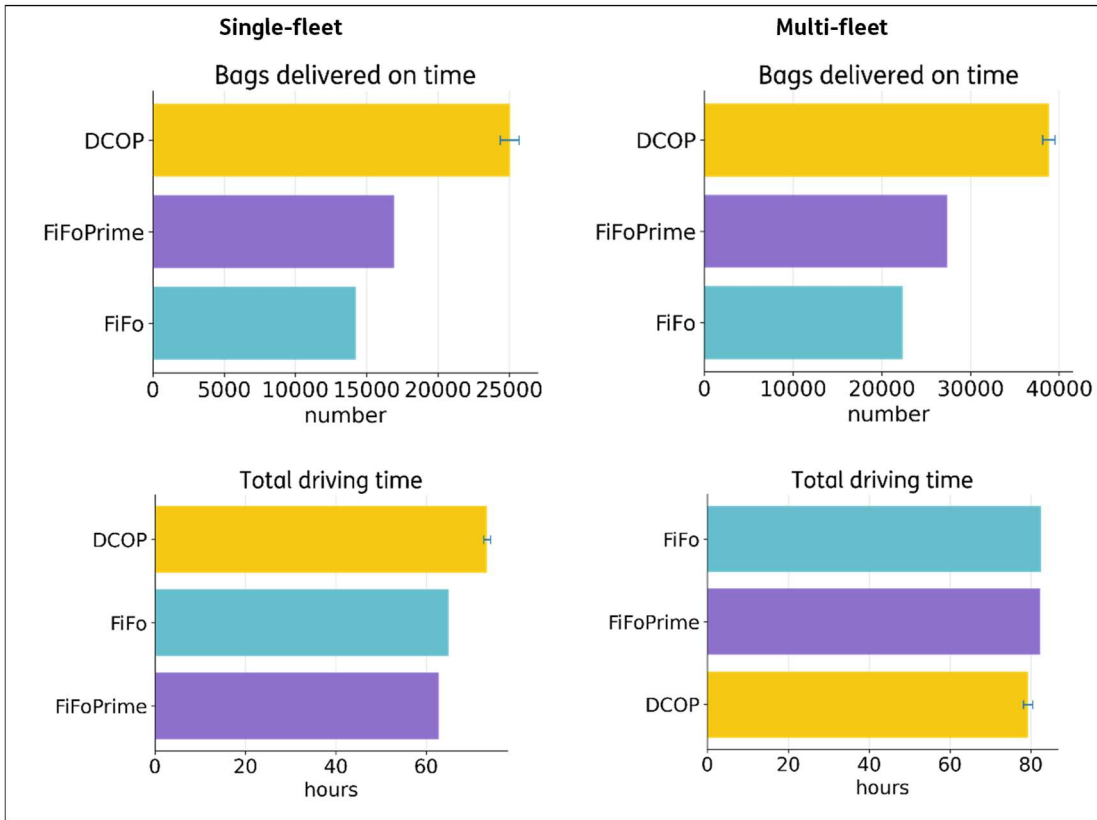


Figure 2: Comparison of single-fleet and multi-fleet scheduling results; for 20 tugs and 500 jobs, for DCOP showing the average over 100 simulation runs

The FiFo'-method is outperformed by the distributed DCOP-scheduler, with more jobs scheduled in both the single- and multi-fleet scenarios. The single-fleet DCOP-schedules perform better than both the single- and multi-fleet schedules of the FiFo-solver. When comparing the DCOP-scheduler with the FiFo'-scheduler the on-time delivery of bags is increased with 48%. Zooming in on the DCOP-solver comparison of single-fleet performance with multi-fleet performance shows that the on-time performance of bag delivery increases by 55% in case of multi-fleet collaboration compared to single-fleet operations.

The multi-fleet scenario with asset sharing allows the tugs to deliver more bags on time for all schedulers compared with the single-fleet scenario without asset sharing. Transporting more bags has a direct consequence with a growth of the total driving time of all tugs, but this increase in driving time is relatively smaller than the increase in on-time delivered bags. As shown in Table 1, we have calculated the fleet efficiency by looking at the average number of bags delivered per tug per hour to give a more direct answer to the question on what the gain of asset sharing in the multi-fleet is. The bags per tug per hour differ per control method and for single and multi-fleet scenarios. Comparison of the single fleet with multi-fleet scenarios shows a tug efficiency increase of 23% to 44%. This implies that multi-fleet asset sharing can reduce the need for tug and tug drivers significantly.

Table 2: Change in tug efficiency in number of bags handled per hour between single and multi-fleet

	FiFo		FiFoPrime		DCOP	
	Single	Multi	Single	Multi	Single	Multi
Bags delivered on time [#]	14248	22414	16920	27380	25042	38838
Total driving time [h]	64.97	82.47	62.76	82.29	73.51	79.29
Bags delivered on-time per hour	209.6	271.8	269.6	332.7	340.6	489.8
<i>Change bags per hour from single to multi-fleet</i>	+29,7 %		+23,4 %		+43,8 %	

5 Conclusions and considerations

5.1 Conclusions

In this study, we have investigated two separate fleets (incoming and outgoing) of KLM Ground Services. We have defined two different fleet setups: (1) a single-fleet scenario in which fleets are separate entities and (2) a multi-fleet scenario in which all resources are shared and the resource pool for the entire problem consists of all resources combined. Inbound and outbound jobs and resources are separated for the single-fleet problem instances: inbound jobs can only be handled by inbound tugs and similarly for outbound jobs and tugs. The inbound and outbound jobs are combined into one pool of jobs for the multi-fleet scenario, in which every tug (both inbound and outbound) can execute any available job, irrespective of its direction.

The analysis has shown that 55% more orders can be delivered in time in the case of the multi-fleet scenario compared to a single fleet scenario. If we also take the transport time into account we see that the multi-fleet scenario shows an efficiency improvement of 44% in on time delivered bags per hour per tug in the decentral approach compared to the single fleet scenario. It can be concluded that the decentral multi-fleet approach clearly outperforms the other scheduling approaches (both single fleet and central) in terms of efficiency. Besides, advantages of the decentral approach are the limited computation time compared to exact central approaches and the limited amount of data that has to be shared between the smart agents (the tugs).

The concept of merging the fleets is not novel to KLM Ground Services. It is relevant to note that there are practical factors complicating the merge of inbound and outbound fleets into one combined pool of tugs. These concern the different driver skills for inbound and outbound jobs and knowledge about the airport processes (which can be overcome quite easily) and the decoupling of inbound and outbound fleets to simplify processes and avoid dependencies (more difficult to overcome; well-known trade-off between efficiency and reliability).

Nevertheless these remarks, the results clearly show the potential benefit of sharing assets between different fleets compared to individual planning of separate fleets. This result confirms our assumption that decentral planning approaches for sharing assets leads to valuable results. Besides, the knowledge gained in this study will be used and further developed in the next step on the roadmap: decentral planning algorithms for multi-fleet multi-party situations including complex horizontal (and vertical) collaborations.

5.2 Considerations

A number of considerations are important for follow-up and other research:

- Comparison and validation with the real-world planning of in this case KLM Ground Services would be an added value to be able to determine benefits compared to current way of working.
- In the current solution a static planning is made meaning a planning for the next day. In a dynamic world like a large airport a dynamic planning is very relevant as well given all kind of last minute changes during the day. Such a dynamic planning might require other combinations of central and decentral control on different levels given amongst other limited available computation time.
- A more extensive analysis of the utility function could improve the impact of the decentral multi-fleet planning approach.

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Artificial Intelligence in Supply Chain Management: Perspectives for Integration within the Physical Internet Paradigm

Monica-Juliana Perez¹, Tarik Chargui¹ and Damien Trentesaux¹

1. LAMIH, UMR CNRS 8201, Université Polytechnique Hauts-de-France, 59313, Campus Mont Houy, France

Corresponding author: Monica.PerezMorales@uphf.fr

Abstract: This study conducts a scoping literature review to examine the application of Artificial Intelligence (AI) in Supply Chain Management (SCM) and explores its potential integration within the Physical Internet (PI) paradigm. Analyzing 48 empirical articles published between 2020 and 2025, the review identifies five thematic clusters: demand forecasting, transportation optimization, terminal operations, risk management, and urban logistics. Results demonstrate that although AI enhances efficiency and decision-making across supply chains, current implementations are predominantly siloed and lack the interoperability required for PI adoption. The articulation between SCM, AI, and PI is made explicit by highlighting how modular, scalable, and decentralized logistics infrastructures demand intelligent systems. The study reveals critical research opportunities to develop modular, explainable, and sustainable AI models aligned with PI principles, thereby paving the way for autonomous, hyperconnected, and environmentally responsible logistics networks.

Keywords: Artificial Intelligence, Supply Chain Management, Physical Internet, Optimization, Sustainability, Scoping Literature Review.

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

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

1 Introduction

The Artificial intelligence (AI) has emerged as a transformative agent in the field of supply chain management (SCM), significantly reshaping the operations that take place in supply chains globally. AI technologies, such as machine learning, predictive analytics, autonomous systems, and natural language processing, are progressively being integrated into SCM processes for the purpose of optimizing operations, improving decision making, and increasing efficiency (Cannas et al., 2024; Singh Chadha & Venkatadri, 2024). Numerous studies have reported successful applications of AI in SCM in various tasks, such as demand forecasting, inventory management, purchasing, logistics, and risk management, achieving significant improvements in operational efficiency and cost reductions (Gedam et al., 2023; Shahzadi et al., 2024). In this context, the integration of AI into SCM is no longer perceived merely as a passing trend, but as a strategic imperative for organizations to remain competitive in today's dynamic environments (Gedam et al., 2023).

Despite these advances and benefits, the widespread adoption of AI faces structural barriers in traditional supply chains. There are persistent challenges related to data quality, technological complexity, cybersecurity, and organizational resistance to change (Hangl et al., 2023). Legacy

and rigid technology infrastructures, in particular, make it difficult to integrate AI solutions with existing systems, creating friction when incorporating new digital tools (Shrivastav, 2022). In addition, it has been observed that data is often siloed within organizational departments, making it difficult to access and integrate information (Pan et al., 2021). The fragmented and multi-actor nature of traditional logistics networks implies disparate and poorly interoperable data sources (Delgado et al., 2025). This lack of interoperability, resulting from inconsistent technology standards and heterogeneous systems, impedes the flow of information along the chain and makes it difficult to fully leverage AI capabilities. These structural barriers, imposed by the very nature of traditional logistics networks, constitute a significant obstacle to AI-driven transformation in the context of conventional SCM (Shrivastav, 2022). This challenge underscores the need to rethink the architecture of supply chains to facilitate the effective integration of AI into logistics management. These limitations highlight the need for a more adaptive logistics infrastructure, leading to the emergence of the Physical Internet (PI) paradigm.

In this context, the PI paradigm emerges as a disruptive vision with the potential to overcome the structural limitations of current supply chains (Cortes-Murcia et al., 2022; Safwen & Németh, 2021). The PI proposes an open, hyper-connected, and modular logistics system, inspired by the Internet's operational principles (Montreuil, Ballot, et al., 2012). In this paradigm, goods are transported and stored through interoperable networks using standardized containers and common protocols. According to Montreuil et al., (2012) PI is defined as "an open global logistics system based on physical, digital and operational interconnectivity through encapsulation, interfaces, and protocols." The underlying philosophy of hyperconnectivity is predicated on the universal integration of all actors, facilities, and means within the supply chain. The concept of modularity, on the other hand, is exemplified by the implementation of interchangeable standard containers and components, thereby facilitating logistics systems that are more efficient and flexible, akin to the plug-and-play functionality of the Internet (Meller et al., 2012). This paradigm aspires to create logistics networks that are as seamless and transparent as the digital Internet, thereby enabling the frictionless exchange of goods and information across multiple organizations.

At a conceptual level, the PI's principles align closely with the requirements of AI in SCM. The proposed hyper-connected and open logistics ecosystem would generate substantial volumes of integrated data and end-to-end visibility, which are ideal conditions for applying machine learning algorithms and predictive analytics to optimize network-wide decisions. The modularity and standardization of IP would simplify the integration of autonomous systems (e.g., intelligent vehicles or robots) operating in a coordinated manner at different nodes of the chain (Gumzej, 2023). The integration of AI with a PI-style infrastructure holds great promise in enhancing the intelligence, agility, and comprehensive optimization of supply chains. This convergence unites the capabilities of digital intelligence with a physical network designed for interoperability. However, it is important to acknowledge that academic research integrating AI into the PI framework in a consolidated manner is still in its infancy.

Recent contributions, as Singh Chadha & Venkatadri, (2024) and (Münch et al., 2024), have initiated the exploration of the intersection between AI and PI. Singh Chadha and Venkatadri provided systematic analysis focusing exclusively on AI applications within the PI framework. Similarly, Münch et al. offered a comprehensive bibliometric mapping of the PI research landscape, highlighting the emergence of AI among other enabling technologies but without performing an in-depth analysis of AI's operational integration into PI systems. While these studies represent important milestones, they approach AI either as a direct contributor to PI implementation without broader SCM context (Singh Chadha and Venkatadri), or as one technological trend among many without detailed articulation of its transformative mechanisms.

This paper aims to bridge this gap by conducting a Scoping Literature Review to map the current landscape of AI applications in SCM and to explore how these developments align with, and can support, the implementation of the PI paradigm. While prior literature explores AI and the PI independently, this paper aims also to synthesize both domains through a systematic review, identifying synergies and future research opportunities.

The remainder of this paper is organized as follows: Section 2 outlines the key concepts related to AI in SCM and the PI framework. Section 3 details the methodology used to conduct the systematic review. Section 4 presents and analyzes the results. Section 5 discusses the implications of the findings. Finally, Section 6 concludes the paper and suggests avenues for future research.

2 Key concepts

This section introduces two foundational concepts, Supply Chain Management and the PI, that underpin the integration of artificial intelligence into next-generation logistics systems.

2.1 Evolution Supply Chain Management (SCM)

In recent decades, Supply Chain Management (SCM) has transitioned from a linear, functionally isolated discipline to a dynamic and system-wide coordination mechanism that governs the flow of goods, information, and value across interconnected global networks (Ivanov, 2022; Fang, Fang, Hu, & Wan, 2022). This evolution reflects a paradigmatic shift in how firms conceptualize and operationalize their logistics and production systems, moving from cost-centered, reactive models to proactive, resilient, and customer-responsive architectures (Büyüközkan & Göçer, 2018; Núñez-Merino, Maqueira-Marín, Moyano-Fuentes, & Castaño, 2022). SCM now encompasses the integration of strategic planning, real-time execution, and continuous adaptation across diverse actors, from raw material suppliers to end-users, within a complex, and often geographically dispersed, ecosystem (Kajba, Jereb, & Obrecht, 2023).

Modern SCM is not only concerned with operational efficiency but also with the alignment of supply chain activities with broader business goals, including sustainability, agility, and digitalization. This requires the orchestration of upstream and downstream processes, such as demand forecasting, procurement, production scheduling, transportation management, inventory control, and reverse logistics (Ma, Zhang, You, & Tian, 2025). The growing volatility of global markets, together with environmental and geopolitical disruptions, has revealed the limitations of rigid, siloed supply chains and has underscored the urgency of developing intelligent, interconnected systems capable of autonomous response and systemic resilience (Bui et al., 2021; Ivanov, 2022).

While modern SCM emphasizes integration, agility, and digital transformation, it remains constrained by traditional logistics infrastructures. The PI emerges as a potential solution to these constraints.

2.2 Physical Internet paradigm

The Physical Internet (PI) constitutes a transformative logistics paradigm inspired by the digital Internet's architecture and principles. Initially conceptualized by Montreuil, Ballot, et al., (2012) the PI reimagines the movement and management of physical goods through open, standardized, and interconnected networks. It seeks to overcome the inefficiencies of conventional logistics systems, which are often siloed, rigid, and asset-centric. Instead, the PI proposes an infrastructure where modular logistics units (π -containers) move seamlessly across interoperable networks (π -nodes and π -handlers), coordinated through universal routing protocols and real-time data synchronization, mirroring how data packets circulate through the Internet.

At the heart of the PI is a commitment to systemic modularity, decentralization, and dynamic orchestration. Its operational logic is rooted in standardized physical elements, such as PI-transporters, conveyors, and containers, interconnected through intelligent hubs and governed by protocols that enable continuous flow optimization. This structural logic fosters asset-sharing, multimodal transport efficiency, and collaborative logistics, while supporting objectives such as environmental sustainability and economic resilience. Rather than functioning as isolated supply chains, PI-based systems operate as open, distributed ecosystems capable of self-organization and adaptive reconfiguration.

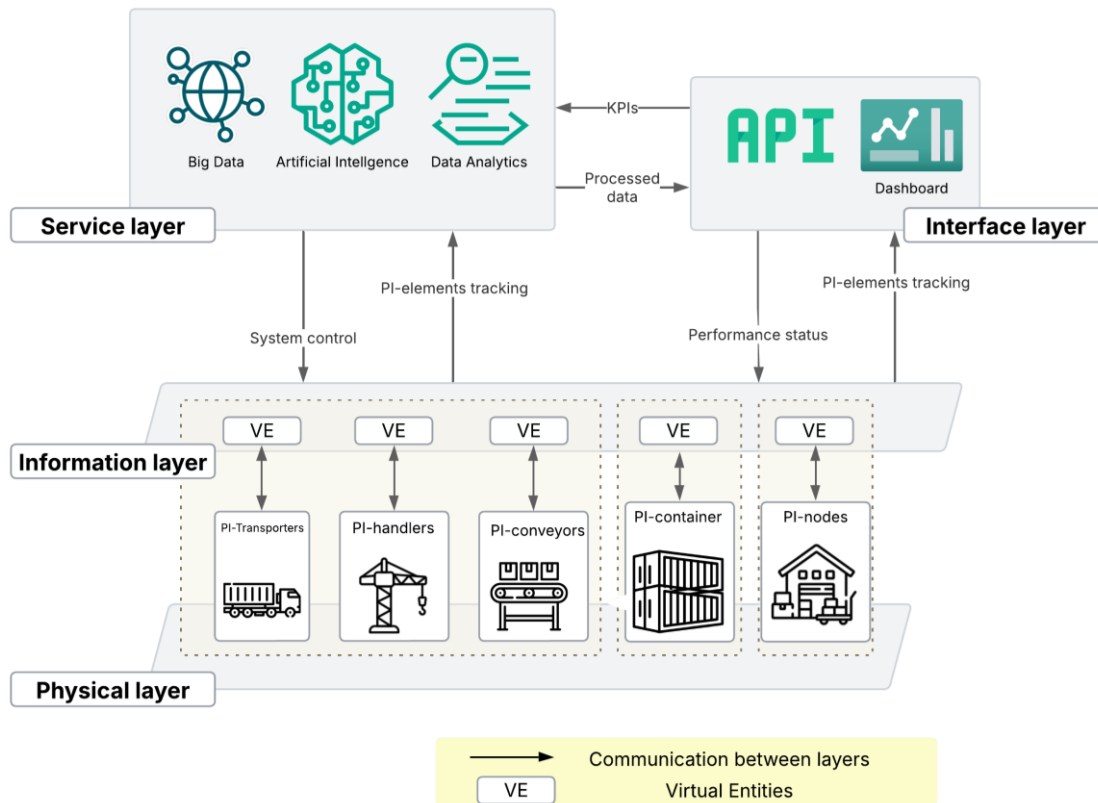


Figure 1: Functional architecture of PI

A defining feature of the PI is its layered architecture, which mirrors the protocol stack of the digital Internet and enables separation of concerns between physical operations and intelligent services (see Figure 1). The four core layers include: (1) the Physical Layer, where tangible logistics entities operate; (2) the Information Layer, which encapsulates these physical components as Virtual Entities (VEs) and ensures traceability and control; (3) the Service Layer, where advanced functions—such as AI-driven forecasting, system control, and data analytics—are executed; and (4) the Interface Layer, which mediates access through APIs and dashboards for human and machine agents. Within this layered model, AI plays a transversal role, particularly in the Service Layer, by enabling cognitive automation, optimization of routing and scheduling, and real-time orchestration across the network. The Interface Layer standardizes the interaction with external stakeholders and supports transparency, monitoring, and real-time decision-making. Together, these layers enable a flexible, intelligent, and scalable logistics network where physical and digital elements are fully synchronized.

3 Scoping Literature Review

To address the objectives of this study, a Scoping Literature Review was conducted. This methodological approach is particularly suited for emerging and interdisciplinary fields, as it

allows for the systematic mapping of existing research, the identification of conceptual boundaries, and the recognition of knowledge gaps (Arksey & O'Malley, 2005). In this case, the scoping review method was selected to capture the breadth and diversity of AI applications in SCM and to explore how these applications intersect with the principles of the PI. Given the exploratory nature of the topic and the fragmented state of current literature linking AI and PI, this approach supports synthesis that responds directly to the three guiding research questions: (1) What are the main AI applications in SCM? (2) How do these applications align with PI principles? and (3) What challenges and gaps exist in AI adoption for PI-enabled supply chains? The scoping review provides a foundation for identifying both established practices and emerging research directions to guide the design and implementation of intelligent, modular, and sustainable logistics systems aligned with the PI paradigm.

To ensure the relevance and thematic coherence of the literature reviewed, the scoping study employed a structured Boolean query approach. The query was designed by clustering key terms, as shown in Table 1, into three conceptual domains: (1) AI techniques, (2) supply chain processes, and (3) operational applications. This structure allowed the search to capture a wide but thematically consistent body of research at the intersection of AI and SCM. By combining clusters using logical "AND" operators, the query retrieved only those articles that addressed all three dimensions simultaneously. Additional filters were applied to restrict the results to peer-reviewed journal articles published in English between 2020 and 2025 and within relevant disciplines.

Cluster	Keywords Included
1. AI Techniques	"artificial intelligence", "AI", "machine learning", "deep learning", "neural network*", "computational intelligence"
2. Supply Chain Scope	"supply chain*", "supply chain management", "SCM", "supply chain", "logistics", "procurement", "distribution", "Physical Internet"
3. Operational Functions	"optimization", "management", "forecasting", "planning", "automation", "use case*", "implementation", "adoption", "integration"

Table 1: Search terms

A clearly defined set of inclusion and exclusion criteria was applied throughout the review process. Studies were considered eligible if they explicitly defined or empirically evaluated an AI application and focused on one or more core supply chain functions, such as procurement, logistics, inventory, or distribution. Articles were excluded if they were editorials, conference proceedings, or tertiary reviews, or if they lacked a clear methodological foundation, adopted a non-supply chain perspective, presented opinion-based arguments without empirical grounding, or treated AI as a secondary or peripheral topic. This filtering strategy ensured the selection of literature that directly addressed the central research questions of the study.

The selection process was carried out in two stages. In the first stage, titles, abstracts, and keywords of all retrieved articles were screened and categorized as included, excluded, or "uncertain" based on the predefined criteria. In the second stage, the full texts of all articles marked as included or uncertain were thoroughly reviewed. At this point, each study was reassessed to confirm its eligibility, and a definitive inclusion decision was made. Studies without accessible full texts were excluded from the final selection. This two-step screening process ensured consistency and transparency in the identification of relevant contributions to the field. Figure 2 provides a visual summary of the article selection procedure, following the structure of the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework.

4 Results and analysis

After applying the selection filters, the final dataset of relevant studies was systematically analyzed. The following section presents the results and key patterns derived from this

literature, organized thematically. The systematic literature review underpinning this study was conducted across two major scientific databases, Scopus and IEEE Xplore. After applying defined inclusion and exclusion criteria a total of 48 articles were retained for detailed analysis.

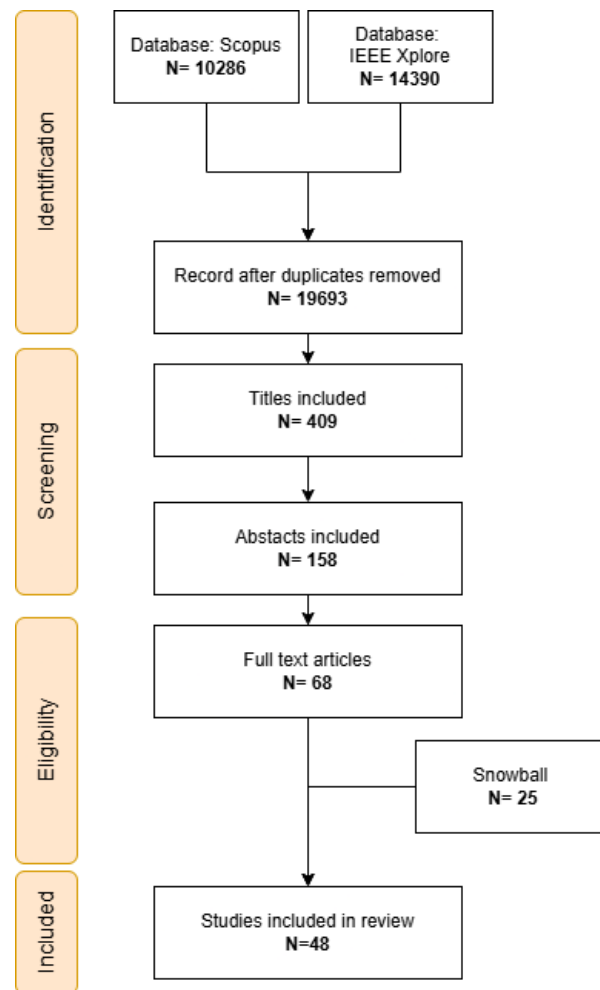


Figure 2: Literature review process

The following sections are organized around the three research questions guiding this review. Section 4.1 identifies and categorizes the main AI applications in SCM into thematic clusters. Section 4.2 evaluates how these applications align with the core principles of the PI, such as modularity, decentralization, and interoperability. Section 4.3 discusses the key challenges and research gaps that hinder AI's integration into PI-enabled supply networks.

4.1 RQ1: What are the Main AI Applications in SCM?

To map the AI applications in SCM, the literature was analyzed and organized into five major thematic clusters:

- Demand and Throughput Forecasting, encompassing predictive models for flow estimation and capacity planning;
- Transportation and Route Optimization, focused on AI-driven routing, scheduling, and multi-modal coordination;
- Terminal and Warehouse Operations, covering applications related to stacking, congestion control, and facility-level decision-making;
- Disruption and Risk Management, which includes models for predictive maintenance, delay propagation, and safety analytics; and

- Urban Mobility and Facility Identification, reflecting studies that apply AI to urban transport dynamics, commuting patterns, and logistics infrastructure mapping.

The next subsections go into further explanation about the debate areas.

4.1.1 Demand Forecasting and Predictive Analytics

AI is increasingly applied in SCM to enhance demand forecasting and throughput estimation. Machine learning (ML) and deep learning (DL) models have demonstrated superior predictive accuracy compared to traditional methods, particularly in dynamic and time-sensitive operational contexts. Ribeiro et al., (2022) apply ensemble learning models, such as XGBoost and random forests, to forecast short-term warehouse energy consumption, improving inventory and energy management responsiveness. Similarly, Mamede et al., (2023) show that Long Short-Term Memory (LSTM) networks outperform classical ARIMA models in predicting transportation demand across Brazilian distribution centers.

Beyond short-term operational gains, AI forecasting is also supporting strategic decision-making. De Nailly et al., (2024) employ deep probabilistic models to estimate pedestrian flows in multimodal hubs, while Cuong et al., (2022) integrate ARIMA with artificial neural networks (ANN) to model seaport throughput variations post-COVID-19.

4.1.2 Transportation & Route Optimization

DL and reinforcement learning (RL) models dominate recent developments, enabling more effective route planning and rescheduling compared to traditional heuristics. For instance, Ding et al., (2023) propose a deep RL model for disruption recovery in airline operations, while Guo et al., (2022) apply a convolutional neural network (CNN)-BiLSTM architecture to predict freight train travel times with high temporal accuracy. Aljanabi et al., (2024) further enhance multimodal travel time estimation by combining singular value decomposition with CNNs and recurrent neural networks, and Pineda-Jaramillo, (2023) demonstrates the utility of gradient boosting models like CatBoost in identifying delay causes in European freight rail networks.

In parallel, AI is increasingly supporting strategic infrastructure forecasting. Asadi et al., (2024) compare physical models such as SWAT+ with ML approaches, including support vector regression and neural networks, for streamflow forecasting, contributing to resource-aware transport planning. Ensemble methods (Aljanabi et al., 2024) and transfer learning strategies (Guo et al., 2024) are also gaining attention to enhance prediction performance under cross-domain and data-scarce conditions.

4.1.3 Terminal and Warehouse Operations

The application of AI to terminal and warehouse operations has become a prominent stream within SCM, focusing on optimizing spatial layout, operational efficiency, and infrastructure sustainability in containerized environments. ML and optimization models are increasingly used to support decision-making in container stacking, berth scheduling, and yard resource allocation. Ambrosino & Xie, (2024) propose a hybrid approach integrating spectral clustering with tactical optimization to reduce yard congestion and container rehandling. Similarly, Zhang, (2023) introduces a hybrid architecture combining dynamic programming with self-attention-based neural networks to enhance stacking decisions, achieving superior performance over classical heuristics. In the domain of congestion management, Jahangard et al., (2025) develop an integrated ML-optimization framework to forecast port congestion and improve container flow management, while Yasuda et al., (2024) apply real-time tracking data within ML models to support operational decision-making.

4.1.4 Disruption and Risk Management

Managing risk and disruption has become a frontier AI application in modern, interconnected supply chains. Recent research increasingly emphasizes predictive models and robust optimization frameworks as essential tools for anticipating failures, supporting contingency

planning, and ensuring operational continuity during crises. For instance, Wang et al., (2022) employ gradient boosting techniques to forecast broken rail incidents in U.S. freight networks, providing a basis for predictive maintenance planning. In high-speed rail systems, Huang, Lessan, et al., (2020) develop a Bayesian network model capable of forecasting delay propagation with over 90% accuracy, supporting proactive disruption management.

AI applications are also enhancing operational safety and situational awareness. Atak and Arslanoğlu, (2022) propose supervised ML models to predict marine terminal accidents using operational and contextual datasets, enabling improved risk classification for port authorities. Similarly, Alvarellos et al., (2021) develop an ML-based model to forecast moored ship movements under varying environmental conditions, providing early warnings to prevent collisions and structural damage.

4.1.5 Urban Mobility and Facility Identification

In the context of last-mile delivery and transport node design have become important areas for AI applications in SCM. Recent models focus on forecasting travel times, analyzing commuter flows, and reorganizing spatial infrastructure to enhance logistics performance. Nejadshamsi et al., (2025) propose a hybrid Graph Convolutional Network–Graph Attention Network model to predict commuting flows across urban networks, improving the adaptability of last-mile logistics. De Beer & Joubert, (2024) utilize GNSS-vehicle data and supervised learning to map the evolution of freight facility locations, offering insights into urban logistics infrastructure dynamics. Pei & Yu, (2023) introduce the PAC algorithm to reconfigure public transport station placements based on mobility patterns, achieving over 20% improvement in accessibility and modular layout efficiency. Having mapped the current landscape of AI applications in SCM, the next subsection evaluates how these innovations align with the core principles of the PI.

4.2 RQ2: How do Current AI Applications Align with Physical Internet Principles?

The PI paradigm is built on four foundational operational principles: modularity, interoperability, decentralization, and openness. To realize PI, logistics systems must be able to function through standardized, modular units; enable real-time information and asset sharing across independent actors; operate via decentralized control mechanisms; and foster open, network-wide collaboration. Certain AI applications demonstrate strong potential to support key PI principles, particularly in enhancing responsiveness and system reactivity. AI-driven forecasting models (de Nailly et al., 2024; Ribeiro et al., 2022) significantly improve real-time demand prediction and throughput estimation, contributing to the dynamic adaptability needed in modular, hyperconnected logistics systems. Similarly, advances in facility reconfiguration, such as the PAC algorithm for transport node optimization (Pei & Yu, 2023), embody modular thinking by enabling infrastructure elements to adapt dynamically to changing mobility patterns. These developments align well with PI's emphasis on modular, flexible network operations.

However, despite these promising areas, the majority of current AI applications exhibit only partial alignment with the full operational vision of the PI paradigm. Transportation and routing optimization models (Ding et al., 2023; Guo et al., 2022) improve operational efficiency under dynamic conditions, reinforcing adaptability at the network level. However, these models often rely on centralized control structures and full system visibility, conflicting with PI's decentralization objectives. Similarly, container terminal optimization frameworks (Ambrosino & Xie, 2024; Jahangard et al., 2025) enhance local modular performance but typically optimize isolated facilities without standardizing interfaces for cross-terminal collaboration, limiting interoperability across the broader logistics network. While some AI applications support core

PI principles, significant challenges and gaps must be addressed to fully enable PI-driven supply networks.

4.3 RQ3: What challenges and gaps exist in AI adoption for PI-enabled supply chains?

Thematic clusters examined in Section 4.1 exhibit common strengths, but also systemic limitations when assessed against PI principles. A common limitation across all clusters is the predominance of firm-centric, siloed architectures. The majority of AI implementations are optimized for single organizations or closed networks, relying on proprietary data, internal control systems, and localized optimization objectives (Ambrosino & Xie, 2024; Mamede et al., 2023).

Interoperability also remains a major unresolved challenge. Although many AI models demonstrate strong performance within bounded domains, their designs often lack standardized interfaces or open communication protocols necessary for seamless integration. For instance, container terminal optimization systems (Jahangard et al., 2025; Zhang, 2023) and last-mile urban logistics models (Nejadshamsi et al., 2025) typically operate as isolated solutions, optimized for specific environments but disconnected from broader logistics ecosystems. This structural limitation severely restricts the scalability, flexibility, and cross-actor collaboration required for PI-enabled networks (Singh Chadha and Venkatadri, 2024).

Another systemic gap concerns the modularity of decision-making. Although emerging works on dynamic facility placement (Pei & Yu, 2023) and modular stacking optimization (Zhang, 2023) suggest a move toward modular thinking, most AI systems still assume fixed optimization boundaries and stable network topologies, rather than embracing reconfigurability at the decision-making level. This undermines the core principle of dynamic modularity critical to PI architecture.

Finally, governance, transparency, and explainability issues in AI models remain underdeveloped across SCM applications. While predictive maintenance and risk forecasting frameworks (Wang et al., 2022; Atak and Arslanoğlu, 2022) demonstrate high technical potential, few incorporate explainable AI methods or ethical data-sharing mechanisms, which are essential for building trust among multiple logistics actors in an open, decentralized PI network.

Future research should prioritize the development of modular, interoperable AI systems that can be embedded within distributed infrastructures and π -hubs, supporting seamless communication, reusability, and system-wide orchestration across diverse operational environments. Sustainability-focused AI design also remains an underexplored frontier. Although select studies have incorporated environmental criteria, such as emission reduction and circular maintenance planning, these considerations are rarely embedded into the core of AI optimization strategies. There is a timely opportunity to advance models that optimize not only for cost or time, but also the inclusion of social and environmental. This would directly reinforce the long-term vision of the PI as a sustainable, resource-aware logistics system.

5 Conclusions

This study has explored the current landscape of AI applications in SCM and examined how these developments align with the foundational principles of the PI. Through a structured scoping literature review, 48 empirical studies were identified, categorized into five thematic clusters: demand forecasting, transportation optimization, terminal operations, risk management, and urban logistics. Each cluster reflects distinct areas where AI is actively enhancing operational efficiency, decision-making, and system responsiveness across the supply chain.

The findings demonstrate that AI is being widely implemented to support key SCM functions such as forecasting, routing, stacking, and disruption detection. These applications increasingly rely on advanced machine learning, deep learning, and hybrid architectures to achieve higher accuracy and adaptability in dynamic logistics environments. Notably, several contributions showcase sophisticated models with measurable impacts on real-world logistics performance. While many of these models are not explicitly designed for PI contexts, they embody principles such as modularity, interoperability, and decentralization, indicating a latent compatibility between current AI capabilities and the PI paradigm.

However, the review also reveals important challenges and gaps that must be addressed to fully realize the potential of AI in PI-enabled supply chains. The majority of existing AI applications are highly localized, often relying on data from specific terminals, regions, or organizations. There is limited evidence of scalable, interoperable AI solutions that can operate across heterogeneous logistics networks or coordinate autonomously across multiple nodes. Additionally, explainability, sustainability, and governance remain underexplored dimensions in the integration of AI with logistics infrastructure.

In light of these findings, future research should focus on developing AI architectures that are not only accurate but also modular, transferable, and compatible with decentralized logistics environments.

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A Technical Blueprint for the Physical Internet

Philippe Michiels, Dries Van Bever, Birger Schrevens

Imec, Leuven, Belgium

philippe.michiels@imec.be

Abstract: *This paper presents a comprehensive technical blueprint for the Physical Internet (PI), consolidating years of research across multiple projects (Michiels et al., 2024; Schrevens et al., 2023). By leveraging data space architecture (Nagel et al., 2021), and integrating PI concepts we introduce a full-stack foundation that addresses key challenges in trust, security, logistics service discoverability, and operational collaboration in decentralized logistics networks. This blueprint provides a technical framework for realizing a truly decentralized, interoperable, and automated logistics ecosystem, reducing inefficiencies and enabling seamless coordination across transport networks.*

Keywords: *Physical Internet, Reference Architecture, Decentralization, Data Spaces, Technical Interoperability*

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1 Introduction

Global logistics remains fragmented, with many processes still coordinated via non-automated channels such as email, spreadsheets, and paper documents. Despite the rise of digital platforms, interoperability between logistics stakeholders remains limited, often requiring costly custom integrations and bilateral agreements. These inefficiencies hinder real-time coordination, increase administrative overhead, and reduce network resilience. The Physical Internet (PI) offers a vision for logistics inspired by the Digital Internet: a decentralized, interoperable system where logistics actors seamlessly publish, discover, and execute transport services. However, operationalizing this vision requires more than high-level principles – it demands a standardized, modular architecture to support secure and scalable collaboration between diverse systems.

Problem Statement: A major barrier to the realization of the PI is the absence of an interoperable connectivity layer that enables secure, decentralized data sharing, trust management, service matchmaking, and process synchronization – without reliance on centralized platforms or bespoke integration workarounds.

Contribution: This paper introduces the Physical Internet Connector (PI Connector) Framework: a standards-based gateway that provides logistics stakeholders with a unified interface to connect with the PI network. Based on data space principles, it addresses six key challenges:

1. Seamless connectivity through modular integration,
2. Trust and identity via decentralized credentials,
3. Dynamic logistics service discoverability,
4. Policy enforcement using machine-readable agreements,
5. Data Exchange,
6. Decentralized orchestration of logistics processes via event-driven messaging.

Related Work: Recent efforts to promote data sovereignty and interoperability in logistics have emerged through data space initiatives such as (iSHARE Foundation, 2024), (Catena-X, 2024), and SYTADEL (Schrevens et al., 2023). These initiatives enable decentralized data sharing via standardized connectors and trust frameworks. However, their focus remains largely on secure data exchange and identity management, with limited support for service discoverability or cross-organizational process execution. Most related work, including the work in PILL (Michiels et al., 2024) and SYTADEL, have resulted in proof-of-concepts with no real quantitative results. Real-life quantitative assessments require larger scale experiments and equally scalable infrastructure. This paper provides a blueprint for such infrastructure.

Standards for semantic interoperability, including DCAT and Linked Data Event Streams (Van Lancker et al., 2021), provide a basis for distributed service publication and synchronization (Nagel et al., 2021; Van Gessel & Hofman, 2023). Yet, their application in logistics is still emerging, and no broadly adopted vocabularies yet support the formal description of logistics services based on PI concepts (e.g., nodes, movers, capabilities).

Existing orchestration tools, such as transport management systems and workflow engines, remain predominantly centralized. Early decentralization efforts—including the FeDeRATED node prototype (Hofman, n.d.) and modular ontologies for event sharing (Bouter et al., 2022)—are promising but lack end-to-end integration across discovery, contracting, and execution. Foundational PI research has defined essential concepts (Montreuil et al., 2010), and capability-based routing has been explored (Cassan et al., 2023), but a unified, full-stack technical architecture remains unaddressed. This paper aims to fill that gap.

2 Technical Architecture Overview

Realizing the PI requires seamless interoperability between independent logistics systems. Enterprise integration practices show that component-based architectures significantly reduce the cost and complexity of system integration. Combined with enterprise interoperability, these principles enable scalable, low-friction collaboration across heterogeneous environments. Data spaces adopt both principles, providing a decentralized foundation for secure data and service exchange while preserving organizational autonomy – making them a natural architectural basis for the PI Connector.

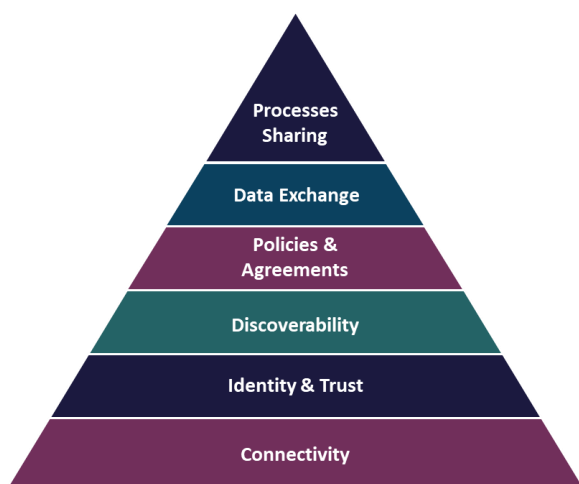


Figure 1: The layered architecture of the PI blueprint, where each layer addresses a key concern.

The six layers of our blueprint address six key concerns that are important to address in relation with interoperable connectivity for the PI.

Connectivity: the PI connector acts as a gateway for data and service integration. It handles message routing, IAM and exposes standardized interfaces for publishing services and receiving updates.

Identity & Trust: This layer governs authentication and access control based on open standards. Trust is established through federated credential issuance and validation, without reliance on a central authority.

Discoverability: Services and capabilities are published using machine-readable metadata. Federated services enable dynamic discovery of logistics services based on filters like geography, transport mode, and capability.

Policies & Agreements: Machine-readable policies define access and usage rights for both data and services. These policies can govern for instance how data is shared, under what conditions, and between which business roles (consignor, consignee, logistics service provider, ...).

Data Exchange: This layer facilitates seamless exchange of data, applying any necessary policies, according to pre-agreed protocols. For instance, the controlled publication of compliance artifacts such as CMRs, Dangerous Goods Declarations, etc. can be facilitated at this level.

Process Sharing: At the top layer, logistics processes are coordinated via event-driven workflows. Messages represent state transitions in shared processes, enabling distributed orchestration and real-time status updates. A business process is executed by exchanging such messages that are validated by the connector. These messages can in turn trigger updates in connected processes.

This architecture provides a composable, extensible framework that aligns with key PI concepts (Pan et al., 2017) and with operational realities in logistics, bridging the gap between data sharing and process execution. In the following sections, we detail each architectural layer, beginning with the PI Connector as the entry point to the PI and progressing through the supporting mechanisms for trust, service discoverability, policy enforcement, and decentralized orchestration.

3 Physical Internet Connectivity

At the core of the proposed architecture is the PI Connector – a modular, standards-based gateway that enables logistics actors to interface with the Physical Internet in a secure, scalable, and interoperable manner. The PI Connector builds on the data space connector model – of which a growing number of implementations are available (Dam et al., 2023; Giulia Giussani & Steinbuss, 2023), extending it with semantics and functionalities specific to logistics, making it the primary enabler of Physical Internet compliant connectivity.

Designed around the principles of openness, modularity, and decentralization, the PI Connector encapsulates key interoperability concerns that traditionally require costly, bespoke system integration. By providing out-of-the-box support for identification, authentication, authorization, data exchange, service publication, and event communication, it allows organizations to connect with minimal effort – removing the need for manual configuration, hardcoded APIs, or bilateral agreements.

The PI Connector adheres to open standards such as:

- OAuth2 and OpenID Connectⁱ for federated identity and access control,
- W3C Decentralized Identifiersⁱⁱ (DID) for issuer independent identities,
- W3C Verifiable Credentialsⁱⁱⁱ for portable trust assertions,
- DCAT^{iv} and LDES^v for service metadata publication and discovery,
- ODRL^{vi} for expressing access and usage policies,
- JSON-LD^{vii} and RDF for semantic data interoperability.

By abstracting these technical responsibilities into a standardized gateway, the PI Connector enables stakeholders to focus on their core logistics capabilities rather than on integration complexity. It acts as a single point of interaction with the PI network – allowing participants to publish logistics capabilities, discover services, negotiate policies, and orchestrate processes without relying on centralized intermediaries. In the following sections, we elaborate on how the PI Connector implements trust mechanisms (Section 4), supports federated service discovery (Section 5), enforces policy constraints (Section 6), and enables decentralized orchestration of logistics processes (Section 7). We do not go into much detail on the data sharing layer itself, since this is a standard feature of data spaces (Otto et al., 2019).

4 Security and Trust

Trust is essential for collaboration in decentralized logistics ecosystems. Without a central authority to mediate interactions, stakeholders must rely on verifiable, machine-readable credentials to authenticate participants, authorize access, and ensure data integrity. The PI Connector leverages open standards for Self-Sovereign Identity (SSI) to support these functions in a federated manner.

Central to this trust framework are Decentralized Identifiers (DIDs) and Verifiable Credentials (VCs), both defined by the W3C. DIDs provide globally unique, cryptographically verifiable identities independent of central registrars. VCs are tamper-evident digital statements issued by trusted parties—such as carriers, customs authorities, or insurers—that can be selectively disclosed and independently verified.

This model eliminates the need for platform logins or paper documentation. Instead, stakeholders carry portable credentials across systems, enabling secure access control, regulatory compliance, and frictionless cross-organizational workflows.

Several open-source implementations support the integration of DIDs and VCs in logistics:

- **walt.id** – a modular SSI framework supporting credential issuance and wallet integration.
- **DIDKit** – a cross-platform toolkit for working with DIDs and VCs across multiple formats.
- **EBSI** – the EU’s blockchain infrastructure, piloting VCs in cross-border services including customs and transport.

Together, these tools allow PI Connectors to issue, present, and verify credentials using open standards—enabling interoperable, trust-based communication at scale.

5 Discoverability

A key promise of the Physical Internet is network transparency – the ability for logistics actors to discover available transport services across organizational boundaries. Traditionally, such service matchmaking in logistics has relied on centralized intermediaries, creating barriers to market access and limiting operational flexibility. A successful PI-implementation requires a robust mechanism to publish and discover logistics services in a decentralized, machine-readable way.

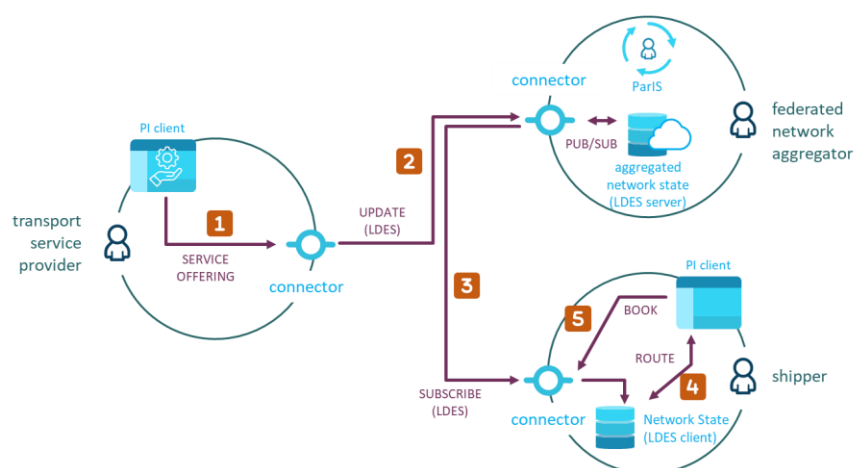


Figure 1: In Federated Logistics Network Discoverability, LSPs publish their services(1) which get aggregated in a Federated Network Aggregator service (2) that Logistics Stakeholders can subscribe to (3) and allows the scalable discoverability of routes (4) before eventually selecting an optimal route (5).

The data space paradigm offers a strong foundation for this. In data spaces, discoverability is supported through federated service catalogs using open standards such as DCAT – a Data Catalog Vocabulary. These allow participants to publish metadata about their services without relying on central registries, while still enabling network-wide visibility and semantic search.

Applied to logistics, these principles allow transport providers, terminal operators, and other stakeholders to publish their available services – such as transport modes, handling capabilities, or storage options – via the PI Connector. These services can be described using metadata covering location, availability, cargo types, and business constraints. Crucially, they can be expressed using the building blocks of the Physical Internet, such as PI-nodes, PI-movers, and PI-capabilities (Montreuil et al., 2010).

However, while the structural standards (e.g. DCAT) exist, the domain-specific vocabularies needed to describe logistics services in a standardized way remain underdeveloped. There is no shared schema today that captures logistics capabilities in sufficient detail to support reliable matchmaking, negotiation, or automated orchestration. The PILL project explored this challenge through a proof-of-concept implementation of a PI Discoverability Service (see **Figure 1**), deployed using a data space connector. By integrating federated data-sharing protocols, shippers, carriers, and logistics service providers can publish and search for services in an open network, allowing for on-the-fly reconfiguration of supply chains based on real-time conditions (Cassan et al., 2023).

To unlock full discoverability within the Physical Internet, further research and standardization are needed. Priority areas include defining PI-aligned service profiles, agreeing on semantics for logistics capabilities and constraints, and ensuring discoverability mechanisms respect policy constraints and trust boundaries.

6 Policies and Agreements

In an open logistics ecosystem like the Physical Internet, seamless interoperability must be balanced with granular control over data access and usage. Participants must be able to specify not only *what* data or services are shared, but also *under what conditions*, with *whom*, and *for how long*. This requires machine-readable policies that can enforce business agreements and regulatory constraints dynamically and at scale.

The PI Connector addresses this challenge through a policy enforcement layer aligned with the principles of data spaces. Policies can be attached to both data and services, expressing who may access them, under which business roles, in what context, and for which purposes. By integrating Open Digital Rights Language (ODRL) as a policy expression standard, the connector supports automated interpretation and enforcement of these agreements.

The SYTADEL (Schrevens et al., 2023) project provided a practical basis for this capability. We experimented with dynamic policy enforcement mechanisms for logistics data sharing (Akaichi et al., 2024). These policies were context-aware, taking into account factors such as the current phase of a logistics process, the role of the requesting party (e.g., shipper, forwarder, terminal operator), geographic constraints, temporal limitations, and the presence or absence of consent from affected actors (see **Figure 2**).

This dynamic approach contrasts with static access control lists or pre-negotiated bilateral agreements. It allows stakeholders to encode usage conditions directly into the data-sharing infrastructure, improving flexibility and scalability. Moreover, it supports self-sovereign policy enforcement, meaning that each participant remains in control of the rules that govern their data and services, without requiring centralized adjudication.






	Parties with access	Access Policy
	Consignor, Consignee	A delivery order is created by the consignor. The consignee can track the details and status of the shipment. At this point no transport company (barge operator in this case) is selected.
	Barge operator	The barge operator is nominated. Consequently, the operator sees delivery details that are relevant for transport purposes. At this point the location of the vessel used is not yet associated to the delivery order.
	Skipper	Tracking the vessel requires consent of the skipper, which is either provided on an ad-hoc basis or via a framework agreement between the skipper and the barge operator. Visibility of the actual vessel location is limited in terms of geography and time, per role (see below).
	Authorities, ports, terminals	Authorities (in this case the Flemish Waterways) can only track vessels as they are inside their geographical region (geographical constraint). Port authorities and terminals can only track vessels as they enter the immediate vicinity.
	Consignee	The consignee can only track the shipment when it is within a certain range of the arrival terminal. Until then the consignee only receives updated ETAs.

Figure 2: Examples of policies that are applicable to delivery order data assets as they have been implemented and tested in the SYTADEL project, based on extensions of the ODRL (Open Digital Rights Language) standard. These include (1) role-based policies, which determine access to data assets in terms of the stakeholder's role (2) consent-based policies requiring the consent of a stakeholder (3) time-based policies, controlling access to data in terms of temporal aspects such as ETA (4) geographical policies, controlling access of data in terms of the vessel position.

In the context of the Physical Internet, such policies play a dual role. They govern access to static information (e.g., service catalogs, transport conditions), but also control the exchange of event data and process states – which are essential for real-time orchestration. As logistics processes unfold, policies determine which events can be shared, with whom, and how frequently. This is particularly important in multi-actor chains, where visibility must be carefully scoped to avoid exposing sensitive commercial or operational details.

The policy layer thus enables a trust-aware network: one where automation can occur without sacrificing control, and where compliance with contractual terms and regulatory requirements can be verified and enforced in real time (Sun et al., 2024). In the next section, we build on this foundation to describe how logistics processes can be orchestrated across multiple actors using event-based communication, while remaining fully compliant with the policies and agreements defined here.

7 Data Exchange

Data exchange is intrinsic to the data-space stack and therefore comes “for free” in the PI blueprint. The same secure channels that carry catalogue metadata also allow stakeholders to expose static datasets—tariffs, timetables, capacity tables—or to share **verifiable digital documents** such as e-CMRs, bills of lading or customs proofs. This capability aligns naturally with forthcoming eFTI^{viii} requirements and, at the other end of the spectrum, provides the trusted transport layer for the high-frequency event streams that underpin process orchestration. Thus, a single federated infrastructure supports both documentary compliance and real-time process exchange.

8 Logistics Process Orchestration

In the Physical Internet, seamless collaboration does not stop at the discovery and contracting of services – it extends into the coordinated execution of logistics operations across autonomous stakeholders. Achieving this requires an orchestration model that is decentralized, event-driven, and resilient to disruption, without relying on centralized control or rigid, predefined workflows.

The PI Connector enables this through a decentralized orchestration model, where logistics processes are synchronized by exchanging standardized event messages (Bouter et al., 2022; Maurin et al., 2024; Van Gessel & Hofman, 2023). Each event represents a meaningful change in the state of a shared process—for example, "shipment dispatched," "container unloaded," or "delivery delayed." Actors publish and subscribe to these events through their connectors, maintaining local control over their systems while contributing to the shared coordination of the logistics network.

Importantly, orchestration in the Physical Internet is not limited to process execution. It also serves as the foundation for visibility and network intelligence. Without timely information on the status of shipments, assets, or infrastructure, it is impossible to optimize operations, anticipate disruptions, or coordinate recovery actions. By exchanging event streams in near real-time, logistics actors gain situational awareness across multi-party supply chains, enabling more dynamic planning, quicker mitigation of disruptions, and improved resource utilization. The proposed architecture can bridge the gap between the different bi-lateral business relationships. An update in one process can trigger another update in a related process as is shown in **Figure 3**.

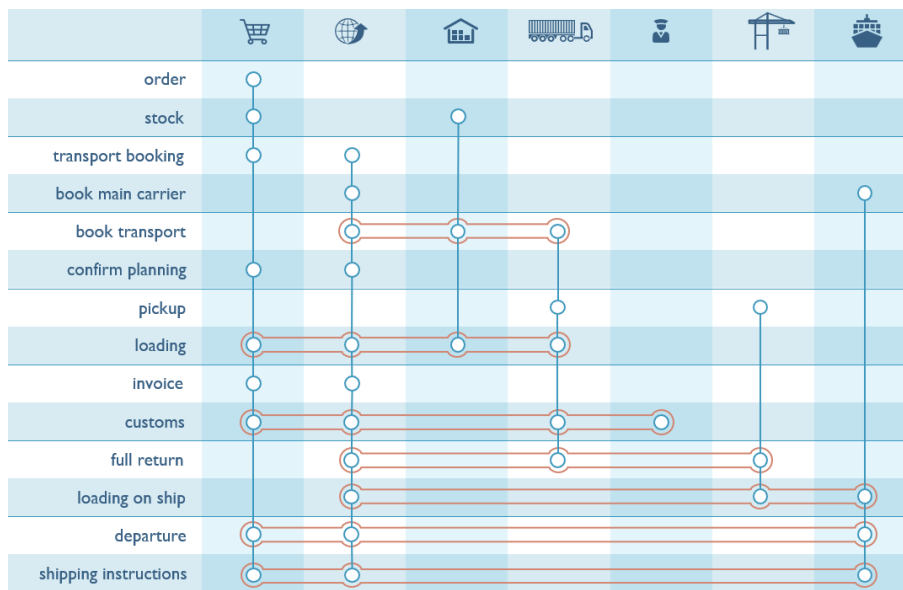


Figure 3: An example of a process metro-map for a maritime container export. This illustrates how the different processes that are under control of a principal party are interlinked by events. Determining a correct abstraction level for defining process events and their semantics is a key challenge.

The historical trace of orchestrated events further unlocks advanced applications. By maintaining an auditable, machine-readable history of process events, stakeholders can enable:

- Predictive analytics: using historical patterns to forecast disruptions or optimize routes,
- Simulations and digital twins: recreating operational scenarios for planning or training,
- Continuous improvement: identifying bottlenecks, inefficiencies, and collaboration opportunities.
- Legal compliance: the detailed logs can be used as a proof of compliance or be used in post-mortem diagnostics when things went wrong.

The PI Connector supports decentralized orchestration by handling:

- Event exchange using standardized, interoperable formats,
- State tracking to monitor the progression of bilateral or multi-party logistics processes,
- Policy enforcement ensuring that sensitive event data is only shared in accordance with predefined agreements.

For relevant progress in this area, we point to the work done in (Hofman, n.d.) and (Maurin et al., 2024). A key challenge is to remain sufficiently open and abstract in terms of defining logistics processes to accommodate for flexibility, and at the same time to be specific enough in their definition to ensure that demand can be linked to offerings. Future work must focus on defining standardized event vocabularies, Logistics Service Profiles for common logistics processes, and reference implementations of orchestration engines that are connector-agnostic. Together, these developments will support a truly autonomous, hyperconnected logistics network, fulfilling the vision of the PI.

9 Architectural Considerations

The Physical Internet can only succeed if today’s fragmented solutions are woven into a single, interoperable “stack”. The proposed PI blueprint does this by aligning six well-scoped layers with one PI-enabled data-space connector as the common gateway. The concerns belonging to these layers have all been addressed at different levels of maturity across projects and initiatives (see **Table 1**).

Concern	Proven in	Key open-standard artefacts
Connectivity	IDS-compatible data spaces iShare, Catena-X, ...	IDS/EDC connector specs,
Identity & VC trust	Commercial DID/VC wallets, Walt.id DID-kit	W3C DID, W3C VC
Discoverability	PILL network state and discoverability	EDC Connector, LDES, JSON-LD
Dynamic policies	SYTADEL usage-control engine	ODRL-based machine-readable rules
Event-based sharing	FEDeRATED node prototype	JSON-LD events

Table 1: An overview of the PI-blueprint layers and and their validation.

Conceptually, the PI-connector acts as a gateway that offers a single REST/messaging interface through which every logistics state change is published or received as an event. The connector handles identification, authentication & authorisation, policy enforcement, and event validation. As a result, time-consuming tasks such as security handshakes, contract enforcement and schema translation move out of ERP, TMS or WMS integrations. A relatively thin adapter that converts native records to PI events – and back again is all that is needed to connect systems with PI.

Evidence that an **event-driven, publish/subscribe style** lowers coupling and accelerates supply-chain integration is well-documented. (Zanfack et al., 2015) argues that a pub/sub bus enhances collaboration between stakeholders and improves responsiveness and decision-making in demand-driven supply networks. Although our proposed blueprint is more decentral in nature, the same reasoning applies here. Recent empirical work on event-driven micro-services for autonomous supply-chain coordination reports a 52 % faster response to market changes and a 63 % cut in downtime when replacing monolithic interfaces with an event mesh (Venkata Anil, Kumar Nilisetty, 2025). Such results corroborate our claim that the PI Connector’s event layer can slash integration

lead-times and provide the high-frequency data streams needed for optimisation, prediction, and simulation.

10 Conclusions

In this paper we argue that the PI can move from aspirational concept to deployable reality by grounding its principles of openness, sovereignty and decentralised control in data space architecture. Because data spaces already embrace federation, semantic interoperability and distributed governance, they provide a ready-made substrate on which the PI-connector can deliver secure connectivity, trusted identity, dynamic service discovery, policy enforcement and event-driven process sharing. Taken together, these layers form a coherent, full-stack blueprint that gives logistics stakeholders a practical route towards a digital, autonomous and friction-free supply-chain ecosystem. Many of the technical building blocks already exist but two non-technical challenges will ultimately decide whether the Physical Internet scales beyond pilots.

First, governance: agreeing on shared semantics, policy vocabularies and reference processes cannot be dictated from the top, yet it must be coherent across communities. Local networks, port communities and hinterland clusters will each have to steward common service profiles, event definitions and compliance rules, while still conforming to a light global backbone so that their data and services remain interoperable.

Second, the business model landscape must shift as the logistics sector moves away from the familiar, centrally-owned platform paradigm. Value will be created less by brokering data and more by operating connectors, issuing credentials, curating federated catalogues and providing higher-level optimisation or assurance services. New revenue-sharing and compensation schemes are therefore required to reward these distributed roles and to entice smaller actors to join.

Besides closing the final technical gaps, resolving these governance and economic questions is now the critical step toward large-scale, federated adoption of the Physical Internet. By unifying proven components under a connector-centric architecture and concentrating future effort on shared semantics, we outline a credible path from isolated pilots to a fully federated, event-driven Physical Internet.

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Hyperconnected Facility Location Contracting

Jiachen Shi, Santanu S. Dey, Benoit Montreuil
Physical Internet Center, Supply Chain and Logistics Institute
H. Milton Stewart School of Industrial and Systems Engineering
Georgia Institute of Technology, Atlanta, U.S.A.

Corresponding author: jshi81@gatech.edu

Abstract: Facility location problems (FLP) in supply chain management involve determining the optimal placement of facilities to support operations of supply chain networks and meet customer demand. In a traditional FLP, decision-makers must weigh the costs of location and allocation, which typically include the construction and operational costs of the facilities, and transportation expenses to customer demand points. In light of Physical Internet (PI), logistics infrastructure is shifting from private networks to an open web of interrelated networks, each involving multiple organizations collaborating to share resources, optimize operations, and enhance service responsiveness. Physical Internet enabled hyperconnected fulfillment, where fulfillment operations are no longer isolated within a retailer's private network; instead, decision makers can access a wide range of open-source fulfillment facilities that are interconnected, openly available, and their service capacity available for contract on demand. This paper studies the Hyperconnected Facility Location Contracting problem that generalizes several FLPs. The framework integrates PI principles and facility location modeling. It consists of determining contracts for open-source facilities to fulfill e-commerce demand over a multi-period planning horizon.

Keywords: Physical Internet, Supply Chain Networks, Facility Location Problem, Hyperconnected Fulfillment, Service Contract, Optimization.

Physical Internet (PI) Roadmap Fitness: ☒ PI Nodes (Customer Interfaces, Logistic Hubs, Deployment Centers, Factories), ☒ PI Networks, ☒ System of Logistics Networks, ☒ Horizontal Supply Chain Alignment.

Targeted Delivery Mode-s: ☒ Paper

1 Introduction

Traditionally, the vast majority of e-commerce retailers operate a limited number of proprietary fulfillment centers, constraining their ability to meet demand flexibly. Most warehouses or fulfillment centers in the market are dedicated to a single retailer, leading to a sparse distribution network. This lack of geographic density poses a significant challenge, particularly for customer segments that are highly sensitive to order-to-delivery time. When consumers expect rapid fulfillment, a substantial portion of demand may remain unservable unless they are willing to tolerate extended wait times. Expanding a private fulfillment network is often prohibitively expensive, and for many companies, financial constraints allow them to establish, at most, a single additional facility.

With the emergence of hyperconnected fulfillment, decision-makers can leverage a far more extensive range of fulfillment options beyond traditional in-house investments. Instead of incurring the capital and operational expenditures associated with building an entire fulfillment

network from the ground up, firms can now access open-source PI fulfillment centers through service contracts. These contracts enable businesses to dynamically scale their fulfillment capabilities by securing warehouse space with predefined capacity, duration, and timing parameters—such as peak-season prioritization or advance reservation incentives. The shift toward hyperconnected facility location contracting offers an adaptable, cost-effective alternative that enhances supply chain responsiveness, reduces last-mile delivery costs, and improves service levels for geographically dispersed customers. By integrating on-demand warehousing solutions into their logistics strategy, retailers can achieve greater flexibility, minimize infrastructure investments, and maintain a competitive edge in an era of increasingly time-sensitive e-commerce fulfillment.

In the US, companies such as Flexe and ES3 are among the top players that offer hyperconnected fulfillment to the industry. Flexe operates one of the largest on-demand warehousing networks with over 2,000 facilities across U.S. and Canada. It offers capabilities like 2-day or next-day delivery by strategically positioning facilities close to demand points. Depending on the desired delivery speed, businesses can use anywhere from a few to 16 warehouses to cover the majority of the U.S. market ES3 uses a 300-acre facility to serve retailers in the consumer goods and food industry. It handles up to 70,000 pallets and ships 5 million cases every week. It helps retailers achieve significant cost savings, while enabling higher frequencies of deliveries.

This paper leverages this new pan-industry business model and develops an optimization model for hyperconnected facility location contracting. To the best of our knowledge, this is the first systematic modeling framework to integrate PI concepts and facility location modeling. The main contribution of the paper lies in the uniqueness of the problem formulation, which dynamically constructs an entire fulfillment network from hyperconnected, contract-based facility networks while accounting for optimizing e-commerce fulfillment operations through the constructed network.

The rest of the paper is structured as the following: in section 2 of this paper, we review some of the relevant literature in Facility Location Problems. Section 3 provides a description of the overall problem settings and section 4 discusses detailed formulation of our proposed model. In Section 5, we present an experimental study and explore the model's performance and computational efficiency. Conclusions are summarized in section 6.

2 Literature Review

The Physical Internet (PI) is an innovative logistics transformation movement that aims to revolutionize global supply chains by shifting from closed, proprietary networks to open, shared systems. Montreuil (2011) defines PI as a “hyperconnected global logistics system enabling seamless open asset sharing and flow consolidation through standardized encapsulation, modularization, protocols, and interfaces” to enhance efficiency and sustainability in fulfilling physical object services. This paradigm encourages a rethinking of traditional logistics by promoting shared access to resources and open networks. The open asset utilization promoted by the PI creates opportunities for affordable access to decentralized networks, enabling companies of all sizes to leverage on-demand, open services regardless of their market share. It lays the foundation for hyperconnected logistics, characterized by multi-plane space structuring and meshed networks that interconnect hubs at multiple levels (Montreuil et al., 2018).

Hyperconnected distribution systems leverage a distributed web of openly accessible deployment centers such as long-stay warehouses, distribution centers (DCs), and fulfillment centers (FCs), owned and operated by multiple parties, offering storage and fulfillment services.

Hyperconnected distribution, in comparison to conventional dedicated and hub-and-spoke based systems, has been modeled and evaluated by Sohrabi et al. (2016) and Kim et al. (2021). Their studies demonstrated significant cost improvement solely by employing hyperconnected distribution while providing higher service levels. Under the context hyperconnected fulfillment, Pan et al. (2015) reported reductions in inventory level and total logistic costs in a multi-echelon supply chain utilizing PI hubs in a hyperconnected network, compared to a classical hierarchical supply chain, through better selection of storage locations as well as flexible and responsive replenishment plans. Although the literature on hyperconnected fulfillment is growing, most of the existing PI-based work emphasize the use of an open fulfillment network instead of how to construct it.

The decisions to be made to construct a hyperconnected fulfillment network through contracting is highly related to the field of Facility Location Problems (FLP). FLP seeks to determine the most cost-effective locations for a set of facilities to serve a set of clients through minimizing the total cost of opening facilities and serving client demands, with respect to certain constraints. Farahani and Hekmatfar (2009) presents a detailed summary on the application and classification, mathematical modeling, and solution techniques of different classes of location problems.

High costs associated with property acquisition and facility construction make facility location or relocation projects long-term investments. The simplest type of location problem is the Single Facility Location Problem, which locates a single new facility relative to a number of existing facilities. Multifacility Location Problem optimally locates more than one new facilities, where each new facility is linked to at least one other new facility (Ostresh, 1977). There are also other variations of the FLP, such as the Location-allocation (LA) problem that simultaneously determines the optimal locations for a set of new facilities and assigns demand to these facilities such that the transportation cost from facilities to customers is minimized or service efficiency maximized (Badri, 1999; Cooper, 1963). While another variation is the covering problem, where decision makers assume that each demand point can receive service by any facility if the distance them is within a threshold (Church and Velle, 1974).

The majority of models developed in the above classes of problems make locating decisions one time only. Decisions to be made to dynamically construct a network of hyperconnected facilities have a time component, as the need for the numbers, locations and capacities of contracted facilities vary over a planning horizon, and need to be made multiple times in accordance with demand fluctuation. Dynamic Facility Location Problem makes time dependent decisions, where decision makers find robust locations that serve changing demand over time, and sometimes even the timing (Daskin et al., 1992). However, the developed models are still limited to locating a fixed number of facilities over the entire planning horizon. Moreover, they can't address unique features inherent in hyperconnected fulfillment that facilities can be contracted on a per-use basis, where contract costs are directly affected by factors such as contract length, capacity and timing.

This paper studies the Hyperconnected Facility Location Contracting problem that generalizes several FLPs and adapts to hyperconnected, contract-based networks. The proposed model accounts for multiple interconnected facilities like the Multifacility Location model, but allows for more flexibility on the number of facilities instead of a fixed number. The decision maker simultaneously optimizes the locations of facilities and assigns demand to these facilities as in the Location Allocation Problem. Our proposed model also assumes fulfillment flexibility in that each demand point can receive service by any facility if the distance is within a threshold. But unlike the general covering problem where the capacity of facilities is unlimited, our model allows capacity dimensioning at facilities (Shulman, 1991) through contracts. Inspired by key

concepts of hyperconnectivity and various Facility Location Problems, our problem consists of determining contracts for open-source facilities to meet e-commerce demand over a multi-period planning horizon for a portfolio of multiple products.

3 Problem Setting

In light of hyperconnected fulfillment, e-commerce retailers can access a wide range of open-source fulfillment centers in the form of service contracts. Through these contracts, decision makers dynamically adjust the durations and capacities at which contracted facilities are operated in accordance with demand trends. This shifts fundamentally away from the traditional business model of owning a private network or long-term leasing. With these services, even a small business can leverage a dense fulfillment network, such as illustrated in Figure 1. As demand patterns shift, retailers can construct entirely different fulfillment networks with very short lead time and without the burden of property acquisition and facility construction, for example, from Figure 1 center to Figure 1 right.

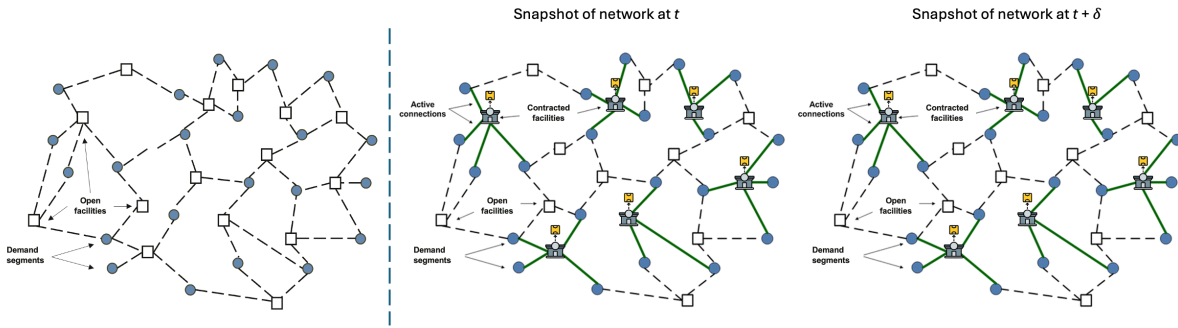


Figure 1: Hyperconnected PI facilities (left) and potential fulfillment networks that can be achieved through contracting (center and right)

We focus on a single e-commerce retailer who utilizes the PI fulfillment web through service contracts for this paper. The decision maker needs to determine a series of contracts for the interconnected PI facilities over a multi-period planning horizon to satisfy e-commerce demand. Each PI facility is subject to capacity dimensioning, where decision maker can determine different capacities to be installed with different contracts. Through the contracted network, the e-commerce retailer routes multiple products to multiple customer regions.

We consider a planning horizon that is much longer than demand trend cycles, hence there is need for multiple chances to make contract decisions. The planning horizon is therefore divided into multiple periods denoted by \mathcal{T} , with the following dynamic in each period $t \in [\mathcal{T}]$: at the beginning of each period and before demand realization, the decision maker has the option to enter into a contract for each of the inactive facilities (facilities not under active contract); for active facilities, each contract has to be executed until completion without breaching or amending; if any adjustments to the duration or utility is required, a new contract has to be created.

We identify four key characteristics that define a contract, namely the length of the contract; the amount of service capacities, be it for storage, processing or loading; the timing of the contract, whether it overlaps peak seasons such as Black Friday; and how much a contract is signed in advance to account for advance reservation incentives. Capacity levels are commonly defined in discrete intervals, like in a staircase function. Models that consider capacity levels as such represent capacities as modular structures (Antunes and Peeters, 2001). A module is a block of capacity associated with a unique operating cost. As a result, an example of a set of contracts to construct a hyperconnected network is illustrated in Figure 2, with multiple

contracts for each facility with different utility modules, and with contracts for multiple facilities at each period over a multi-period planning horizon.

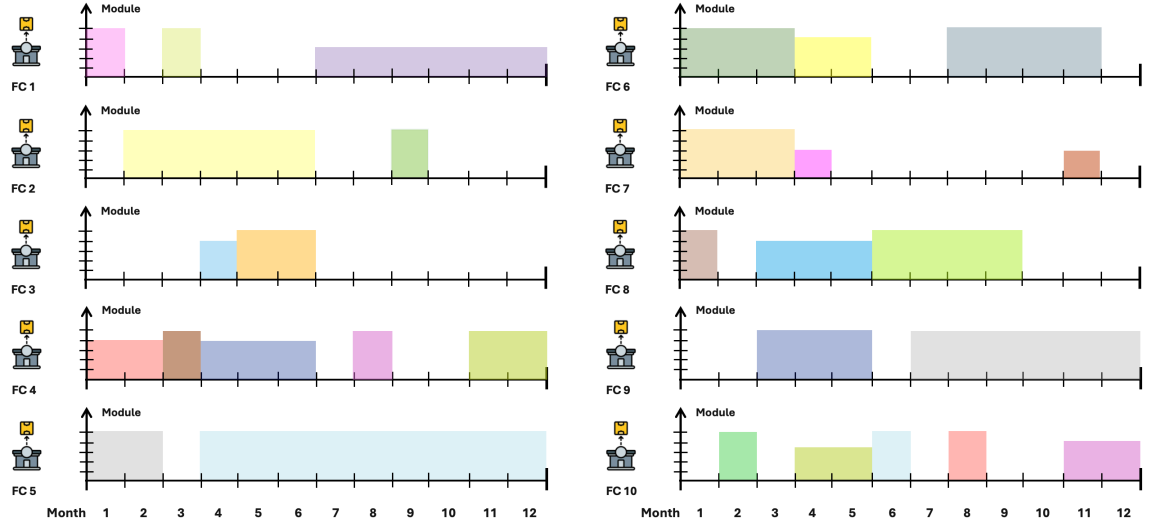


Figure 2: Example of contracts that form a hyperconnected fulfillment network over a multi-period planning horizon

Order fulfillment decisions are considered in our problem periodically with the network of contracted FCs of each period. Order fulfillment is flexible in that customer orders may be fulfilled through multiple channels. So, the problem in each specific period is effectively analogous to a covering problem, where services that customers can receive service by each facility if the distance between the customer and facility is equal or less than a predefined number. To be more specific, an order can be fulfilled by any contracted FC within a predefined radius. Alternatively, a contracted FC can fulfill e-commerce demand from any customer region within that radius.

4 Model Formulation

In this section, we formally introduce our optimization model for decision making to construct a hyperconnected fulfillment network of open-source PI facilities through contracting. The model determines the start, the end, and the module of utility contracted of each contract in optimal quantities, given different costs. The model also accounts for demand fulfillment quantities for different markets with the fulfillment network constructed with the contracted open-source FCs. We formulate the problem as a mixed integer programming (MIP) model.

In this MIP model, we introduce two types of constraints. We use constraints that regulate the timing of the contracts to ensure their legitimacy and feasibility over the entire planning horizon. We then enforce demand fulfillment constraints for each period to model the fulfillment behaviors of contracted facilities with the chosen utility modules, so that the model constructs a hyperconnected network that best meets e-commerce demand for a portfolio of multiple products from various demand sections.

The problem of determining optimal contracts of open-source fulfillment centers to form a hyperconnected network is modeled with the following parameters and variables.

Sets:

\mathcal{F}	set of hyperconnected fulfillment centers (FC), index by f
\mathcal{P}	set of unique products, index by p
\mathcal{T}	set of time periods, index by t
\mathcal{K}	set of markets, index by k
\mathcal{L}	set of utility modules, index by l
\mathcal{K}_f	subset of markets that can be served by fulfillment center f
\mathcal{F}_k	subset of fulfillment centers that can serve market k

Decision Variables:

$x_{p,f,k}^t$	proportion of demand for product p from market k served by FC f in period t
$y_{t_1,t_2,f,l}$	binary variable indicating a contract is bound for FC f from period t_1 to period t_2 with module l
$z_{f,l}^t$	binary variable indicating if FC f is active or under contract in period t with module l

Parameters:

$u_{f,l}$	utility of FC f associated with operating module l
$c_{t_1,t_2,f,l}$	contract cost function of a PI facility f that begins in period t_1 , ends in period t_2 and contracted with utility module l

The objective of our model is to maximize the total profit across the constructed hyperconnected fulfillment network, the product portfolio and the planning horizon. The total profit of the system is defined as gross sales revenue minus contract costs. As shown in (1), the objective function accounts for gross revenue from demand fulfillment, while contracts are determined by the start, end, the contracted module of each open-source fulfillment centers:

$$\underbrace{\sum_p \sum_f \sum_k \sum_t r_p \cdot x_{p,f,k}^t}_{\text{revenue for fulfilled demand}} - \underbrace{\sum_{t_1} \sum_{t_2} \sum_f \sum_l c_{t_1,t_2,f,l} \cdot y_{t_1,t_2,f,l}}_{\text{contract cost}} \quad (1)$$

The constraints in this optimization model can be presented as follows: Constraint (2) is the time feasibility constraint, which defines that a contract is only feasible when it ends after it has started. Constraint (3) ensures that at most one contract can be active for any potential FC f at any given time t . Constraints (4) – (5) link the binary variable $z_{f,l}^t$, which indicates if there is an active contract at time t for facility f , with the binary variable $y_{t_1,t_2,f,l}$, which represents the begin, end, and module of a contract. Constraint (6) represents that the entire contracted hyperconnected fulfillment network combined doesn't fulfill more than there is demand. While constraint (7) stipulates that each of the contracted fulfillment centers operates within its contracted module's utility $u_{f,l}$:

$$y_{t_1,t_2,f,l} = 0, \quad \forall t_1 > t_2, \quad \forall f \in \mathcal{F}, \quad \forall l \in \mathcal{L}. \quad (2)$$

$$\sum_{t_1 \leq t \leq t_2} \sum_l y_{t_1,t_2,f,l} \leq 1, \quad \forall f \in \mathcal{F}, \quad \forall t \in \mathcal{T} \quad (3)$$

$$z_{f,l}^t \geq y_{t_1,t_2,f,l}, \quad \forall t_1 \leq t \leq t_2, \quad \forall f \in \mathcal{F}, \quad \forall l \in \mathcal{L} \quad (4)$$

$$z_{f,l}^t \leq \sum_{t_1 \leq t \leq t_2} y_{t_1,t_2,f,l}, \quad \forall t \in \mathcal{T}, \quad \forall f \in \mathcal{F}, \quad \forall l \in \mathcal{L} \quad (5)$$

$$\sum_f x_{p,f,k}^t \leq d_{p,k}^t, \quad \forall p \in \mathcal{P}, \forall k \in \mathcal{K}, \forall t \in \mathcal{T} \quad (6)$$

$$\sum_p \sum_k x_{p,f,k}^t \leq \sum_l u_{f,l} \cdot z_{f,l}^t, \quad \forall f \in \mathcal{F}, \forall t \in \mathcal{T} \quad (7)$$

$$x_{p,f,k}^t \geq 0, \quad y_{t_1,t_2,f,l} \in B, \quad z_{f,l}^t \in B, \quad \forall p \in \mathcal{P}, \forall f \in \mathcal{F}, \quad \forall l \in \mathcal{L}, \quad \forall t_1, t_2 \in \mathcal{T} \quad (8)$$

5 Computational Experiment

In this section, we develop an experimental framework to study and evaluate the performance of the proposed hyperconnected facility location contracting model. The case study considers a single e-commerce retailer with access to a number of interconnected, open-source fulfillment centers located over the United States. The e-commerce retailer routes a portfolio of 44 products jointly to 98 demand segments represented by the 3-digit zip codes of US through the network of FCs. We simulated facility contracting and fulfillment operations over a 12-month period (2020/01/01 – 2020/12/31) with one-month intervals. Real data for sales, prices, costs and product information from an online e-commerce company were used to conduct the computational experiments.

We develop three scenarios of facility density over the US markets: low density, moderate density and high density. We identified the top 50 metropolitan statistical areas based on total population (U.S. Census Bureau, 2024) and divided them into three tiers: tier I metro areas (population > 5,000,000); tier II metro areas (population > 2,000,000); and tier III consisting of the rest. This gave us a total of 10 tier I areas, 25 tier II areas and 15 tier III areas, and we construct facility density scenarios in proportions to population densities. For the low facility density case, one open-source facility is allocated to each of the tier I metro areas, giving a network of 10 facilities. Two facilities are allocated to each of the tier I metro areas to create the moderate facility density case, in addition to one facility to each of the tier II metro areas, which gives 45 facilities combined. Finally, five facilities are allocated to each of the tier I areas, two to each of the tier II areas and one to each of the tier III areas, which constructs the scenario of high facility density with a total of 115 hyperconnected open facilities.

The results of with the three different facility density scenarios are illustrated below in Figure 3, with the color of the circle interior representing the proportion of time a facility is contracted, the color of the circle border representing the number of contracts as an indication of the complexity of contracting at a specific facility, and the size of the circles representing the amount of flow through each contracted facility. Furthermore, a detailed representation of contracts spanning over the multi-period planning horizon for the 10 facilities case can be found in Figure 2.

5.1 Model Performance Results

The goal of this study is to examine the benefits of leveraging open PI fulfillment facilities to dynamically construct a fulfillment network through contracting. We focus on several key performance metrics including total profit, contract cost, and service level. The experiment compares the proposed hyperconnected facility contracting approach with a static benchmark in accordance with common industry practice. The benchmark is analogous to a traditional multifacility location problem, where the model selects a number of facilities from the set of available open facilities to construct the fulfillment network at the beginning of the planning horizon. The facilities can only be leased at their full capacity and for the entire horizon, as a result, the fulfillment network remains unchanged throughout.

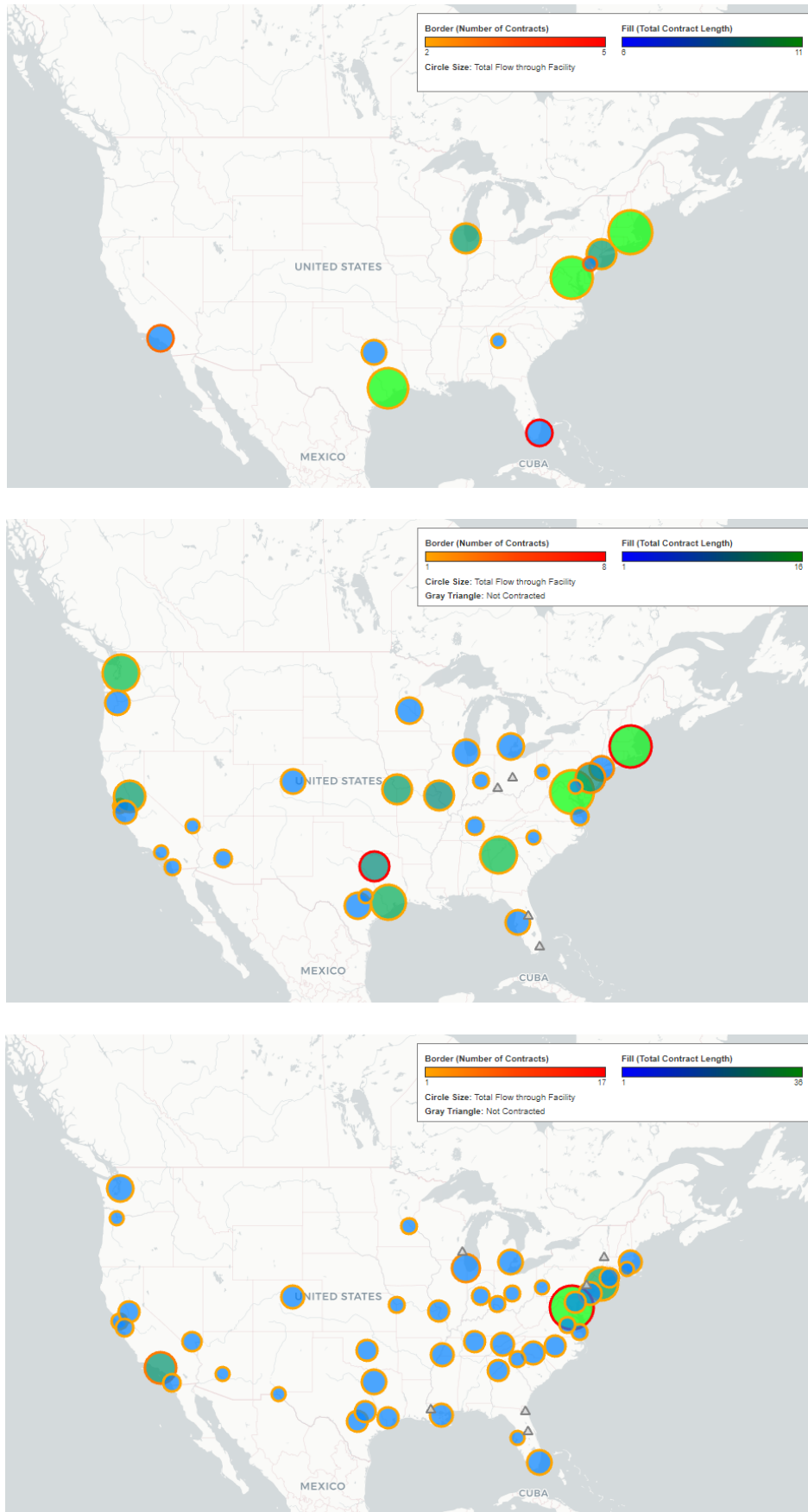


Figure 3: Results with low (top), medium (middle), and high (bottom) facility density scenarios

Table 1: Model performance compared to benchmark

	Benchmark	Proposed Model
Total Revenue	844486	915235
Contract Cost	500520	429191
Total Profit	343966	486044

The results of this case study are presented in Table 1. We observed that our proposed model reduced total contract cost significantly, by 14.2%, compared to the benchmark model. This was achieved through the flexibility of dynamically adjusting service contracts. It is worth noticing that our model fulfilled more demand and achieved a higher total revenue, 8.4% more compared to benchmark, while saving on contract costs. As a result, our proposed model increased total profit by 29.2%.

5.2 Computational Efficiency

We compare the computation time of our proposed model under different problem instances to demonstrate how the MILP scales as the network of open-source facilities grows. To limit the source of error, we run the different instances using the exact same initial conditions. We repeat the experiment for all settings 25 times, where our model is tested with 10, 45 and 115 open FCs respectively. Each run is timed and recorded, and the runtimes are presented in a table.

Table 2: Comparative analysis on model computation times

FC Density Scenario	Runtime Mean (sec)	Runtime Standard Dev (sec)
Low (10)	600.13	163.77
Medium (45)	2656.24	987.54
High (115)	9522.69	2677.34

The results of this study are presented in Table 2. On average, we observed that as the number of open-source FCs increased, the runtime grew more than linearly with problem scale. Moreover, the variance of the computation times also increased with the number of open facilities, i.e., as the size of the problem instances increased. These observations demonstrate that our original proposed formulation may face challenges from the standpoint of computational efficiency and problem scalability.

6 Conclusion

We proposed an innovative mixed integer programming model to solve the problem of hyperconnected facility location contracting, integrating Physical Internet concepts into facility location modeling. The model leverages service contracts to dynamically utilize open-source PI facilities and optimizes e-commerce fulfillment through the constructed hyperconnected, contract-based facility networks. The proposed framework shifts fundamentally away from stylized assumptions and structures such as private supply chain networks, and offers promising insights into how a new business model like hyperconnected fulfillment can reshape e-commerce logistics, paving the way for more flexible and responsive supply chain networks.

Application of the proposed framework has been demonstrated through a real-world e-commerce retailer. Experiments were conducted to examine the proposed approach under difference scenarios of PI facility density. The proposed approach achieved improvements both in terms of saving costs and increasing service level and profit compared to a benchmark approach in accordance with common industry practice. Scalability issues of the model arise as the number of open facilities increases. Future research will explore various computational and analytical approaches to effectively manage and mitigate these challenges. Algorithms like Benders decomposition and analytical solution methodologies like product clustering hold promise for advancing the theoretical robustness and practical applicability of our framework.

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Designing Logistics Networks Resilient Against Multi-Period Disruptions Through the Physical Internet

Simon Anthony Lorenzo^{1,2}, Russell Thompson¹, Greg Foliente^{1,3}

¹University of Melbourne, Australia

²University of the Philippines Diliman, Quezon City, Philippines

³De La Salle University, Manila Philippines

Corresponding author: lorenzos@student.unimelb.edu.au

Abstract: Disruptions that significantly affect global supply chains and logistics networks have been increasing in frequency and intensity in recent years, a trend that is expected to continue in the future. These lead to significant losses to various stakeholders. Consecutive, multi-period disruptions compound this issue by further damaging networks that are already affected, leaving little to no time for recovery. This study develops a methodology to evaluate the vulnerability of a given logistics network to these recurring disruptions and presents a network design approach that increases the network's robustness and resilience, alongside traditional objectives such as costs and profit. Based on a systematic literature review on logistics resilience measures and models, we applied a Physical Internet inspired collaboration and shared hub approach on an actual grocery retail network in Metro Manila, Philippines, which had recently been affected by multi-period, recurring disruptions caused by typhoons. Results showed that the PI-based collaborative approach to network design simultaneously yields substantial benefits to multiple objectives regardless of the occurrence of typhoons. This initial study also helped identify key areas for further research and development.

Keywords: Resilience, disasters, extreme events

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

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

1 Introduction

Amongst the key motivations in the development and application of the Physical Internet (PI) concept in logistics are increased productivity, improved sustainability and enhanced system resilience (Montreuil, 2011). A few studies have explored the concept of resilience through PI, primarily through the use of a hyperconnected network design. Studies such as Kulkarni et al. (2022) and Peng et al. (2021) leverage the open and connected nature of PI-enabled networks and evaluate their effects towards the networks' efficiency as well as resilience.

In recent years, some places around the world have experienced major disruptions (i.e., typhoons, flooding) within weeks or even days of each other. For example, the Philippines experienced 6 typhoons in November 2024, the highest number of typhoons experienced by the country in one month since official records began. Although these 6 typhoons had different tracks and hit different areas, certain regions of the Philippines were still significantly affected by the winds and rains caused by these typhoons. Another example is the state of Queensland in Australia, which experienced continuous flooding in various regions from January to April 2025 due to continuous rains. Like the Philippine case, certain regions in Queensland were affected by constant, repeated flooding, resulting in population centers being isolated for several days at a time.

The occurrence of multi-period disruptions is a significant concern since traditionally, freight transport and logistics studies that look into resilience assume a stable environment during the recovery period after a major disruption. Post-disruption, reactive resilience strategies often involve actions such as capacity recovery, emergency capacity acquisition, and the general temporary increase in operations. However, it would not be feasible to implement these strategies if a consequent disruption of similar magnitude arrives within a few days of the initial one, there will not be enough time to implement these recovery strategies. Without proper planning, this sequence of disasters would cause a significant performance loss across the network.

This paper aims to assess the performance of a PI-enabled network in a setting where multi-period disruptions are likely to occur, with respect to efficiency metrics as well as resilience metrics. We look into real instances of such disruptions, and analyze their effects on a logistics network with varying characteristics against these types of disruptions.

2 Related Work

Resilience in logistics networks has been addressed through several different ways. These include (but are not limited to) redundant inventory, redundant capacity, network topology adjustments and resource sharing through collaboration. Rahman et al. (2022) and Ponomarov & Holcomb (2009) provides a review of these methodologies, and their applications towards logistics network resilience. In general, the focus of these papers is more operations rather than design, with greater emphasis on supply and capacity fortification rather than improving the structure and policies of the system.

When it comes to the Physical Internet, resilience in the presence of disruptions is not a new concept. A number of studies explore what is known as the hyperconnected network structure, stemming from Hyperconnected City Logistics (HCL), the marriage of PI with City Logistics (CL) (Crainic & Montreuil, 2016). Within these networks, Kulkarni et al. (2022) focuses on determining routing to maximize resilience, while Peng et al. (2021) looks into the production-inventory-distribution (PID) contextualization of such a network.

Other works such as Labarthe et al. (2024) focused on connecting people and freight mobility through the joint usage of various transportation options, building on hyperconnectivity principles found within. Xue et al. (2023) proposed a PI-enabled hyperconnected order-to-delivery system (OTD), which modelled the production-distribution system by multi-objective mixed-integer-nonlinear programming with economic, environmental and social impacts. It stated exploration of resilience metrics as one of the main avenues for future work. Ji et al.

(2023) investigated the relationship between resilience and sustainability in PI-enabled supply-production-distribution networks. They developed a resilient-sustainable performance scoring method with mixed-possibilistic programming to determine the relationship between the two.

These studies show that current research on logistics network resilience design deals with single occurrence of disruptions only. While several concepts would still be applicable to the multi-period disruption scenario, there are certain considerations and adaptations that must be made in this new setting. Certain papers outside the scope of PI have touched on the topic. Ghasemi & Khalili-Damghani (2021) looked at a scenario where the inventory of goods was modelled as a location-allocation-inventory problem set in Tehran in preparation for a major disruption in the form of an earthquake. The model becomes a multi-period planning problem due to the nature of the earthquakes having aftershocks days after the main earthquake, causing continuous and repeating disruptions to the logistics network. Wang (2021) did a similar study set in China, and similarly were able to show that proper planning for multi-period disruptions results in more efficiency operations for the network. This study looks into a similar methodology of planning towards multi-period disruptions, but in the context of typhoons and flooding instead of earthquakes. A system's adaptive capacity and resilience vary with different types of disruptions or extreme events (Hasan & Foliente, 2015). The work undertaken herein is through case study involving a real-world logistics network and multi-period disruptions.

3 Methodology

PI solutions for multi-period disruptions

In order to provide address logistics network resilience against multi-period disruptions, we carry over some key concepts and characteristics exhibited by PI-enabled networks. Specifically, we look into how collaboration, facilitated through the open nature of these networks, can improve the logistics network resilience.

Collaboration within PI is similar to the shared logistics concept in literature (Qi et al., 2018). In this setting, facilities such as PI-hubs can serve as source and transshipment nodes within a transportation network. Depending on the level of collaboration and openness of the network, these PI-hubs can greatly increase the efficiency of the system, as well as other metrics such as resilience.

In the setting of multi-period disruptions, planning must be considered with consideration to possibility of multiple events that disruption the operations of the network. In such cases, operations and components of the network need to be adjusted differently compared to situations where only one disruptive event is considered (Ghasemi & Khalili-Damghani, 2021).

In this study, we adapt a similar methodology to develop a multi-period collaboration and design of a PI-enabled network toward the improvement of efficiency as well as resilience. We focus on two main strategies: collaboration and facility location. Collaboration would allow for sharing of assets and resources, specifically distribution centers (DCs) and delivery vehicles, among retailers to achieve a higher level of utilization across the system. Facility location, meanwhile, would provide more cost-efficient routing and inventory management, especially in tandem with collaboration.

PI-enabled Network Model Establishment

To assess how the implementation of the proposed network would perform, we establish a retail network model with source nodes (i.e. DCs, PI-hubs) and destination nodes (i.e. store locations, end-customers). Each retailer is assumed to perform delivery functions using multiple delivery vehicles from its source nodes to its destinations, either replenishing inventory in stores or completing deliveries for customers.

Varying levels of collaboration is explored in the model. Specifically, we look at 3 collaboration levels: *no collaboration*, *partial collaboration*, and *full collaboration*.

- *No collaboration* – This scenario reflects the current one where all facilities are dedicated to their respective retailers. No retailer can access a DC that is owned by another retailer.
- *Full collaboration* – A full-open network, one envisioned by PI, would allow any retailer to access any DC that is present in the network.
- *Partial collaboration* – This scenario reflects an intermediate scenario where dedicated DCs still exist, but certain DCs are designated as open. The partial collaboration scenario is a more feasible and practical scenario in terms of feasibility, especially when considering stakeholder reluctance.

These scenarios are evaluated with respect to several objectives that reflect various aspects of the network, including operational efficiency and resilience. Specifically, for each run, we evaluate the following objectives:

- *Vehicle-Kilometers Travelled (VKT)* – VKT is seen as a measure of travel cost, in the form of total distance travelled by all the vehicles in the system. This measure is seen to be both an economic measure as well as an environmental one, as VKT influences both travel costs and vehicular greenhouse gas (GHG) emissions.
- *Performance Loss* – This measure is derived as the percentage that service level is reduced upon disruption onset, where service level is defined to be the proportion of fulfilled demand. Performance loss is thus primarily a measure of resilience in the network. In the multi-period disruption scenario, performance loss is evaluated over the entire period of all disruptions considered.
- *Stockout Count* – Each instance of stockout is recorded when demand is incurred but not fulfilled. Depending on the nature of the logistics network, each stockout may be of critical importance to the network's customers. In the context of essential goods such as food, stockouts might also mean food insecurity, affecting the health and well-being of the population within the area. As such, stockout count is an objective that primarily measures socio-economic costs in logistics networks.

4 Case Study

To illustrate how the theoretical model can be applied to a multi-period disruption scenario, a simulation model is developed in the setting of Metro Manila in the Philippines, which replicates the sequential flooding events in November 2024. Metro Manila, the capital region of the Philippines, is home to a population of 13,484,462 over an area of 55,083 km², making it the most densely populated region in the country. Within the region, 3 grocery retailers control more than half the market. The network of these 3 retailers is replicated through the simulation model, with location, demand, and capacity data being derived from information that is publicly available.

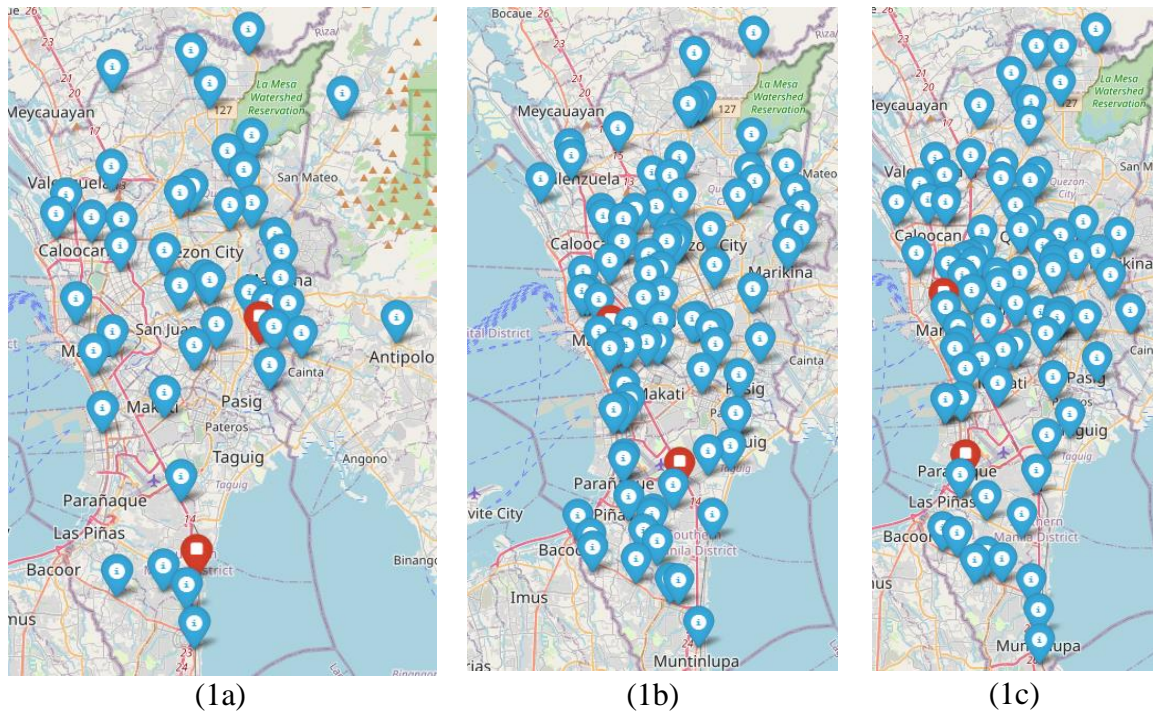


Figure 1. Grocery retail network in Metro Manila.

Figure 1a, 1b and 1c show the locations of source nodes (i.e. DCs) in red and demand node (i.e. stores) nodes in blue, for each of the 3 retailers previously identified.

Travel times are obtained via Google API, and the model assumes that deliveries are made in the evening. This makes travel times relatively short compared to values during rush hour.

For the case of Metro Manila, we explore the scenarios where partial and full collaboration is implemented, as well as the location of a strategically-located open PI-hub that can be used by all retailers to supplement their current operations. Specifically, we test three collaboration scenarios: no collaboration (current setup), partial collaboration, and full collaboration. On the PI-hub location option, we identify the ideal location of a singular shared PI-hub and see its effect to the base case of no collaboration as well. These strategies are evaluated with respect to several metrics, include ones that address economic and resilience aspects, in order to ensure a more holistic evaluation of the retail networks.

Regarding the multi-period set of disruptions, we consider the time period where international typhoons Trami, Kong-rey, Yinxing, Toraji, Usagi and Man-yi affected the northern region of

the Philippines late 2024. There were only 24 days from the landfall of the first typhoon to the last one in this series, which averages out to typhoon every 4 days. Four out of these six typhoons brought significant rains to Metro Manila, causing flooding in various areas in the region. Since there is no data on the actual flooding experience during each of these typhoons, we make use of the publicly-available flood hazard map (<https://noah.up.edu.ph/>) as shown in Figure 2. Flooded pathways are modeled on the low, medium and high hazard level maps shown, as determined by the magnitude of rainfall brought by each typhoon that affected the region.



Figure 2. Metro Manila flood hazard map.

The simulation is ran over the course of the 24-day period, and is assessed with respect to the previously-identified 3 metrics: Vehicle-kilometers travelled (VKT), performance loss, and the number of stockouts.

Lastly, we consider a control scenario where there is no multi-period disruption that occurs. This additional analysis would provide insights on the possible benefits of adapting partial and full collaboration scenarios even without the occurrence of disruptions.

5 Results and Discussion

Table 1 shows the logistics network simulation results in Metro Manila, based on the November 2024 Metro Manila multi-period disruption setting:

Table 1. Simulation results for multi-disruption scenario.

	No Collaboration	Partial Collaboration	Full Collaboration	Optimal PI-Hub Location (No Collaboration)	Optimal PI-Hub Location (Full Collaboration)
VKT	31,354.99	25,741.27	19,050.89	30,344.52	15,286.28
Performance Loss	27.36%	21.51%	7.73%	22.760%	5.20%
Stockout Count	21,126.60	16,901.28	11,830.90	17,441.28	9,001.83

We can see that all three metrics improve from the no collaboration to the partial collaboration scenario, and even further when the full collaboration scenario is adapted. These results indicate that collaboration is a viable strategy to achieve resilience, even for multi-period disruptions. For VKT, sharing of DCs would result in shorter travel distances for vehicle routing, reducing the overall travel distance within the networks. Performance loss and stockout count also benefits from collaboration by providing more reliable transportation through alternative source nodes.

On the PI-hub strategy, we see that simply implementing a shared hub without other collaboration schemes would still result in a decrease in the identified metrics, but the magnitude of the decrease is not as significant. Implementing a full collaboration scheme alongside the PI-hub results in the best values for all metrics, and is seen is the ideal solution before costs of implementation and operation.

To illustrate the possible benefits collaboration scenarios even without the occurrence of disruptions, we run additional simulations where no disruptions occur. Results of this scenario are summarized in Table 2.

Table 2. Simulation results for no-disruption scenario.

	No Collaboration	Partial Collaboration	Full Collaboration	Optimal PI-Hub Location (No Collaboration)	Optimal PI-Hub Location (Full Collaboration)
VKT	26,024.64	22,812.16	15,666.94	22,471.06	11,508.30
Performance Loss	0.00%	0.00%	0.00%	0.00%	0.00%
Stockout Count	688.08	582.83	645.34	613.83	610.79

We can see from the results of the secondary scenario that unsurprisingly, there is no performance loss since there are no disruptions that occur. With regards to VKT, values are reduced similar to the multi-period disruption scenario. As expected, the highest reduction in VKT comes from the scenario where both full collaboration and the establishment of the open PI-hub are pursued. This is in line with previous studies that utilize PI to achieve routing efficiency in logistics networks. Finally, looking at stockout counts, we see that the values are similar for all setups evaluated. This is due to the fact that retail companies would perform deliveries in all scenarios in order to meet demand. In setups such as *no collaboration*, however,

we see that in order to perform the deliveries required to meet demand, more deliveries are required, and thus a higher VKT count is incurred instead.

6 Conclusions and Recommendations

The study showed improved network resilience of grocery supply chain logistics in multi-period disruption through PI-based collaboration and, specifically, via the implementation of an open PI-hub accessible to all retailers. In the Metro Manila case study, where several consecutive typhoons that caused disruptions in the region over multiple periods, the implementation of collaboration and the shared hub was shown to lead to significant improvements in efficiency and resilience metrics, with the largest improvement being gained from the implementation of both measures. Specifically, in the setting of Metro Manila, VKT can be reduced by up to 51.25%, performance loss by up to 80.99% and the number of stockouts by 57.39%. These improvements are also shown to be retained even in scenarios where no disruptions occur. Thus, the PI-based collaboration and shared hub approach to network design can be considered as a “no regrets” measure (i.e., yields benefits regardless of the occurrence of typhoon and flood scenarios).

Future work can incorporate costs of implementation and operation, possibly extending the model objectives to key financial outcomes. This is important as the implementation of measures towards resilience would often have mostly financial costs that may not reap any apparent benefits if no disruptions occur. Other locations and multi-period disruptions can also be tested to establish the robustness of the methodology. In particular, disruptions other than flooding can be investigated to see if and how much PI concepts can improve logistics networks if they are disrupted in a different manner or by a different event (Hasan & Foliente, 2015). Finally, to further contribute to the implementation collaborative and open networks encouraged by PI, the policy and governance aspects of these resilience strategies can be explored as well. The results of the study do not consider the common reasons for reluctance in collaboration, such as data privacy and security, so going into more detail on the implementation of collaboration could further strengthen the claim of the proposed setup being a “no regrets” measure.

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The Role of Artificial Intelligence and Data Skills in Improving Gender Diversity across Europe: A Case Study of Logistics Sector

Ahmad Zakari Salihu^{1,2}, Azadeh Haratiannezhadi¹ and Giuseppina Schiavone²

1. Open Institute of Technology, St. Julian's, Malta

2. Sustainability Advance Analytics Consultancy, Amsterdam, Netherlands

Corresponding author: ahmad.salihu@students.opit.com

Abstract: This study explores the intersection of gender diversity and Artificial Intelligence (AI) in the European logistics sector, with a focus on how AI can support more inclusive hiring practices and workplace environments. Using a mixed-methods approach, primary data was collected through a gender-disaggregated survey, while secondary data was gathered by scraping job listings on LinkedIn to assess AI skill demands and diversity-related language. Due to a low survey response rate, AI-generated responses were initially considered using GPT-3.5 but ultimately excluded to preserve the authenticity and reliability of the dataset. Survey findings indicate limited effectiveness of existing diversity initiatives, with structural barriers such as mentorship gaps and work-life balance constraints persisting. While respondents expressed interest in AI training, current adoption of AI for diversity purposes is limited. Job postings show growing demand for AI and data skills, mostly in IT roles, with limited emphasis on inclusive hiring language. The study recommends AI-driven bias detection tools, targeted training, and flexible work policies to bridge gender gaps. These insights are valuable for logistics firms and policymakers seeking to align digital transformation with inclusive workforce development.

Keywords: Gender Diversity, Artificial Intelligence, Logistics Sector, Workforce Inclusion, Physical Internet.

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

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

1 Introduction

Gender diversity in the workplace has long been recognized as a critical factor in enhancing organizational performance, fostering innovation, and driving sustainable growth. Diverse teams bring a wide range of perspectives, which can lead to better decision-making, increased creativity, and improved problem-solving abilities (Hunt et al., 2015). Despite these benefits, many industries, particularly logistics, continue to struggle with significant gender disparities. The logistics sector, characterized by physically demanding work and a traditionally male-dominated culture, has historically failed to attract and retain women, especially in leadership and technical roles (Yang et al., 2024). This underrepresentation not only limits the industry's ability to leverage diverse talent but also hinders its capacity to address the evolving demands of a globalized and increasingly complex supply chain.

The logistics industry plays a pivotal role in the global economy, serving as the backbone of international trade and e-commerce. As such, achieving gender diversity in this sector is not merely a social imperative but also a strategic business consideration. Organizations with diverse workforces are better positioned to understand and meet the needs of a varied customer base, thereby enhancing their competitiveness in the global market (Hunt et al., 2018).

However, structural challenges such as gender bias in recruitment, limited professional development opportunities for women, and a lack of flexible work arrangements continue to impede progress toward gender parity in logistics (Yang et al., 2024). These barriers are compounded by cultural stereotypes that portray logistics roles as unsuitable for women, further discouraging female participation in the sector (Tadić et al., 2024).

In recent years, advancements in Artificial Intelligence (AI) and data analytics have emerged as promising tools for addressing workplace diversity, equity, and inclusion challenges. AI technologies have the potential to mitigate biases in recruitment, performance evaluations, and career progression by analysing vast datasets to identify and correct discriminatory patterns (Hunt et al., 2018). AI-powered recruitment tools like HireVue can help ensure that hiring decisions are based on skills and qualifications rather than unconscious biases. Additionally, data analytics can uncover gender-specific trends within organizations, enabling the development of targeted interventions to support women's career advancement. However, the effectiveness of AI in promoting gender diversity is contingent on the quality and diversity of the data used to train these systems. If historical data reflects existing societal biases, AI models may inadvertently perpetuate or even exacerbate these inequalities, a phenomenon often referred to as "bias in, bias out" (Schwartz et al., 2022). This underscores the importance of ensuring that AI systems are designed and implemented with careful attention to data quality, algorithmic transparency, and ethical considerations.

2 Literature Review

2.1 Introduction to Gender Diversity in the Workplace

Gender diversity in the workplace refers to the equitable representation and inclusion of individuals of all genders, ensuring that both men and women have equal opportunities for recruitment, advancement, and decision-making roles. Over the past few decades, significant progress has been made in promoting gender equality, yet gender imbalances persist across various industries, particularly in leadership and technical roles. Achieving gender diversity is not only a moral and social imperative but has also been shown to provide substantial benefits to organizational performance, creativity, and decision-making (Hunt et al., 2020). Research by McKinsey & Company indicates that companies with the highest quartile of gender diversity on executive teams are 21% more likely to outperform their peers in terms of profitability and 27% more likely to create greater value (Hunt et al., 2015). This correlation demonstrates that gender-diverse teams contribute new perspectives and innovative solutions, leading to improved problem-solving and decision-making processes.

Moreover, gender diversity has been linked to enhanced corporate governance and risk management. Studies have shown that organizations with mixed-gender boards experience a lower incidence of financial fraud, suggesting that diverse leadership teams bring a variety of ideas and experiences that result in more effective planning and risk management strategies (Wahid, 2019). In addition to improving financial performance, gender diversity fosters a more conducive workplace atmosphere. Inclusive environments that celebrate diversity have been shown to increase employee morale and engagement while reducing negative workplace behaviours such as bullying and discrimination (Perry & Li, 2019). This positive work culture is particularly important in industries like logistics, where operational efficiency and collaboration are critical to success (Luu et al., 2019).

Despite these benefits, the logistics sector continues to face significant challenges in achieving gender parity. Women account for only approximately 22% of the logistics workforce in Europe, with even lower representation in higher-level positions (EIGE, 2023). This underrepresentation is driven by a combination of historical, cultural, and structural factors, including gender bias in recruitment, limited access to mentorship and professional

development opportunities, and work-life balance challenges (Yang et al., 2024). Addressing these barriers is essential for fostering a more inclusive and equitable logistics sector.

2.2 Artificial Intelligence in the Workplace

Artificial Intelligence (AI) is rapidly transforming the workplace across various industries, enhancing productivity, decision-making, and operational efficiency. AI applications extend beyond the automation of routine tasks to more complex functions such as recruitment, performance evaluation, and strategic planning. In the logistics sector, AI-enabled systems have revolutionized supply chain management by optimizing inventory, improving demand forecasting, and enhancing route planning (Goswami et al., 2022). These systems can predict demand fluctuations, optimize transportation routes, and improve warehouse management, resulting in significant efficiency gains across logistics operations (Rane et al., 2024).

AI has also transformed recruitment and talent management processes, making hiring more efficient and less biased. AI-powered tools can scan resumes, match candidates with job requirements, and even conduct preliminary interviews. These systems use algorithms to analyse vast amounts of data to identify the most qualified candidates, speeding up the hiring process and reducing the workload for HR professionals (Kohli, 2024). Additionally, AI enhances strategic talent management by identifying future workforce needs aligned with organizational growth strategies, thereby improving long-term planning (Zhang, 2024). However, concerns have arisen about the potential for bias in AI-driven recruitment tools. If the data used to train these algorithms is biased, it may result in discriminatory hiring practices, underscoring the importance of using diverse, unbiased datasets and ensuring transparency in AI decision-making processes (Schwartz et al., 2022).

AI's role in employee performance management has also gained prominence in recent years. AI tools can track employee productivity, analyse work patterns, and provide insights into performance metrics. These systems can help managers identify high-performing employees and those who may need additional support or training (Sampath et al., 2024). However, the implementation of AI in performance management raises privacy concerns, as employees may feel uncomfortable with constant monitoring, and there is a risk of over-reliance on data-driven insights at the expense of qualitative evaluations (Monica et al., 2024).

2.3 Artificial Intelligence and Gender Diversity

AI has the potential to play a transformative role in promoting gender diversity within organizations. One of the most promising applications of AI is its ability to minimize unconscious biases in recruitment and hiring processes. Traditional hiring practices often allow biases, both conscious and unconscious, to influence decisions, leading to the underrepresentation of women, particularly in technical and leadership roles. AI-driven recruitment tools can help mitigate this issue by focusing on skills and experience rather than gender or other demographic characteristics (Kohli, 2024). By using algorithms to scan resumes and match candidates to job requirements, AI can help ensure that candidates are evaluated based on merit alone, thereby promoting a more diverse workforce (Oman et al., 2024).

Beyond recruitment, AI technologies can significantly enhance work-life balance by automating repetitive tasks, enabling employees to focus on strategic and meaningful work—a benefit particularly valuable for women managing both career and family responsibilities. Additionally, AI-driven flexible work arrangements can cater to diverse employee needs, fostering gender parity by creating a more inclusive and adaptable workplace environment (Kohli, 2024). AI-driven mentorship platforms can also provide real-time support and personalized learning pathways to female employees, helping them gain the support they need to advance in their careers (Chang et al., 2024). This is especially critical in industries like logistics, where women are often underrepresented in leadership roles.

However, AI is not without its limitations, particularly when it comes to addressing deep-seated gender biases. AI systems are only as unbiased as the data they are trained on. If historical data reflects gender imbalances, such as the underrepresentation of women in leadership roles or technical positions, the AI may perpetuate these disparities (Schwartz et al., 2022). Addressing these challenges requires diverse development teams, comprehensive auditing, and robust ethical oversight to ensure inclusivity and fairness in AI applications.

3 Methodology

3.1 Survey Methodology

The survey component of this research aims to gather firsthand data on the role of AI and gender diversity in the logistics sector across Europe. Two distinct questionnaires were designed—one targeting men and the other targeting women working in the logistics industry. The objective is to assess gender perceptions, experiences with AI, and the overall inclusiveness of the workplace.

Figure 1 illustrates the survey methodology flowchart, depicting the key stages of survey design, distribution, data collection, and analysis.

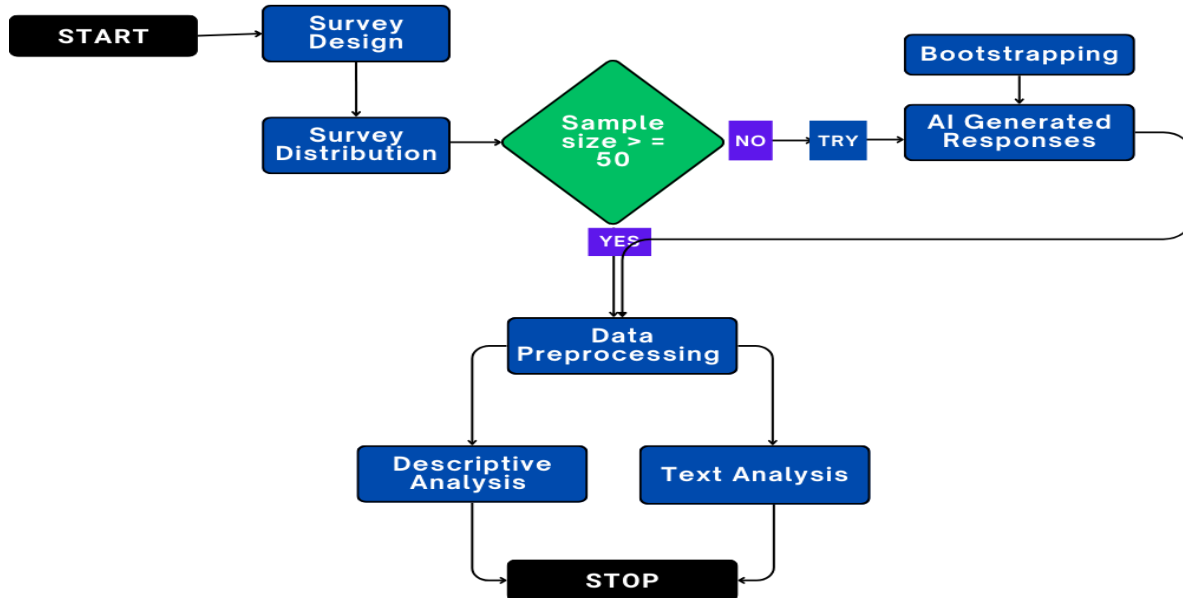


Figure 1: Survey Methodology Flowchart

Table 1 provides an overview of the survey distribution process, timeline, and key demographic characteristics of respondents in the logistics sector.

Table 1: Overview of the job listing methodology, data collection, cleaning, and analysis

Aspect	Details
Survey Design	- Two distinct questionnaires: one for men and one for women.
	- Included both quantitative (Likert scale ratings) and qualitative (open-ended) questions.
	- Focused on gender diversity, AI usage, and workplace inclusivity.
Sample Size	- Target sample size: 50 respondents.
	- Final sample size: 19 respondents (10 men, 9 women).
Distribution Channels	- Distributed via LinkedIn and email.

Aspect	Details
	<ul style="list-style-type: none"> - LinkedIn: Targeted logistics professionals through direct messages and posts. - Email: Sent to logistics companies and professionals across Europe.
Respondent Demographics	<ul style="list-style-type: none"> - Countries represented: Netherlands (5), Italy (4), UK (3), Belgium (3), Germany (1), Portugal (1), Poland (1), Turkey (1). - Age groups: 18–24 (1), 25–34 (5), 35–44 (3), 45–54 (6), 55–64 (4).
Data Collection	<ul style="list-style-type: none"> - Quantitative data: Ratings on gender diversity, AI usage, and effectiveness of initiatives. - Qualitative data: Open-ended responses on challenges, opportunities, and perceptions of AI and diversity.
Data Preprocessing	<ul style="list-style-type: none"> - Merged male and female survey datasets. - Cleaned text data: Removed special characters, lowercased text, removed stop words, and applied lemmatization.
Data Analysis	<ul style="list-style-type: none"> - Descriptive Analysis: Summarized demographics, job roles, and perceptions using frequency distributions and central tendencies. - Text Analysis: Identified recurring themes and sentiments from open-ended responses.

3.1.1 Handling of AI-Generated Responses

To supplement the limited survey responses, this study explored the use of AI-generated responses through OpenAI’s GPT-3.5 model. A structured prompt was designed to simulate realistic survey answers from logistics professionals, incorporating parameters such as job role, experience level, and regional context. The AI generated 50 synthetic responses mirroring the original survey’s thematic scope.

However, these responses were ultimately excluded from the final analysis due to three critical limitations:

1. **Lack of Contextual Depth:** While grammatically coherent, the AI outputs generalized statements (e.g., “AI helps reduce bias”) without industry-specific insights or nuanced personal experiences.
2. **Repetition Bias:** The model reproduced similar phrasing across responses, reducing variability—a key requirement for robust qualitative analysis.
3. **Authenticity Gap:** AI responses lacked the subtle contradictions and idiosyncrasies typical of human respondents, flattening data complexity.

Table 2 summarizes the comparison between human and AI-generated responses highlighting key differences in response quality, authenticity, and thematic depth that informed our decision to exclude AI-generated data from the final analysis.

Table 2 Comparison between Human and AI-generated Responses

Criterion	Human Responses	AI-Generated Responses
Specificity	Role-specific examples (e.g., “Our warehouse uses AI for shift scheduling”)	Generic claims (e.g., “AI optimizes logistics”)
Bias Patterns	Reflects real-world biases (e.g., skepticism toward AI in male-dominated roles)	Overly “neutral” tone, masking systemic biases
Usefulness	High (authentic insights)	Low (supplementary only)

3.2 Job Listing

The job listing data for this research was collected via web scraping using Python's Selenium library. The goal of this method was to gather current job postings related to logistics roles across Europe, focusing on keywords such as "logistics," "warehouse," and "supply chain."

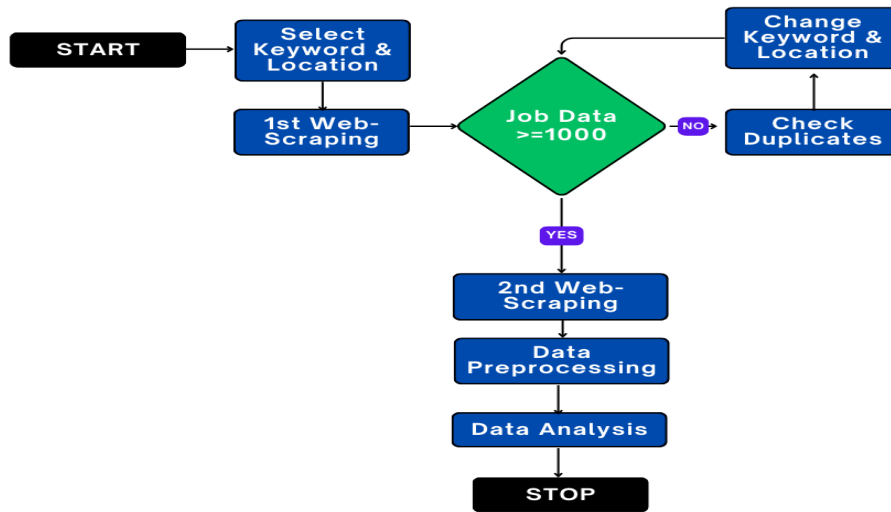


Figure 2: Job Listing Methodology Flowchart

Table 3 provides an overview of the job listing methodology, outlining the data collection, cleaning, and analysis processes used to examine LinkedIn job postings.

Table 3: Overview of the job listing methodology, data collection, cleaning, and analysis

Aspect	Details
Data Collection	- Platform: LinkedIn.
	- Tools: Python's Selenium library for web scraping.
	- Keywords: "Logistics," "Supply Chain," "Warehouse," and related terms.
	- Scope: Job postings from 21 European countries.
Data Analysis	- Descriptive Analysis: Summarized job titles, locations, employment types, and seniority levels.
	- Text Analysis: Used NLP techniques to identify AI-related skills and diversity-related keywords in job descriptions.
Ethical Considerations	- Complied with GDPR and LinkedIn's Terms of Service.
	- Only publicly available data was scraped, with no personal or private information collected.

4 Results and Findings

4.1 Survey Results

The survey findings provide valuable insights into the perceptions, experiences, and challenges related to gender diversity and the role of Artificial Intelligence (AI) in the European logistics sector. As summarized in the table 4, the survey revealed key demographic trends, workplace dynamics, and attitudes toward AI and diversity initiatives.

Table 4: Summary of survey findings on gender diversity, AI usage, and workplace inclusivity

Category	Findings	Discussion
Demographics	- Over 50% of respondents were aged 35 or older	The experienced respondent pool suggests seasoned professionals may have differing views
	- 70% of male respondents held master's degrees, compared to 44% of female respondents.	on AI and diversity initiatives. Educational disparities may influence perspectives on AI adoption and inclusivity.
Job Roles	- Male respondents were distributed across various sectors.	The concentration of women in management roles reflects broader industry trends, where women are often underrepresented in technical or specialized fields, potentially limiting their exposure to AI tools and career advancement.
	- 77.8% of female respondents held management roles.	
Gender Diversity Initiatives	- 44% of female respondents reported workplace gender diversity initiatives compared to 40% of male respondents.	The presence of initiatives is inconsistent, and their perceived effectiveness is limited. This suggests a need for more impactful and well-communicated diversity programs to foster inclusivity.
	- Effectiveness rated moderately (2.67/5 by women, 2.9/5 by men).	
Perceptions of Gender Diversity	- Female respondents rated workplace gender diversity lower (2.8/5) than male respondents (3.8/5).	Women's lower ratings may reflect their experiences or expectations for inclusivity. The low prevalence of discrimination suggests progress, but
	- 22% of female respondents reported experiencing gender-based discrimination.	structural barriers remain, particularly in leadership and technical roles.
Importance of Gender Diversity	- Both genders acknowledged the importance of gender diversity (women: 4/5, men: 4.3/5).	The consensus on the value of gender diversity highlights its strategic importance. However, the moderate ratings of its benefits suggest scepticism about the full implementation and impact of diversity programs.
	- Benefits cited include improved decision-making, innovation, and company culture.	
AI and Data Skills	- Men expressed higher confidence in AI's potential to improve gender diversity (3.8/5) compared to women (3.44/5).	Gender differences in AI tool familiarity and usage reflect a technical skills gap. Bridging this gap through targeted training could empower women
	- Men used AI for technical tasks, while women used AI for customer-facing roles and foster inclusivity in technical roles. (e.g., chatbots).	
Interest in AI Training	- 50% of women and 55% of men expressed interest in AI training.	The strong interest in AI training across genders highlights its perceived value for career growth. However, women's focus on management-level training suggests a need for structural support to implement AI skills effectively.
	- Women emphasized the need for management-level training to support younger employees.	

Category	Findings	Discussion
Challenges and Opportunities	<ul style="list-style-type: none"> - Key challenges include gender bias, work-life balance issues, and stereotypes. - Opportunities include mentorship programs, flexible work arrangements, 	Addressing structural and cultural barriers is essential for fostering inclusivity. Targeted initiatives, such as mentorship and flexible work policies, can help attract and retain more women in logistics.

4.2 Job Postings Analysis

The analysis of LinkedIn job postings in the logistics sector provides critical insights into recruitment practices, skill demands, and diversity-related language. Table 5 summarizes the job listing findings, highlighting trends in seniority levels, employment types, demand for AI skills, and the presence of diversity-related language in job postings.

Table 5: Summary of job listing findings, including seniority levels, employment types and AI skills.

Category	Findings	Discussion
Job Functions	<ul style="list-style-type: none"> - "Management" roles were the most common (highest number of listings). - Other prominent functions: Supply Chain, Manufacturing, Purchasing, Business, Sales, and Distribution. 	<p>The dominance of management roles reflects the sector's need for leadership and oversight. The variety of job functions highlights the multifaceted nature of logistics, requiring expertise across technical, operational, and managerial domains.</p>
Industries	<ul style="list-style-type: none"> - "Manufacturing" was the most frequently noted industry. - Other industries: Non-Profit, Education, Transportation, Retail, Non-Profit, Technology, and Consulting. 	<p>The prevalence of manufacturing-related roles underscores logistics' foundational role in supporting production processes. The presence of non-traditional industries (e.g., Education, Non-Profit) suggests the expanding reach of logistics into emerging fields.</p>
Seniority Levels	<ul style="list-style-type: none"> - Mid-senior and director-level roles comprised approximately 60% of the total positions. - Entry-level roles were underrepresented. 	<p>The emphasis on senior roles suggests that companies may rely on alternative recruitment channels for entry-level positions. The lack of entry-level postings on LinkedIn may reflect industry trends or platform-specific biases.</p>
Employment Types	<ul style="list-style-type: none"> - Full-time roles dominated (94% of listings). - Part-time and contract roles were rare (6% combined). 	<p>The lack of flexible work arrangements may deter women from pursuing careers in logistics, particularly those balancing caregiving responsibilities. Increasing flexibility in senior roles could enhance gender inclusivity.</p>
AI and Data Skills	<ul style="list-style-type: none"> - Low overall demand for AI and data skills, with mentions concentrated in IT-specific roles. 	<p>The limited integration of AI skills in non-technical roles suggests a disconnect between the industry's digital transformation goals and current hiring practices.</p>
Diversity Keywords	<ul style="list-style-type: none"> - Diversity-related keywords appeared frequently but were often generic. 	<p>This indicates an emerging emphasis on inclusivity. However, the lack of gender-specific language suggests a need for more explicit diversity goals and targeted initiatives.</p>

5 Conclusion and Recommendation

This study examined the role of Artificial Intelligence (AI) and data skills in promoting gender diversity within the logistics sector across Europe. Findings from surveys and job listing analyses revealed persistent gender disparities, especially in leadership and technical roles, despite growing awareness of inclusivity. Female respondents reported lower perceptions of workplace diversity and limited access to support structures such as mentorship or flexible working arrangements. The study also found that AI and data-related skills are primarily concentrated in IT roles, with little emphasis on leveraging these tools for diversity enhancement in broader logistics functions.

A significant limitation of this research lies in the low response rate to the survey, with only 19 respondents out of the 50-targeted sample. This limited the statistical power and generalizability of the findings. While AI-generated responses were tested to compensate for this limitation, they were excluded due to their lack of authenticity and nuance. Future studies should therefore adopt broader outreach and sampling strategies, perhaps incorporating partnerships with industry networks and professional associations to boost engagement and ensure diverse representation.

To operationalize the findings across different logistics contexts, organizations should implement AI-driven tools designed to detect and mitigate bias in recruitment and performance evaluation. Integrating diversity-focused analytics into workforce planning can support more equitable advancement opportunities. Tailored training programs that equip employees especially women with data and AI competencies should be prioritized, creating pathways for inclusive participation in digital transformation. Additionally, logistics companies must address structural barriers by embedding inclusive policies such as flexible work arrangements and leadership development initiatives.

Policymakers can contribute by developing governance frameworks that promote ethical AI use in workforce management, providing incentives for inclusive hiring practices, and setting industry benchmarks for gender equity. Through collaborative efforts, AI can be responsibly harnessed to close the gender gap and shape a more inclusive, resilient logistics sector.

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Pragmatic Hyperconnected Freight Systems Design: A Data-Driven Case Study in the US Southeast Megaregion

Ariana Garbers¹, Praveen Muthukrishnan¹, Benoit Montreuil^{1,2}

1. Physical Internet Center, Supply Chain and Logistics Institute

H. Milton Stewart School of Industrial & Systems Engineering

Georgia Institute of Technology, Atlanta, USA

2. Coca-Cola Material Handling & Distribution Chair

Corresponding author: arianagarbers@gatech.edu

Abstract: Throughout the last decade, Physical Internet research on Hyperconnected Freight System Design has demonstrated significant improvements over traditional end-to-end logistics systems. Building on this, our research develops a practical framework for multi-tier space pixelization, logistic region and area design, multi-tier hyperconnected inter-region and inter-area logistic network design, and selection. We select global, regional, and gateway hub cluster locations, using a case study of the Southeast United States. By integrating freight flow data from the Freight Analysis Framework (FAF) with logistics infrastructure data, including roads, rail, and physical facility locations, we establish a data-driven approach to identify hub locations and clusters aligned with freight demand and existing networks. This framework provides a baseline blueprint network design to support stakeholder engagement, enabling discussions on how a hyperconnected model could integrate with and enhance current logistics operations.

Keywords: Physical Internet, Hyperconnected Supply Chain & Logistics, Sustainability, Net Zero Emissions, Network Design

Conference Domain Fitness: Investigating, shaping, enhancing, and enabling the further emergence and large-scale implementation and adoption of the Physical Internet across industries in urban and rural areas, and regions; Imagining, shaping, and engineering the forthcoming generations of hyperconnected supply chain, logistics, fulfillment, transportation, and networks built with physical, digital, and operational interconnectivity at their core.

Physical Internet (PI) Roadmap Fitness: ☒ PI Nodes (Customer Interfaces, Logistic Hubs, Deployment Centers, Factories), ☒ PI Networks, ☒ Access and Adoption.

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

1 Introduction

Many current supply chains and logistic networks function unsustainably from economic, environmental, and social aspects. The global freight and logistics industry accounts for 9.6% of global GDP, 24% of the global CO₂ emissions, and employs 10.3% of the U.S. Labor Force (Allied Research, 2025; Carbon Care, 2025; BTS, 2025). Many of the issues with the industry are deeply rooted and affect all players in the market, from low truck fill rate, wasted packaging, fleet management, poor worker conditions, rising costs, route optimization, etc. Barriers to fixing these issues lie in the disconnect between players in the industry.

As the industry continues to grow, these issues will compound if a shift in logistics and supply chain principles is not implemented. As Montreuil (2011) introduced, the Physical Internet redefines these principles by applying hyperconnectivity and modularity concepts. A

hyperconnected logistics network includes multiple tiers of interconnected clustered territories and hub networks to enable efficient, resilient, and sustainable service of markets at all scales. Applying Physical Internet concepts, these hubs are open to a wide variety of clients and modes, and the interconnected networks can serve as an open logistics web. Prior research in hyperconnected networks highlights solutions for many current logistics and supply chain issues by creating a multi-tiered network of regional, gateway, and local hub networks to connect sets of origin-destination pairs describing applicability at scale (Grover et al., 2023). These solutions have proven to outperform the traditional point-to-point networks and hub-and-spoke network designs through cost, resiliency, sustainability, travel time, lead time, and service capability metrics. The hyperconnected networks accomplish this performance boost by taking advantage of consolidation, efficient routing, and open organizations.

Up till now, hyperconnected network research has mostly focused on conceptual frameworks, approximate optimizations, and simulations, but it often overlooks spatial, infrastructural, and environmental constraints. Integrating the location of intermodal connection ports, such as airports, train yards, and ports, and logistics infrastructure, such as major highway intersections and major metropolises, can increase the model's fidelity and effectiveness of a solution. A gap in this field of research that this paper aims to bridge is the importance of a pragmatic data-driven methodology for identifying and leveraging locations of existing sites and facilities that can be utilized as PI hubs and how demand moves throughout territories using those hub networks.

After reviewing relevant literature, the paper introduces scalable methodologies for hyperconnected freight system design, including clustering territories and identifying potential hub locations for each network tier. It then leverages a case study focused on these methodologies for a hyperconnected network design in the Southeast USA to be used as a blueprint by stakeholders. It then proposes avenues for practical implementation and further research.

1.1 Literature Review

Multi-tier space clustering and hyperconnected network design are fundamental Physical Internet concepts (e.g. Crainic et al., 2023). The literature has explored a variety of avenues for space clustering. Tu (2019) implemented a greedy algorithm following the monotone sub-modular function maximization method for local cell clustering to balance demand and maintain a maximum allowable distance between the cluster and hub candidate. Hettle (2021) developed a large mixed integer program combining graph partitioning and min-cost flow problems. This approach was applied to the lower level of unit zone, local cell, and urban area for redesigning SF Express's hyperconnected network in Shenzhen. The results proved compact and balanced clusters, but it relied on a large optimization model and fixed hub locations, which are not scalable to larger regions.

Grover et al. (2023) provided a comprehensive framework for defining the multi-tiered network topology and their purposes. The design approach highlighted the strength of hyperconnected networks as a crucial PI component. They utilized proximity-based clustering and optimization models to assign hubs to clusters while balancing demand using USA population data. While they enabled a strong understanding of clustering applicability at a large scale, the population-based modeling is not directly representative of the mixed freight demand the network would experience. Other factors contribute to the distribution of freight flow, such as commodity type, employment, and industry activity (FAF, 2025), as well as the underlying infrastructure and availability of locations.

Due to the computational difficulty of the previously proposed methodologies, incorporating practical constraints such as ensuring the intersection of highways is contained within a cluster and ensuring hub proximity to transport ways and other logistics infrastructure is challenging.

1.2 The Southeast United States as a case study

The case study leveraged through the paper focuses on designing a hyperconnected freight system for the US Southeast megaregion, including the states of Alabama, Arkansas, Florida, Georgia, Louisiana, Mississippi, North Carolina, South Carolina, and Tennessee. There are 755 different counties across the entire Southeast, with each state averaging 83 counties. In this case, we use an extended version of the multi-tier space pixelization introduced in Montreuil et al. (2018), starting with the world at the highest tier, then hierarchically down to block, megaregion, region, area, local cell, and unit zone. The study focuses on the US Southeast megaregion down to the Southeast counties as local cells, ignoring finer-granularity unit zones. It aims to define appropriate areas as clusters of counties, the basic local cells, and appropriate regions as clusters of areas.

Freight transportation demand into, out of, and within the Southeast is estimated annually at the finest granularity, thus from county to county, based on the Freight Analysis Framework Database (FAF, 2025). The counties vary highly in inbound and outbound freight demand distribution, with the largest county, Miami-Dade County in Florida, having 65 M tons of annual demand and the smallest, Taliaferro County in Georgia, having 236K tons of total annual demand. The main interstates and railroads through the Southeast are shown in Figure 1. Fixed for the case are the global hubs corresponding to Southeast cargo seaports and airports where freight flows into and out of the USA, notably the largest Southeast port is Savannah with a throughput of 42.1M tons in 2024. (GPA, 2025) The hyperconnected networks to be designed are the inter-regional network, whose nodes are regional hubs, the inter-area network, whose nodes are gateway hubs, and the interconnections between the inter-regional network and the global hubs in or near the Southeast, and between the inter-regional and inter-area networks.

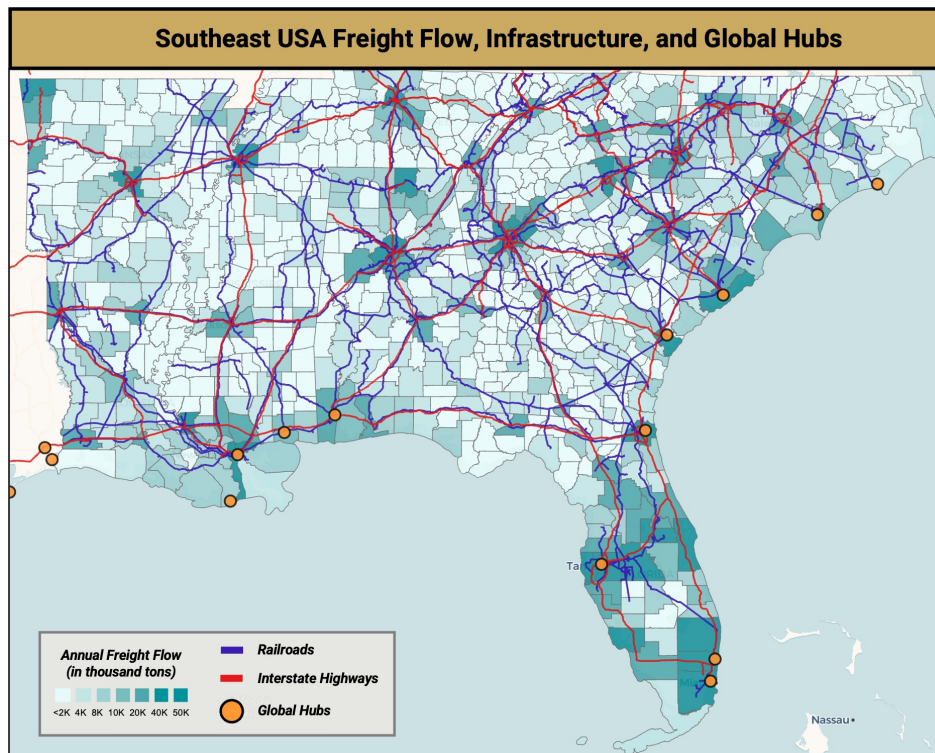


Figure 1: Southeast United States Counties and Logistics Infrastructure

2 Methodology

2.1 Inter-County Freight Demand Estimation

As a first step, we estimated robust freight demand from each origin county to each destination county. This was achieved using data from the Freight Analysis Framework (FAF, 2025). FAF provides an annual tonnage of demand flow for all county pairs. Tonnage was filtered based on the commodity and transportation type to represent freight flow across the Southeast in terms of trucks. From the five types of commodities in FAF County-County Flows data, we filtered out non-palletizable commodities (coal and gravel) as these are not going to be handled by PI Networks. This determined each county's annual total, inbound, internal, and outbound flows. From an initial analysis, we found the majority of the flow in the Southeast U.S. was either internally from the Southeast or externally from the US Midwest megaregions. This guided some initial planning of interregional hubs in the Southeast. For the purposes of sizing hub capacity requirements, a peak daily volume estimate was needed. The Truck Tonnage Index from the Bureau of Transportation Statistics was utilized to determine a monthly factor (FRED, 2025). A daily demand flow factor was approximated through IEEE's truck volume flow. (NTDAS,2025) This data represents the volume of vehicle travel in 5-minute intervals selected for 2023 of each Traffic Message Channel (TMC) segment across the United States. A TMC segment is defined relative to important intersections or interchanges. We selected the highway/roadway lane segment, corresponding to a TMC segment in the IEEE database, closest to each county and calculated the robust maximum percentage of volume for all the days in the highest TTI month. The peak daily demand value for each county was estimated by multiplying the monthly factor by the largest flow (Inbound or Outbound) and by the daily percentage of volume. This will be used later to determine the throughput requirements of hubs and the number of hubs needed per area. The flow presented in all the graphs is in thousand tons.

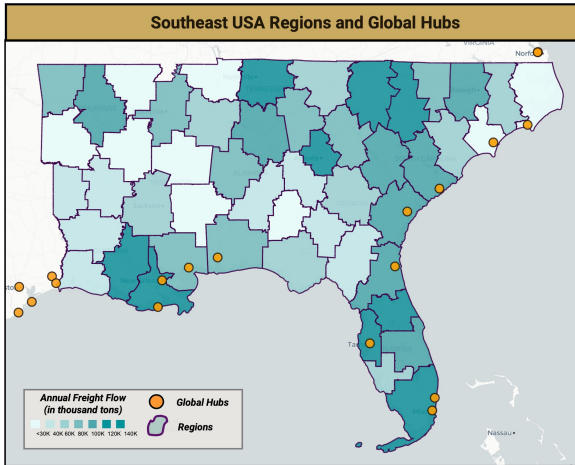


Figure 2: Proposed Regional Areas

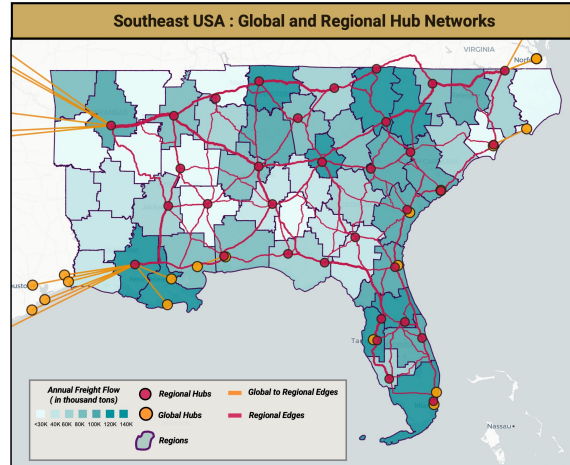


Figure 3: Proposed Inter-Region Network of Regional Hubs

2.2 Regional Clustering, Network Design, and Hub Location Selection

We proceed to define the multi-tier space pixelization from a top-down perspective, defining regions as clusters of counties, and then at a next stage defining areas as smaller clusters of counties that are each fully contained within a unique county, so that each county corresponds to a clustering of areas. The regions are jointly served by a cross-region logistics network linking regional hubs. These hubs are strategically placed near major intersections, ports, and railroads, located relative to each other for overall logistics performance for supporting intra-region and inter-region freight flows. Our first clustering step utilized the weighted k-means approach, creating Southeast regions as clusters of counties given a target number of clusters.

K-means is a simple method, used here with the main objective of balancing demand between the regional clusters. We solved for many numbers of target regions, then the final clustering with 50 regions was chosen based on the resulting distribution of demand amongst regions, the balance of regional sizes, and the travel time between regions. The set of 50 regional clusters was post-processed to improve contiguousness, compactness, distribution of demand across regions, and proximity to interstates and other logistics infrastructure. To measure the compactness of these clusters, we calculated the maximum distance between any two points along the border of the cluster, to be defined as the average region-crossing distance. The resulting regions depicted in Figure 2 have an average region-crossing distance of 148 miles, corresponding to about 2.5 hours of travel.

We selected the regional hub locations in the cross-region network primarily based on proximity to existing infrastructure (interstates, railroads, ports, freight corridors, etc.) while ensuring travel between neighboring connected hubs is robustly within 5.5 hours or less to ease having drivers back home daily if they so desire. These locations minimize the gap between the direct distance between any pair of hubs and their distance traveling through the network and facilitate inter-regional freight flow consolidation. The resulting cross-region network serving freight demand through the 50 regions is depicted in Figure 3. It has 33 regional hubs, or more precisely, regional hub clusters. A hub cluster is a group of interconnected hubs collectively having the capacity to handle the freight demand stemming from/to other networked hubs. Each hub cluster is aggregated into a single location at this pixelization level. The total freight flow throughput for each regional hub cluster will be discussed in Section 3. We then identified ten hub clusters as proxy Entry/Exit hubs to/from the Southeast for freight demand estimation. These hubs are near the border of the Southeast and serve as the first stop for flow coming from outside of the Southeast and the last stop out of the Southeast.

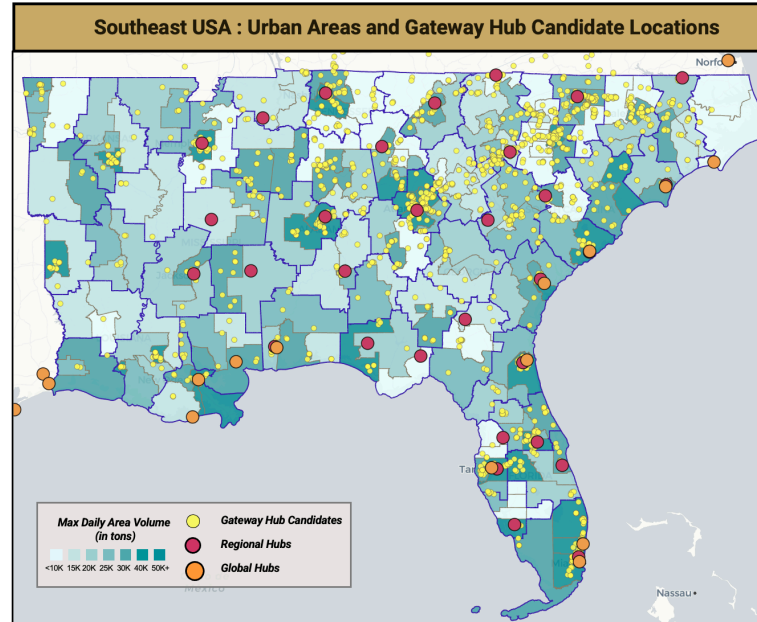


Figure 4 Proposed Urban Area Boundaries and Gateway Hub Candidate Locations

2.3 Urban Area Clustering and Hub Location Selection

Next, we proceeded to define a satisficing set of areas as clusters of counties within a region. Areas differ by their mix of urbanity, peri-urbanity, and rurality, by their population size and characteristics, by their gross domestic product, and by their mix of residential, industrial, agricultural, commercial, and institutional spaces, and by their topography. As a first clustering step, we used the Max-P Regions Heuristic proposed by Juan (2010) for each region to form

area clusters of the region's counties. This heuristic generated spatial clusters that partition counties into the maximum number of (p) contiguous areas while satisfying specifically imposed threshold constraints of up to 20, 15, and 10 thousand tons of freight flow demand per area to balance diverse degrees of demand across the urban areas within the region, parameterized to aim for similar freight demands and proximity. As done for region clustering, we then post-processed the most satisfying heuristically generated area clustering to ensure highway intersections and railroads/yards were contained within an urban area, to take advantage of the local consolidation capabilities, to increase network robustness, to enable dynamic routing within the network, and to minimize coordination overhead. As displayed in Figure 5, the final clustering combining the region-specific area clusters proposes 186 areas out of the 755 counties in the Southeast, including 46 single-county areas due to the flow magnitude in these counties. The areas have an average cross-area distance and time travel of 82 miles and 1.18 hours, respectively. This notably provides ample routing optionality for truck drivers within the daily regulation of maximum eleven driving hours (Kim et al., 2021). At this level of granularity, we opted to use the CoStar database to define a realistic set of candidate sites for gateway hubs as part of the inter-area network. (CoStar, 2025) We targeted existing locations with 20k+ ft² space availability with facilities currently identified as either warehouses, truck terminals, distribution centers, or manufacturing sites, see Figure 4. When no such sites are available, we targeted open plots of land or in-construction buildings. The candidate set contained 4,338 locations, the density of which increases towards metropolitan areas.

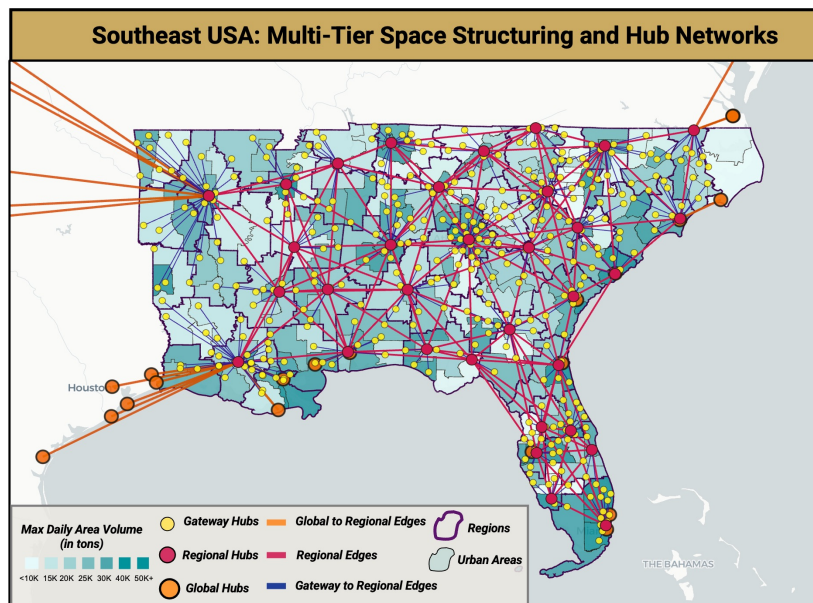


Figure 5 Proposed Multi-Tier Space Structuring and Hub Networks for Southeast USA

Gateway hub selection was performed using a Set Covering optimization model similar to (Muthukrishnan, 2021), by setting the number of hubs serving each urban area to be the greater of 2 or the maximum daily demand of that urban area divided by the capacity of that hub. We imposed that each selected hub may accommodate at maximum a throughput of 20k tons per day, and that selected hubs must be greater than 20 miles apart from each other to enhance resilience and routing optionality. This sizing constraint was based on a robust distribution of the space available in the candidate hub locations. Based on the optimization results and our post-processing to meet practical constraints, we propose a pan-Southeast network of 556 gateway hubs across the 186 urban areas, for a ratio of about three hubs per area. The resulting inter-area network is shown in Figure 5, with blue connections between gateway hubs and regional hubs. Not displayed are the flow connections between nearby gateway hubs, in our

case bounded to be in the same region or at maximum 30 miles from each other. While this may seem like a large number, it enables swift responsiveness and minimized travel across areas throughout the entire Southeast megaregion, it provides a cushion against fluctuations in demand and availability of routes, and disruptions across the network. Figures 6 and 7 focus on the proposed gateway hub networks for Atlanta and Birmingham metropolitan areas, highlighting their proposed hub density and distribution, the respect of having highway intersections fall within urban area boundary, and the aim for gateway hubs to be near the highways (red) and railroads (blue).

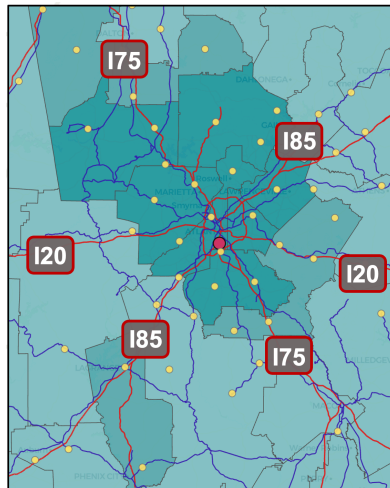


Figure 6 Proposed Gateway Hub Network Metro Atlanta

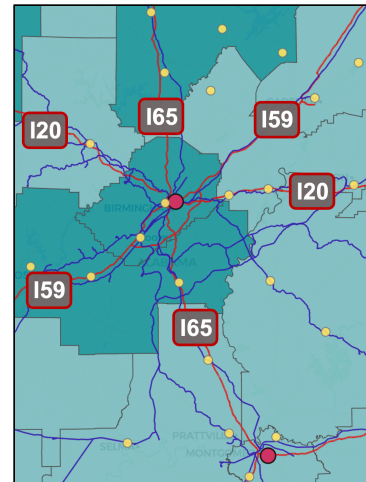


Figure 7 Proposed Gateway Hub Network Metro Birmingham Area

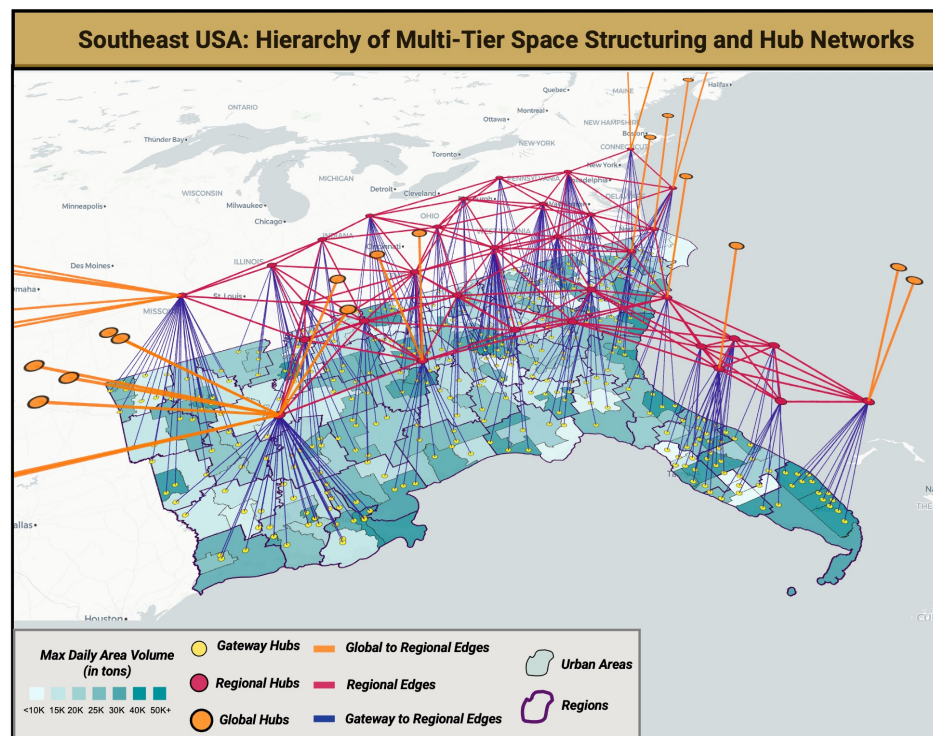


Figure 8 Proposed Hyperconnected Hierarchical Multi-tier Logistics Networks for Southeast USA

To visualize the connectivity between the regional hub network and the gateway hub network, we provide in Figure 8 a tridimensional projection of these networks on two planes. As there is high flow in the metropolitan areas, there are more gateway hubs in these areas, and more flow connections from urban gateway hubs to regional hubs.

3 Flow Analysis and Observations

We here examine how the selected 50 regions and their associated regional hub clusters influence freight flows to, from, and within the US Southeast. We assume that all intra-regional movements within these 50 regions are handled by a lower-tier meshed network composed of Gateway, Local, and Access hubs. For flows involving external origins or destinations, all non-Southeast areas are aggregated into 108 FAF regions, as defined in FAF User Guide (FAF, 2025). Based on this framework, the network handles three main types of flows (1) shipments between regions within the Southeast megaregion, (2) inbound shipments from external FAF regions to regions within Southeast, and (3) outbound shipments from regions in the Southeast to FAF regions outside the megaregion.

The objective of this analysis is to estimate the throughput of freight flows across various regional hub clusters in order to identify major flow corridors, high traffic entry/exit hubs in the Southeast USA, and external FAF Regions that are connected through key corridors. To structure this analysis, we formally define a set of origin-destination pairs, which are either external FAF regions or regions within the Southeast, that must be routed efficiently through the regional hub network.

The analysis begins by identifying the primary entry and exit hubs facilitating freight movement between the Southeast and each external FAF region. To ensure scalability and tractability, we adopt a set of simplifying assumptions. Specifically, all road inbound flows from external FAF regions are assumed to be aggregated and dispatched to their destinations in the Southeast through the nearest entry hub via the road network. Similarly, all outbound flows from the Southeast to each external FAF region are assumed to be consolidated and dispatched through the nearest exit hub, also using the road network. For example, all freight flows originating from the Los Angeles, CA region are first routed through the entry hub located in Little Rock, Arkansas, as shown in Figure 9.

At the end of this step, each external FAF region is connected by a defined edge to its closest entry or exit hub within the Southeast, forming the foundational links for analyzing cross-Southeast freight movement. The next step involves mapping each region to the potential hubs that can serve it. We assume that a region is connected to its nearest hub in each cardinal direction, provided that a hub exists within a 50-mile radius in that direction via the road network. For example, the region in pink is connected to a hub in each direction, as illustrated by the green lines in Figure 9.

As a result, we now have a graph consisting of nodes representing FAF regions, regional hubs, and Southeast regions, with bi-directional edges between FAF regions and their corresponding entry/exit hubs, edges between hubs, and bi-directional edges between regions and hubs.

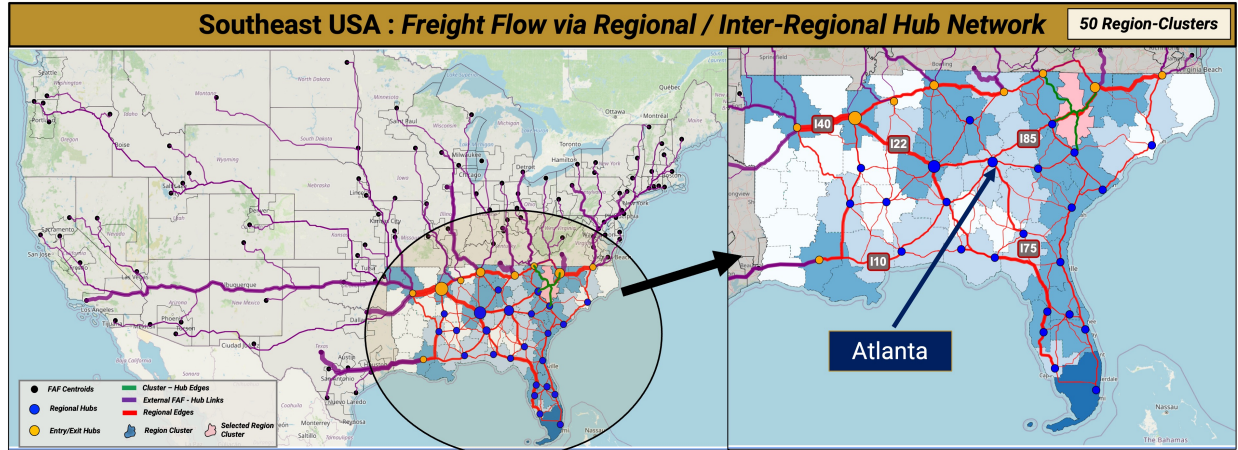


Figure 9: Freight flows via Proposed Regional/Inter-Regional Network in Southeast USA

The problem can now be formulated as a Minimum Cost Multi-Commodity Network Flow Problem, with the objective of optimizing the flow of commodities through the network while minimizing the total miles traveled. To develop a more balanced model, future studies could consider minimizing multiple objectives, such as meeting service time commitments, reducing greenhouse gas emissions, and incorporating directional consolidation of shipments. (Shaikh et al., 2024, Shaikh et al., 2025). Figure 9 illustrates the freight flows resulting from our optimization along hub-to-hub connections as well as the flows entering and exiting the Southeast via external FAF regions. Line thickness represents the flow volume, hub node size is throughput dependent, and hub color differentiates entry/exit hubs from other regional hubs.

Several key observations emerge from the analysis. Notably, freight flows with the western regions tend to be highly consolidated into a few major corridors, whereas flows with the Midwest and Northeast are more dispersed across a broader set of corridors. At the individual FAF region level, the highest inbound freight flows into the Southeast originate from the remainder of Texas, Dallas, and Los Angeles. However, when aggregated by megaregion, the Midwest emerges as the largest source of freight flow into the Southeast. This suggests a more even geographic distribution of industrial, agricultural, and manufacturing activity across the Midwest, in contrast to the more centralized flow structure seen in the West.

Among entry and exit hubs, Memphis and Baton Rouge emerge as key high-throughput regional hubs. Their prominence highlights not only their strategic geographic locations but also the strength of their surrounding road infrastructure, which enables efficient connections to multiple external FAF regions. From there, the freight flow is largely dispersed through regional hubs in Birmingham and Atlanta, eventually extending toward Miami. Disruptions at any of these hubs could significantly affect the entire freight network, delaying deliveries and increasing transportation costs to/from Southeast. Therefore, it is essential to ensure that these hub clusters are well-protected and resilient to potential disruptions.

In terms of corridors, I-75, I-10, I-22, I-40, and I-85 are the high-volume corridors for flows within, into, and out of the Southeast. Strengthening and maintaining the resilience of these corridors will be crucial for safeguarding the efficiency and stability of the entire Southeast freight network.

While this section presents a framework for flow analysis through a regional hub network, future studies could expand on this by analyzing concurrently the multi-tiered network, where the destinations and origins are more granular. Instead of just looking at flows at the regional level, future work could explore the movement of goods from larger regions down to urban areas, providing a more detailed understanding of freight flows within cities. By considering

area-level granularity, such studies could provide more actionable insights for improving the efficiency of both regional and local freight systems using Physical Internet hyperconnectivity. Further, the origin-destination flows can be distributed among multiple paths, so that the risks of commodity flow being disrupted are spread, and demand fulfillment could still meet service time deadlines in disruption scenarios (Muthukrishnan et al., 2024).

4 Conclusion and Further Research

This paper has introduced a systemic pragmatic data-driven approach for multi-tier space clustering and a multi-tier hyperconnected network for a megaregion, incorporating practical constraints and considerations. Utilizing geographic, infrastructural, and flow-based data increases the fidelity of the proposed networks, which can be used as a blueprint for strategic planning and action by industry and institutional stakeholders and as a baseline for further research studies. By combining existing political boundaries, such as counties with key logistics infrastructure, this approach ensures that the clusters are not only geographically coherent but also optimized for efficient freight movement. This flexibility allows the framework to be highly adaptable, facilitating the development of robust, scalable freight networks in different regions and supporting the broader goals of global logistics and supply chain optimization. In the Southeast, our proposed regions, areas, and in turn our proposed multi-tier hyperconnected networks can already be used as a vantage point to start discussions with communities to understand their unique constraints and needs further and to reflect on how our propositions enable enhanced performance, resilience, and sustainability. As shown with the availability of sites for PI hubs, implementing a PI hyperconnected network does not have to rely mainly on new buildings. This paper adds to the narrative of the feasibility of PI networks and operations and provides a proof of concept for actual implementation.

As future research avenues, there is need to extend the scope: *downward* to finer pixelization at lower tiers including intercell and interzone networks, *upward* to coarser pixelization at higher tiers including transcontinental and global networks; *sideward* to other megaregions to contrast contexts, available data, applicable methods, proposed network alternatives; *mode-ward* to include seamlessly key modes by investigating hyperconnected road, rail, water, underground, and air based modes; *depth-ward* by enhancing analysis, design, and stress testing methods from AI, optimization, simulation, digital twins, and extended reality; and *field-ward* by shifting to pilot testing the propositions with industry and institutional leaders at various scales for applicability, efficiency, sustainability, and resilience, starting with limited ambitions and corridors or networks, then growing in scale and scope through a rigorous roadmap.

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Hydrogen Refueling Facilities in Logistic Hubs across the Physical Internet: Adapting the Deployment to Vehicle Autonomy

Mina Kim, Nishanth Karupaiyan, Praveen Muthukrishnan, and Benoit Montreuil
Physical Internet Center, Supply Chain & Logistics Institute
School of Industrial & Systems Engineering
Georgia Institute of Technology, Atlanta, U.S.A.
Corresponding author: mkim939@gatech.edu

Abstract: *This study investigates the strategic deployment of hydrogen refueling infrastructure for fuel-cell electric heavy-duty trucks (FCEV HDTs) within a hyperconnected Physical Internet (PI) logistics network. Focusing on the southeastern United States, we analyze 31 logistics hubs and propose an optimized multi-stage deployment sequence based on the drivable range and operational autonomy of current FCEV HDT models. Using real-world specifications from commercial and prototype vehicles, we evaluate how hub-based refueling infrastructure impacts network coverage. The selection of hubs is guided by their marginal contribution to increasing feasible freight routes. Our simulation results illustrate an effective deployment sequence of hydrogen refueling facilities across regional Physical Internet hubs, determined by the drivable range of FCEV HDTs. This work advances the literature on hydrogen infrastructure planning by incorporating Freight Analysis Framework data and logistics hub topology—an approach not previously explored in this context.*

Keywords: *Graph-based Optimization, Network Optimization, Discrete Algorithm, Routing, Physical Internet, Freight Analysis Framework, Clean Energy, Sustainability, Infrastructure Planning, Fuel-cell Electric Vehicle*

Physical Internet (PI) Roadmap Fitness: ☒ PI Nodes (Customer Interfaces, Logistic Hubs, Deployment Centers, Factories), ☒ System of Logistics Networks

Targeted Delivery Mode-s: ☒ Paper, ☒ In-Person presentation

1 Introduction

This research investigates the strategic deployment of hydrogen refueling infrastructure for fuel-cell electric heavy-duty trucks (FCEV HDTs) at Physical Internet (PI) hubs, using the southeastern United States as a testing ground. Leveraging a potential hyperconnected network of 31 logistic hubs across seven states, we develop an optimized sequence for implementing hydrogen refueling facilities based on varying autonomy of FCEV HDT drivable hours. The hubs to be equipped for hydrogen refueling are selected according to their impact on expanding the number of feasible routes for FCEV HDTs once a refueling facility is established.

This study serves as a cornerstone in investigating how a PI hub network can effectively support the transition of the freight system to rely on clean-energy vehicles in the quest toward net-zero emissions. Integrating hydrogen refueling facilities into logistics hubs, rather than constructing stand-alone stations, has the potential to significantly reduce transportation energy consumption and enhance refueling convenience, addressing one of the biggest challenges in the adoption of alternative fuel vehicles (Xu et al., 2024).

The transition to FCEV HDTs has been widely recognized as a promising and necessary development. As Li et al. (2022) discuss, this shift presents numerous opportunities in energy

efficiency, long-haul viability, and emissions reduction, provided that adequate refueling infrastructure is in place. While the hydrogen refueling station location problem has been explored in various studies, to the best of our knowledge, no prior research has utilized Freight Analysis Framework (FAF) data and logistics hub locations as candidate sites for refueling infrastructure planning.

2 Related works

2.1 Physical internet and regional hubs

PI is a transformative logistics concept proposed by Montreuil (2011) to tackle the inefficiencies and unsustainability of global supply chains. As originally envisioned and now gradually emerging, PI is a hyperconnected, open logistics system where physical goods move through standardized, modular containers across interoperable networks, akin to data in the digital internet. In PI, regional logistic hubs serve as higher-plane gateway nodes that consolidate and manage parcel flows across broader geographic areas beyond individual urban zones (Montreuil et al., 2018).

The hyperconnectivity of PI leverages an open network of interoperable hubs, dynamic information flows, and distributed interconnected decision agents, to allow trucks to reroute based on dynamically fluctuating distributed freight shipment demand, current hub capacities, delays, or disruptions. Crainic and Montreuil (2016) emphasize that hyperconnected city logistics networks empower vehicles to dynamically select optimal paths and intermediate hubs based on real-time accessibility and demand. Further, Shaikh and Montreuil (2024) propose a sector-based dynamic directional routing framework, in which trucks adapt their trajectories by selecting among multiple feasible hubs depending on flow patterns and service level conditions. Such adaptability enhances system resilience, reduces congestion at overloaded hubs, and improves resource utilization across the entire network.

2.2 Hydrogen refueling facility location

The placement of hydrogen refueling stations has long been a subject of study within the vehicle refueling facility location problem, with Kuby and Lim (2005) introducing the Flow-Refueling Location Model to ensure that vehicles can complete round trips along major corridors without fuel depletion. Their work emphasized strategic station siting along traffic flows to maximize coverage and minimize user deviation from optimal travel routes. Building on this foundation, Zhou et al. (2024) propose a multi-period, many-objective optimization framework that incorporates real-world spatial data—including geographic information such as land use, population density, and economic activity—to determine both the location and capacity of hydrogen refueling stations in urban areas. Their findings show that demand evolves spatially over time, with stations initially deployed in peripheral city areas and later concentrated in urban centers as hydrogen vehicle adoption increases.

Compared to diesel refueling infrastructure, which is mature and widely available globally, and electric vehicle (EV) charging infrastructure, which is rapidly expanding, hydrogen refueling station deployment remains in its early stages, being highly concentrated in a few regions and mostly targeted toward large industrial heavy-duty vehicles. According to the International Energy Agency (2023), public EV charging points worldwide exceeded 2.7 million units by the end of 2022, driven by declining battery costs and strong government incentives. In contrast, as of 2023, there were approximately 1,000 public hydrogen refueling stations globally, with the majority located in China, Germany, South Korea, Japan, and a few U.S. states such as California (LBST and T²UV S²UD, 2024). Unlike EV infrastructure, which primarily requires

grid connectivity, hydrogen systems necessitate synchronized planning across electrolyzer production, high-pressure storage, delivery logistics, and station operations, making scalability more complex within decentralized freight networks.

2.3 Hydrogen fuel-cell electric heavy-duty trucks

FCEV trucks are becoming vital part of decarbonizing long-haul freight transport. Proven commercial models such as Hyundai's Xcient demonstrate the scalability of this technology, featuring modular hydrogen storage and advanced fuel-cell systems. In addition to these flagship vehicles, multiple manufacturers—including Mercedes-Benz, Toyota, and Volvo—are actively developing FCEV truck platforms for commercial deployment (Basma and Rodriguez, 2021). While the Xcient offers a driving range of approximately 400 km, the prototype of Mercedes-Benz GenH2 has achieved over 1,000 km on a single fill of liquid hydrogen (Hyundai Motor Company, 2024; Daimler Truck AG, 2023). At highway speeds of 80 km/h, these ranges support 5 to 12.5 hours of continuous operation, rivaling conventional diesel trucks in performance.

3 Simulation setting

This simulation aims to explore how strategically deploying hydrogen refueling infrastructure at regional logistics hubs can enable FCEV HDTs to operate within a hyperconnected freight network. The simulation evaluates the impact of different refueling facility deployment strategies on route feasibility for FCEV HDTs. The following subsections describe the data sources and preprocessing steps used to build the network (Section 3.1), followed by the algorithms designed to assess and optimize infrastructure deployment (Section 3.2).

3.1 Data description and preprocessing

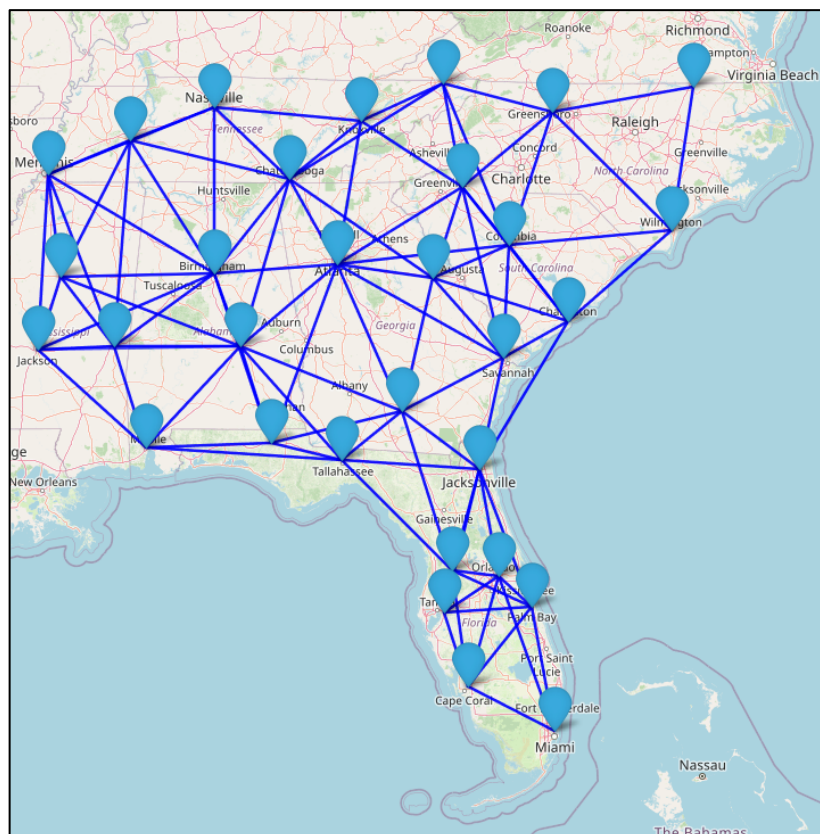


Figure 1: Map of regional logistic hubs and the network of feasible paths connecting them

FAF, developed by the U.S. Department of Transportation's Bureau of Transportation Statistics in collaboration with the Federal Highway Administration, offers comprehensive estimates of freight flows among states and metropolitan areas (U.S. Department of Transportation, Bureau of Transportation Statistics & FHWA, 2017). As input to our simulation model, we utilize FAF data, the locations of 31 regional logistic hubs, drivable paths between these hubs, and the travel time for each path, across seven southeastern states: Alabama, Florida, Georgia, Mississippi, North Carolina, South Carolina, and Tennessee, as shown in Figure 1. Upon reaching a hub in the network, trucks may simply pass by it without stopping, or stop for a sojourn at the hub to park during trucker rest time, to decouple trucker and truck, the decouple tractor and trailer, to decouple modular containers and truck or trailer and then to reconsolidate them toward their next destination, and/or to decouple modular containers from their encapsulated shipped objects (freight) and then reconsolidate them into other containers having the same next destination.

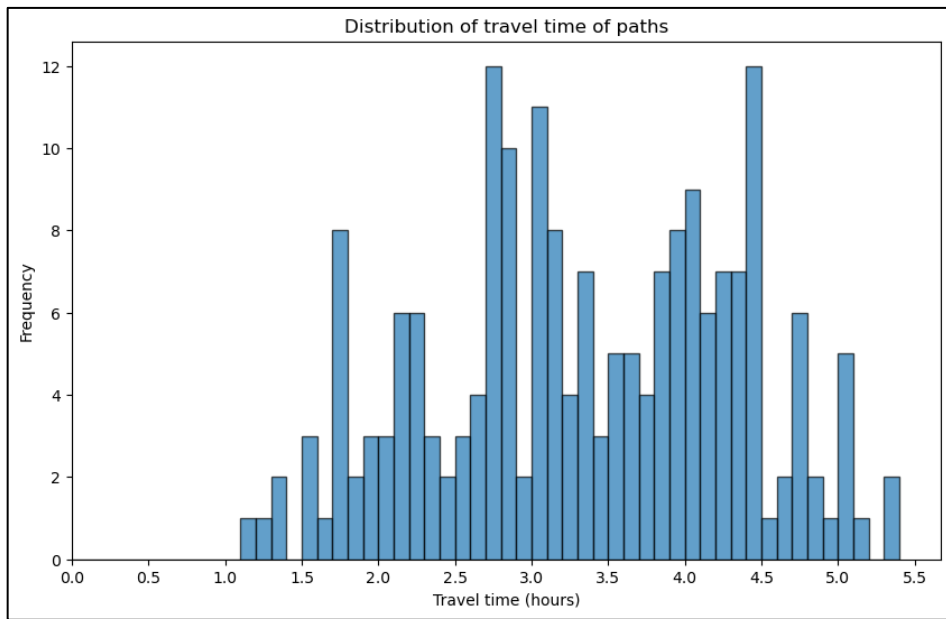


Figure 2: Distribution of travel times of the 195 feasible direct inter-hub links in the US Southeast hyperconnected logistic hub network

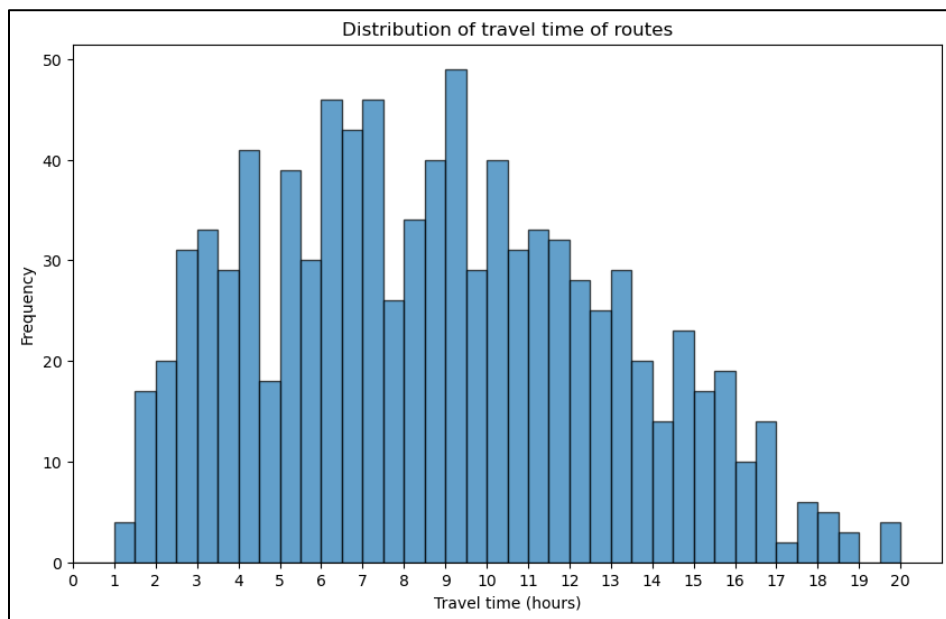


Figure 3: Distribution of travel times of the shortest routes between all 930 directed hub pairs

Using the hubs as nodes and the paths as edges, we build a directed graph, as travel times vary depending on the direction of travel. It is possible for a truck to go directly from its origin hub to its destination hub without stopping at any intermediary hub, corresponding to a full-graph 930 possible inter-hub path. This said, as shown in Figure 1, the graph is not represented as being fully connected but rather mostly as a mesh with only neighboring hubs being connected, here those within a 5.5-hour travel time to enable roundtrip travel by a driver within a single day, enabling the driver to come back home every day if desired. The depicted graph has 195 direct inter-hub paths. The distribution of travel times for these direct paths is shown in Figure 2, ranging from 1.18 to 5.36 hours. The shortest routes for 930 directed hub pairs through the graph are computed using the Dijkstra algorithm (Dijkstra, 1959, 2022). The resulting distribution of travel times for these shortest routes ranges 1.18 to 19.83 hours and is shown in Figure 3.

3.2 Algorithms descriptions

Routes that can be covered by FCEV HDTs are directly determined by their allowable drivable time per full hydrogen refueling. In this study, we simulated various drivable times for FCEV HDTs, ranging from 5 to 20 hours. This range was selected based on existing and prototype models, such as the Hyundai Xcient Fuel Cell Truck, which has a driving range of 400 km, and the Mercedes-Benz GenH2 Truck prototype, which has recorded a range of 1,000 km. Assuming an average speed of 80 km/h across the network, these ranges translate to different feasible driving durations before requiring refueling.

To heuristically optimize the deployment of hydrogen refueling facilities, the algorithm identifies the optimal sequence of hub installations based on their impact on FCEV HDT route coverage, as shown in Algorithm 1. A route is considered covered if it is reachable by refueling at hubs equipped with hydrogen refueling facilities. Since we cannot determine how far a truck can travel without knowing its remaining level of hydrogen at each point along the route, we frame the truck routes such that they begin and end at hubs equipped with refueling facilities. We assume that the trucks are fully refueled at these hubs, which allows us to estimate their reachable range throughout the route.

Algorithm 1 Selecting Hubs for Hydrogen Refueling Facility Installation

```

1: Input: Set of hubs  $H$ , set of routes  $R$ , drivable time  $T$ 
2: Output: Sequence of hubs for facility installation
3:  $C \leftarrow \emptyset$  ▷ Set of hubs with facility
4:  $U \leftarrow R$  ▷ Set of uncovered routes
5: while  $U \neq \emptyset$  do
6:   for each hub  $h \in H \setminus C$  do
7:     Compute  $N_h$ , the number of routes in  $U$  that can be covered with facility by adding  $h$  to  $C$ 
8:   end for
9:   Select hub  $h^* = \arg \max_h N_h$  ▷ Choose hub with highest coverage
10:   $C \leftarrow C \cup \{h^*\}$  ▷ Add selected hub to facility set
11:  Update  $U$  by removing routes covered by  $h^*$ 
12: end while
13: return Sequence of hubs in  $C$ 

```

Algorithm 1: Selecting Hubs for Hydrogen Refueling Facility Installation

However, this does not imply that trucks must depart and arrive at only the refueling-equipped hubs. Some segments of covered routes are also considered covered if they are included in the list of shortest routes, as these segments are expected to be traveled as part of the overall trip. This framing enables us to assess the coverage potential of a given facility deployment without tracking vehicle-level fuel consumption in real time. It is intended to estimate the maximum

number of reachable routes under the assumption that FCEV HDTs determine their routes prior to departure. While this constraint may limit the operational flexibility of FCEV routes, such flexibility is expected to be improved once FCEV HDTs reach broader market adoption and additional refueling stations are deployed. The objective of this study is to propose a strategic deployment roadmap for refueling facilities with early steps that maximizes impact while minimizing cost and deployment time.

The process begins by evaluating each hub individually to assess the number of routes it can support if a refueling facility is installed, as shown in Algorithm 2, to select the hub with the highest initial coverage. The algorithm calculates the number of hub-to-hub routes that can be completed when a hydrogen refueling facility is placed at a given hub. It first checks whether a round trip is directly drivable within the vehicle's range and then considers routes that can be completed via intermediate hubs with refueling capability.

Algorithm 2 Counting the number of routes a single facility can cover

```

1: Input: Set of hubs  $H$ , set of routes  $R$ , drivable time  $T$ 
2: Output: Number of routes that can be covered for each hub
3: for each hub  $h$  in  $H$  do
4:   ForwardList  $\leftarrow$  all hubs reachable from  $h$  within time  $T$ 
5:   BackwardList  $\leftarrow$  all hubs that can reach  $h$  within time  $T$ 
6:   for each hub  $f$  in ForwardList do
7:     if travel time from  $h$  to  $f$  + travel time from  $f$  to  $h$   $< T$  then
8:       count the route between  $h$  and  $f$  as covered
9:     else if
10:      for each hub  $b$  in BackwardList do then
11:        if travel time from  $h$  to  $f$  + travel time from  $f$  to  $b$  + travel time from  $b$  to  $h$   $< T$  then
12:          count the route between  $h$  and  $f$  as covered
13:        end if
14:      end for
15:    end if
16:  end for
17: end for
18: return Number of routes that can be covered for each hub in  $H$ 

```

Algorithm 2: Counting the number of routes a single hub with hydrogen refueling facility can cover

Once the first facility is selected, the algorithm proceeds to identify the next most impactful hub by measuring the marginal increase in route coverage. Algorithm 3 quantifies the additional routes that would be enabled by installing a facility at each candidate hub not yet selected. It considers both direct and indirect connections with intermediate hubs included, and accounts for driving range constraints. To ensure that the newly added facility meaningfully improves network coverage, the set of segmented routes is re-evaluated at each iteration before making the next selection. These marginal gains are then used to iteratively select the next facility, ensuring the most efficient expansion of the refueling network.

4 Simulation results

Table 1 and Figure 4 and Figure 5 depict the results of simulations for given drivable hours of FCEV HDTs. As shown in Figure 4, the number of required hydrogen refueling facilities decreases as the drivable time of FCEV HDTs increases. When the drivable time is limited to 5 hours, even equipping all 31 hubs with refueling facilities is insufficient—only 880 out of 930 routes are covered, since some paths require more than 5 hours of travel time, as illustrated in Figure 2. However, when the drivable time increases to 6 hours or more, full coverage becomes achievable without installing facilities at every hub. This is because longer drivable

ranges expand the number of routes that can be reached via intermediate hubs with existing facilities, thereby reducing the total number of required installations.

Algorithm 3 Counting the marginal number of routes covered by adding new facility

```

1: Input: Set of hubs  $H$ , set of routes  $R$ , drivable time  $T$ , set of existing facilities  $F$ 
2: Output: Marginal route coverage for each candidate hub  $h \in H \setminus F$ 
3: for each hub  $h \in H$  such that  $h \notin F$  do
4:    $NewCoveredRoutes \leftarrow \emptyset$ 
5:   Use Algorithm 2 to compute single-hub coverage from  $h$ 
6:   Add routes covered from hub  $h$  alone to  $NewCoveredRoutes$ 
7:    $TowardsH \leftarrow \emptyset$ 
8:   for each hub  $f \in F$  do
9:     Add hubs reachable from  $f$  within  $T$  to  $TowardsH$ 
10:  end for
11:  for each hub  $t \in TowardsH$  do
12:    if travel time from  $f$  to  $t$  + travel time from  $t$  to  $h < T$  then
13:      Add route  $f \rightarrow t \rightarrow h$  to  $NewCoveredRoutes$ 
14:    end if
15:  end for
16:   $OutFromH \leftarrow$  all hubs reachable from  $h$  within  $T$ 
17:  for each hub  $o \in OutFromH$  do
18:    for each hub  $f \in F$  do
19:      if travel time from  $h$  to  $o$  + travel time from  $o$  to  $f < T$  then
20:        Add route  $h \rightarrow o \rightarrow f$  to  $NewCoveredRoutes$ 
21:      end if
22:    end for
23:  end for
24:   $MarginalCoverage[h] \leftarrow |NewCoveredRoutes| - |CoveredRoutes|$ 
25: end for
26: return  $MarginalCoverage$ 

```

Algorithm 3: Counting the marginal number of routes covered by adding new facility

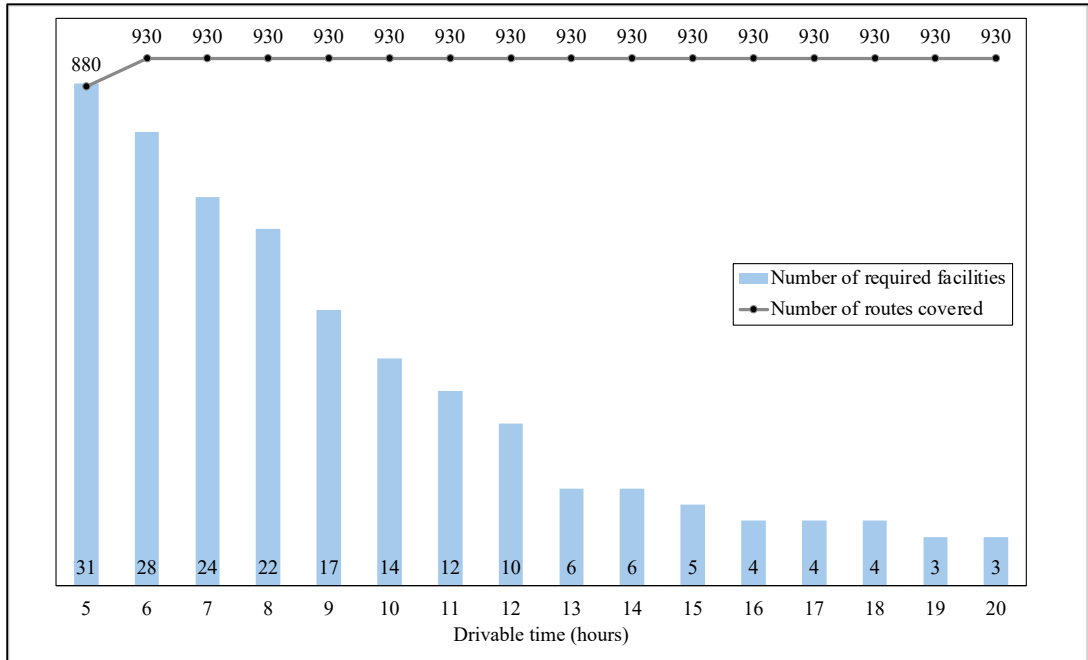


Figure 4: Number of required facilities to ensure full route coverage for a given drivable time of FCEV HDTs

An interesting finding is that the sequence of hubs selected for facility installation changes as the drivable hours vary, indicating that the most impactful hub is dependent on the allowed driving duration. Table 1 and Figure 5 further illustrates this variation, showing that the hub in

Orlando (Azalea Park, Florida) is included in the list of hubs with refueling facilities only when the drivable time is set to 11 hours, but not in the other two scenarios. This suggests that optimal facility placement is sensitive to vehicle range assumptions, underscoring the importance of tailoring infrastructure planning to specific operational constraints.

Table 1: Hydrogen refueling facility deployment roadmap by drivable time

Drivable hours	Hydrogen refueling facility deploying hub sequence
6	Azalea Park, Florida → Tallahassee, Florida → Jacksonville, Florida → Mobile, Alabama → Montgomery, Alabama → Winona, Mississippi → Fort Myers, Florida → Chattanooga, Tennessee → Thomson, Georgia → North Miami, Florida → Charleston, South Carolina → Atlanta, Georgia → Port Wentworth, Georgia → Spartanburg, South Carolina → Willacoochee, Georgia → Knoxville, Tennessee → Wilmington, North Carolina → Winston-Salem, North Carolina → Gumberry, North Carolina → Lexington, Tennessee → Birmingham, Alabama → Memphis, Tennessee → Jackson, Mississippi → Bonifay, Florida → Blountville, Tennessee → Brandon, Florida → Meridian, Mississippi → West Columbia, South Carolina
7	Bushnell, Florida → Jacksonville, Florida → West Columbia, South Carolina → Spartanburg, South Carolina → Montgomery, Alabama → Willacoochee, Georgia → Chattanooga, Tennessee → Port Wentworth, Georgia → Birmingham, Alabama → Winona, Mississippi → Nashville, Tennessee → Wilmington, North Carolina → North Miami, Florida → Gumberry, North Carolina → Blountville, Tennessee → Bonifay, Florida → Mobile, Alabama → Atlanta, Georgia → Memphis, Tennessee → Thomson, Georgia → Meridian, Mississippi → Winston-Salem, North Carolina → Lexington, Tennessee → Fort Myers, Florida
8	Azalea Park, Florida → Port Wentworth, Georgia → Atlanta, Georgia → Tallahassee, Florida → Mobile, Alabama → Spartanburg, South Carolina → Birmingham, Alabama → Winona, Mississippi → Nashville, Tennessee → Bushnell, Florida → North Miami, Florida → Winston-Salem, North Carolina → Chattanooga, Tennessee → Jacksonville, Florida → Wilmington, North Carolina → Blountville, Tennessee → Montgomery, Alabama → Thomson, Georgia → Meridian, Mississippi → Lexington, Tennessee → Bonifay, Florida → Palm Bay, Florida
9	Azalea Park, Florida → Port Wentworth, Georgia → Birmingham, Alabama → Tallahassee, Florida → Spartanburg, South Carolina → Atlanta, Georgia → Mobile, Alabama → Charleston, South Carolina → Wilmington, North Carolina → Chattanooga, Tennessee → Memphis, Tennessee → Winston-Salem, North Carolina → Willacoochee, Georgia → Montgomery, Alabama → Meridian, Mississippi → North Miami, Florida → West Columbia, South Carolina
10	Birmingham, Alabama → West Columbia, South Carolina → Jacksonville, Florida → Tallahassee, Florida → Palm Bay, Florida → Meridian, Mississippi → Atlanta, Georgia → Knoxville, Tennessee → Gumberry, North Carolina → Willacoochee, Georgia → Lexington, Tennessee → Winona, Mississippi → Wilmington, North Carolina → Winston-Salem, North Carolina
11	Birmingham, Alabama → West Columbia, South Carolina → Jacksonville, Florida → Bonifay, Florida → Azalea Park, Florida → Atlanta, Georgia → Chattanooga, Tennessee → Gumberry, North Carolina → Meridian, Mississippi → Winston-Salem, North Carolina → Lexington, Tennessee → Willacoochee, Georgia
12	Birmingham, Alabama → West Columbia, South Carolina → Bushnell, Florida → Montgomery, Alabama → Thomson, Georgia → Winston-Salem, North Carolina → Jacksonville, Florida → Knoxville, Tennessee → Lexington, Tennessee → Tallahassee, Florida
13	Birmingham, Alabama → Port Wentworth, Georgia → Brandon, Florida → Winston-Salem, North Carolina → Montgomery, Alabama → Atlanta, Georgia
14	Atlanta, Georgia → Jacksonville, Florida → Montgomery, Alabama → Winston-Salem, North Carolina → Birmingham, Alabama → Brandon, Florida
15	Atlanta, Georgia → Jacksonville, Florida → Gumberry, North Carolina → Meridian, Mississippi → Brandon, Florida
16	Atlanta, Georgia → Jacksonville, Florida → Gumberry, North Carolina → Montgomery, Alabama
17	Atlanta, Georgia → Jacksonville, Florida → Gumberry, North Carolina → Montgomery, Alabama
18	Atlanta, Georgia → Jacksonville, Florida → Gumberry, North Carolina → Montgomery, Alabama
19	Atlanta, Georgia → Brandon, Florida → Thomson, Georgia
20	Atlanta, Georgia → Port Wentworth, Georgia → Brandon, Florida

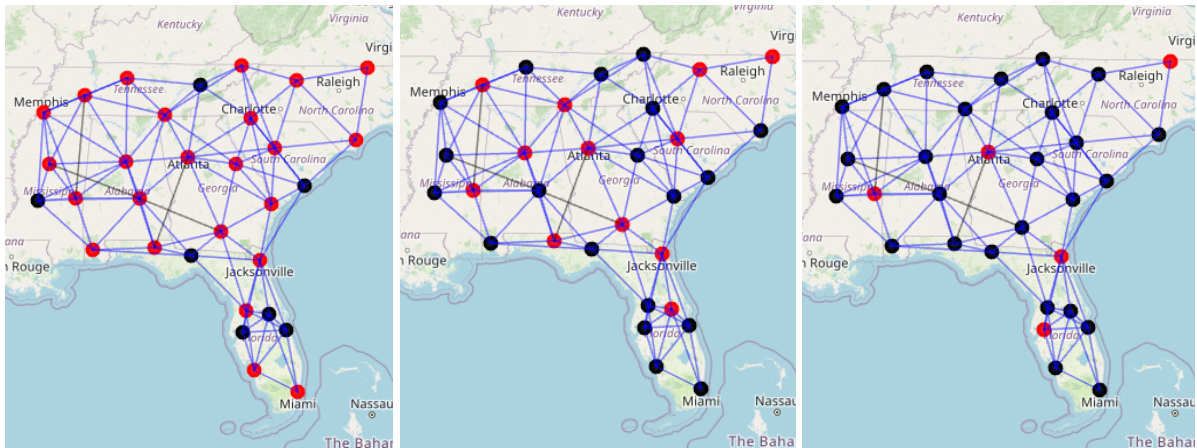


Figure 5: Hydrogen refueling facility final deployment for full route coverage with different drivable times of FCEV HDTs: (left) 7 hours, (middle) 11 hours, (right) 15 hours
Red nodes: hubs with refueling facilities, black nodes: hubs without them, edges: inter-hub paths

5 Conclusion

This paper contributes to the advancement of hydrogen infrastructure planning for FCEV HDTs by proposing a novel, hub-integrated approach based on the PI framework. Unlike conventional station siting methods, our model incorporates logistic hub network topology, drivable range constraints, and FAF-based freight flow data to prioritize deployment locations. By leveraging real-world vehicle specifications and evaluating each hub's impact on network-level connectivity, the proposed method aims to offer a potential roadmap that could help guide the early stages of transitioning toward net-zero emissions in freight transport systems.

Despite the contributions of this study, several limitations should be acknowledged. First, the model relies on static assumptions regarding vehicle specifications and travel conditions. In practice, both factors are subject to significant variability due to ongoing technological advancements in hydrogen fuel-cell systems, differences in vehicle load profiles, and dynamic environmental factors such as weather, road grade, and congestion. These elements can considerably influence energy consumption and thus alter the effective driving range and refueling frequency of FCEV HDTs. Second, the model does not incorporate the truck flow data; instead, it uses a range-based coverage approach to evaluate refueling hub effectiveness. While this method captures the potential geographic reach of a hydrogen station and ensures the feasibility of the strategy, it does not reflect real freight traffic volumes, route preferences, or temporal demand fluctuations. Third, the model assumes a uniform driving range across all FCEV HDTs, whereas in actual markets, vehicles with varying drivable ranges are likely to be deployed simultaneously, and their distribution may shift over time as technology and adoption patterns evolve.

Future research can extend this work by incorporating dynamic freight demand models, energy pricing variability, and lifecycle cost analysis of hydrogen supply chains. Simulation-based models integrating real-time traffic and fleet telemetry could enhance routing realism. Moreover, co-optimizing hydrogen production, storage, and distribution networks with the location of refueling stations would provide a more holistic infrastructure planning framework. Expanding the scope to compare multi-modal integration and policy-driven deployment incentives would also deepen its applicability for logistics and transportation planners and policymakers.

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Dynamic Pricing System for Physical Internet Enabled Hyperconnected Less-than-Truckload Freight Logistics Networks

Tiankuo Zhang, Paria Nourmohammadi, Sixtine Guerin, Benoit Montreuil, Alan Erera
Physical Internet Center, Supply Chain & Logistics Institute,
School of Industrial & Systems Engineering, Georgia Institute of Technology, Atlanta, U.S.A.
Corresponding author: tzhang417@gatech.edu

Abstract: *Less-than-truckload (LTL) shipping plays a critical role in modern supply chains by consolidating freight from multiple shippers into shared vehicles. Despite its operational flexibility and potential sustainability benefits, the LTL sector faces persistent challenges, including high per-unit costs and financial instability, as evidenced by recent industry bankruptcies. This paper investigates two structural issues limiting LTL performance: the constrained consolidation potential imposed by proprietary logistics networks, and the inefficiency of fixed pricing models that fail to reflect real-time network conditions. To address these, we explore a Physical Internet (PI)-enabled, hyperconnected LTL logistics system based on open asset sharing and dynamic flow consolidation. We then propose a dynamic pricing framework tailored for this network. Through a simulation-based study grounded in Freight Analysis Framework data and cost estimates from industry sources, we evaluate system performance across three demand and cost uncertainty scenarios in the Southeastern U.S. The results validate our system's effectiveness and suggest a promising path forward for building more efficient LTL logistics operations.*

Keywords: *Physical Internet; Less-than-Truckload; Hyperconnected Logistics; Freight Systems; Pricing System*

Physical Internet (PI) Roadmap Fitness: ☒ PI Networks, ☒ System of Logistics Networks

Targeted Delivery Mode-s: ☒ Paper, ☒ In-Person presentation

1 Introduction

Less-than-truckload (LTL) shipping strategies involve consolidating multiple shippers' goods into shared trucks or trailers en route to common intermediate or final destinations. Compared to full truckload (TL) shipments, where a single shipper's freight fills an entire vehicle, LTL provides a flexible alternative that improves truck utilization, reduces empty miles, and supports more sustainable and efficient supply chain operations. As e-commerce and decentralized supply chains continue to grow, the role of LTL in enabling cost-effective, frequent, and distributed shipping has become increasingly central.

However, despite its strategic importance, the LTL industry has faced mounting operational and financial pressures. Recent high-profile bankruptcies, including Yellow Corp's collapse in 2023 and following similar cases in 2019, have underscored the instability within the LTL market. These incidents have cast doubt on LTL carriers' ability to remain profitable in an increasingly competitive and volatile logistics environment. A critical pain point is the cost structure: while LTL offers improved capacity utilization, the cost per pound is significantly higher than that of TL shipments. This disparity is particularly stark when shipments are compared based on similar promised delivery windows, suggesting that LTL customers often pay a premium for similar services.

In this paper, we focus on two key reasons for this phenomenon. The first is that consolidation potential of LTL service providers is bounded by their dedicated network of logistic hubs and their dedicated fleet of trucks and trailers, leading them to constantly compromise between delivery velocity and vehicle fill rate. The second reason is that LTL companies rely on fixed pricing systems with minimal adjustments concerning current network status and shipment details. Therefore, the fixed shipment rates are usually above the underlying real-time rate to stay profitable.

We address the first reason by focusing exclusively on Physical Internet (PI) enabled hyperconnected freight logistic systems for LTL services, based on open asset sharing and open flow consolidation. We propose a PI-LTL hyperconnected freight logistics network based on open asset sharing and open flow consolidation. The services of logistic hubs are openly accessible at a price depending on required sorting, transloading, or crossdocking services, and they can consolidate packages encapsulated in modular PI containers according to intermediary or final destination as required. Similarly, the vehicles used need not to be dedicated to a specific LTL service provider and they can load, move, and unload modular containers under the responsibility of multiple LSPs concurrently. Ultimately, most LTL freight moves in fully loaded trucks and spend minimal dwell time at hubs.

We address the second price-related reason by introducing a dynamic pricing system specifically conceived for hyperconnected LTL logistic systems, with two intelligent agents within a hyperconnected LTL logistics platform. The first pricing agent estimates the shipment price by identifying historical and real-time requests with similar characteristics and computing a robust price using a weighted confidence interval method. The second pricing agent receives the actual optimized cost after a shipment is completed, calculates the deviation, and updates the real-time data pool, enabling continuous learning and refinement. Together, these agents allow the system to adapt pricing dynamically based on evolving network conditions, improving both accuracy and responsiveness over time. This pricing mechanism supports more efficient decision-making while maintaining financial viability for carriers in a shared, open logistics network.

Based on the developed system, we report a simulation-based experiment and examine the pricing system's effectiveness in a hyperconnected LTL network in the Southeastern U.S. and in three scenarios. In scenario 1, we consider a smaller portion of the overall commodity flow with no cost uncertainties, meaning the real-time network has full clairvoyance on arc cost information that is the same with the historical data. In scenario 2, we consider the same commodity flow portion with cost uncertainties, such that the real-time arc costs are different from the historical data, and the arc cost information within the historical data also varies. In scenario 3, we consider a larger commodity flow portion with cost uncertainties. The experiment was set on a multi-day horizon with hourly time instances to spawn requests. It utilizes Freight Analysis Framework (FAF) data to generate representative synthetic LTL freight demand scenarios and to simulate shipment requests between hub pairs. It uses Uber Freight and American Transportation Research Institute (ATRI)'s reports to estimate cost parameter. In each scenario, we compare accumulated profits of our proposed dynamic pricing system versus the fixed pricing strategy. The comparison results validate the dynamic pricing model's ability to increase carrier profitability and market acquisitions.

The full paper is organized as follows. Section 2 presents the related literature. Section 3 demonstrates our proposed PI-LTL hyperconnected freight logistics network. Section 4 proposes the framework of our dynamic pricing system. Section 5 analyzes the simulation-based experiment. Section 6 summarizes the contributions, limitations, and future work directions.

2 Related Literature

This literature review is divided into two main sections: the first explores research on Physical Internet (PI) networks, while the second focuses on dynamic pricing mechanisms, particularly in less-than-truckload (LTL) logistics.

2.1 PI Networks

The Physical Internet (PI) represents a transformative paradigm shift in global logistics, first conceptualized by Montreuil (2011) as a response to the "global logistics sustainability grand challenge," centering on several architectural innovations: hyperconnected network, standardized modular containers, universal interconnectivity protocols, and open logistics networks (Ballot et al., 2014).

Based on these core concepts, researchers have studied applications and impact of PI networks. Hakimi et al. (2012) applied PI concepts and designed an open logistics web in France. Through their research, they reported notable improvements in economic, environmental, and social efficiency and performance by adopting PI concepts in real-world logistics systems. Li et al. (2022) designed a PI operating system based on hyperconnected relay network that provides truck drivers with more return-to-domicile opportunities. Other researchers focused on design frameworks of PI networks, aiming to provide conclusive guidance for designing PI networks fitting into different scenarios and criteria. Shaikh et al. (2021) introduced in-hub protocols for dynamically generating consolidation sets of modular containers and requests for on-demand transportation services, ensuring reliable pickup and delivery within promised time windows. Grover et al. (2023) proposed a framework on PI-hyperconnected network design framework that integrates key concepts such as tiered network topology, hub interconnectivity, consolidation, and containerization.

2.2 Dynamic Pricing Models in Physical Internet Framework

As the PI ecosystem evolves, pricing mechanisms have emerged as a critical research area. The unique nature of PI environments, characterized by dynamic, stochastic transport requests in open logistics hubs, necessitates innovative pricing approaches distinct from traditional models. Less-than-truckload (LTL) requests with varying volumes and destinations continually arrive and remain available only briefly, creating a complex decision environment for carriers (Sarraj et al., 2014a; Xu & Huang, 2013; Pan et al., 2014). Qiao et al. (2016) made a notable contribution by developing a dynamic pricing model for LTL carriers operating in PI-hubs. Their approach employs dynamic programming and auction theory to optimize bid prices in real-time, adapting to the stochastic arrival of requests with different characteristics. At the core of their research is a pricing estimation function that highlights in capturing opportunity costs of serving one request not others. Yet, this research is limited to only one origin hub and one destination hub, which lacks adaptabilities in large-scale PI networks.

Building on this foundation, Qiao et al. (2020) then expanded the research scope with a more comprehensive model addressing both dynamic pricing and request selection. Their enhanced approach incorporates forecasting and uncertainty and considers the multi-leg transport problem. However, while valuable insights can be drawn from these parallel domains, they often focus on capacity control and acceptance/rejection decisions rather than flexible pricing mechanisms. Moreover, the current carrier-based pricing models in PI research remain rooted in competitive market paradigms that optimize individual carrier revenue rather than system-wide efficiency—a limitation that fails to fully utilize PI-based open asset sharing or realize the collaborative potential of the PI vision.

3 Proposed PI-LTL Hyperconnected Freight Logistics Network

At the hub level, once a truck arrives, containers are first sorted based on their next destination. The system prioritizes which containers remain on the truck (those destined for the truck's next stop), while others are unloaded and, later, reallocated to outbound trucks heading toward their respective next stops. If two shipments are bound for the same next destination but only one spot remains, priority is given based on shipment urgency, time window, or contractual service tier. This decision-making process is handled by the digital planning agent, which evaluates available capacity and urgency constraints in real time. The hub operations follow a structured flow: arrival, unloading, reconfiguration, preparation, loading, and departure; each optimized for minimal handling and high-speed turnover, in line with PI container standards and automation compatibility.

At the network level, the PI-LTL (Physical Internet–Less-than-Truckload) network leverages hyperconnected and relay-based transportation, with the key design principle that transportation arcs between hubs should remain under 5.5 hours. This duration enables short-haul relays that comply with driver hour-of-service regulations, reduce driver fatigue, and maximize vehicle and driver productivity through more predictable shift scheduling. The short-haul structure also allows for increased frequency of dispatches and improves service reliability by reducing exposure to long-haul disruptions. Such a hyperconnected and relay-based network framework is modular and highly scalable—it can be applied to any given set of hubs. This modularity allows the network to dynamically grow or shrink by adding or removing hubs, as long as connectivity and capacity thresholds are respected. Each transportation arc supports bidirectional movement, facilitating flexible load balancing and repositioning of assets. Hubs are designed to function as universal access points rather than assets of certain carriers, which enables cooperations between different carriers and logistics service providers. This open-access approach allows for greater integration of regional, national, and even international carriers, promoting a more inclusive and efficient freight system.

The platform also reinforces open asset sharing through centralized orchestration of both capacity and pricing. Instead of relying on traditional competition, where carriers independently bid for individual shipments and customers choose from a fragmented pool, the system acts as a neutral coordinator. It matches shipment requests to available assets (trucks, drivers, and hub capacity) regardless of ownership. This centralized matching engine incorporates real-time data and optimization algorithms to allocate resources fairly and efficiently. Carriers share both trucks and hub capacities and are compensated transparently based on their participation in fulfilling shipment requests, using a usage-based or performance-based revenue-sharing model. This collaborative model leads to improved resource utilization, higher asset uptime, and a more resilient logistics ecosystem that can absorb demand surges or infrastructure disruptions with greater agility. By decoupling service provision from asset ownership, the platform lowers the entry barrier for small and mid-sized carriers, encourages broader participation, and reduces redundancy in fleet and infrastructure deployment. Over time, this structure fosters a more balanced, efficient, and environmentally sustainable freight network—capable of dynamically adapting to evolving customer needs, regulatory constraints, and macroeconomic conditions.

Figure 1 illustrates our designed PI-LTL hyperconnected freight logistics network implemented in our test bed of 8 hubs across Georgia and Florida. The green arcs represent relay transportation arcs (each under 5.5 hours), showcasing the interconnectedness and time-constrained feasibility of the network. The subgraphs on the right depict hub-level PI container handling processes and container movements, highlighting how reconfiguration and dispatch are orchestrated in real-time under PI principles.

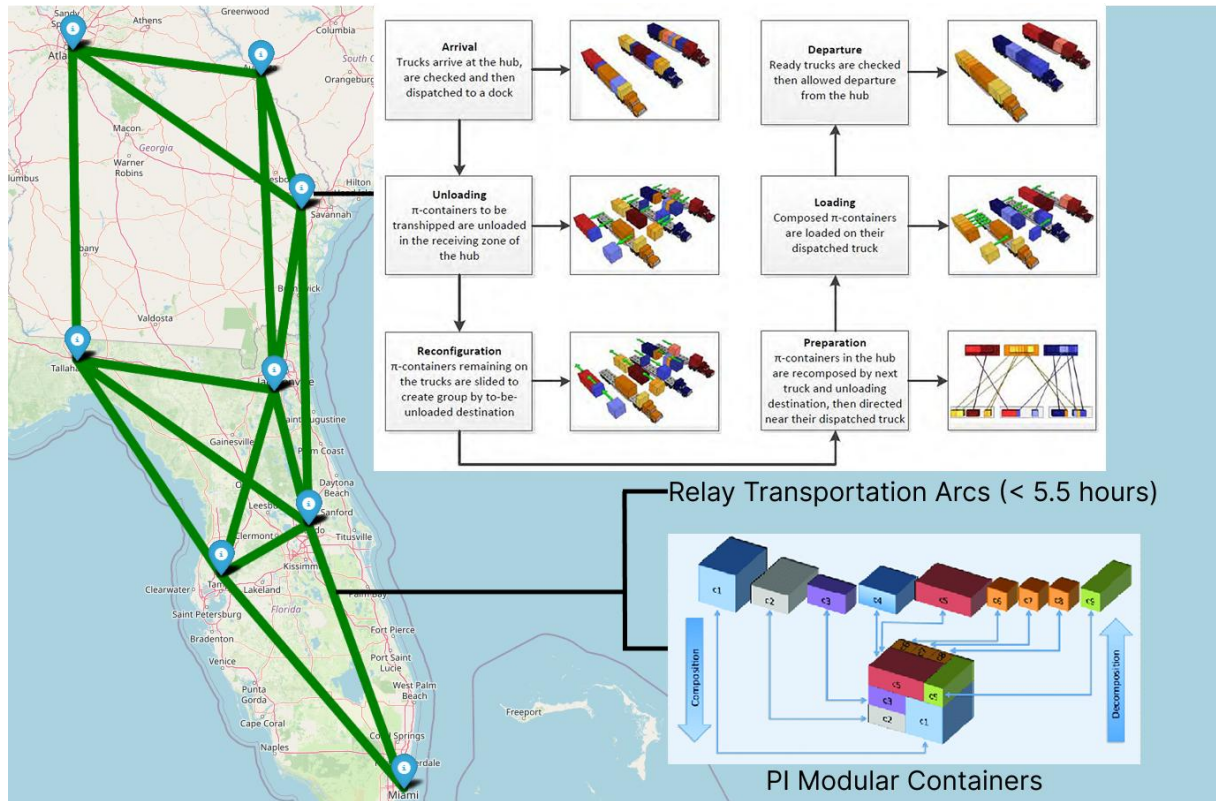


Figure 1: Illustrating the PI-LTL Hyperconnected Freight Logistics Network

(Montreuil, 2011; Montreuil et al., 2013)

4 Proposed Dynamic Pricing System

Our proposed dynamic pricing system is built around two types of intelligent pricing agents. The first pricing agent 1) combines historical data and real-time outcome into shipment request groups based on similar origin, destination, time window, and 2) generates a pricing estimation from the respective request group for the current shipment request based on a given confidence interval for guaranteed robustness. The second type of pricing agent traces the optimized cost of each shipment, calculates the deviation from the absolute difference between the previous estimate and the optimized cost, and logs the outcome to update the real-time outcome pool for the first pricing agent's further use. These two pricing agents are part of a more extensive hyperconnected LTL logistic operating system, as shown in Figure 2, with connections to a consolidation agent and a planning agent that are not the focus of this paper. The above flow chart shows a detailed view following a new shipper request:

- 1) A shipper asks for a shipment request with specifications to be delivered.
- 2) The consolidation agent consolidates the request into units of PI modular containers.
- 3) The first pricing agent finds similar shipments in the system's logs, including historical data and real-time outcomes, and estimates the price of shipping this request.
- 4) The shipper pays for the estimation, and the planning agent derives the optimal routing and consolidation plan in consideration of open resource sharing and carrier collaboration.
- 5) After the shipment request is fulfilled, the second pricing agent backtracks the accurate cost of this shipment request and updates logs for further use, and the operating system distribute respective rewards to carriers involved in the shipment requests' fulfillment.

Therefore, as new requests come in and new decisions are made, the pricing system iteratively updates its dynamic pricing estimation matrix with the aims of fast response time, with minimal run-time sacrifice to update results, and increments in accuracy of the pricing estimates.

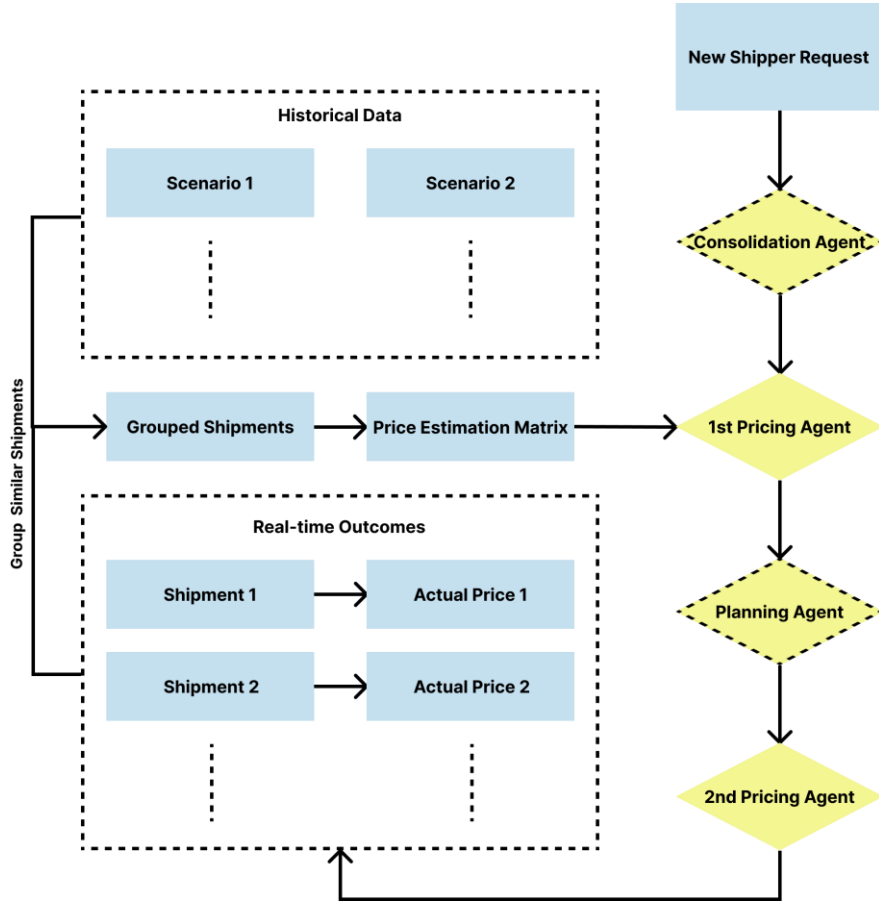


Figure 2: Demonstrating the Hyperconnected LTL Logistics Operating System

The first pricing agent estimates price through a weighted confidence interval methodology, in which requests in the historical data and requests in real-time outcomes have different impact to the estimated price. Therefore, in conditions where the current network status is different from the historical data pool, the pricing agents will depend more on information gathered from the current network and can quickly adjust and adapt to the status. For the current shipment request k with origin o_k , destination d_k , release time r_k , deadline l_k , and demand v_k , the first pricing agent identifies the request's corresponding stored request group K_s . For each shipment request k_s in K_s , the second pricing agent provides its optimized cost c_k and a confidence weight w_k based on whether k_s belongs to historical data or real-time outcomes. The first pricing agent then calculates the group's weighted mean:

$$\bar{c} = \frac{\sum_{k \in K_s} w_k c_k}{\sum_{k \in K_s} w_k} \quad (1)$$

and the group's weighted variance:

$$s^2 = \frac{\sum_{k \in K_s} w_k (c_k - \bar{c})^2}{\sum_{k \in K_s} w_k} \quad (2)$$

From the weighted mean and weighted variance, the first pricing agent then calculates the group's standard error of the weighted mean as:

$$SE = \sqrt{\frac{s^2}{n_{eff}}} \quad (3)$$

, where $n_{eff} = \frac{(\sum_{k \in K_S} w_k)^2}{\sum_{k \in K_S} w_k^2}$ is the effective sample size.

With a desired robust level and its corresponding z value, the first pricing agent then gives the robust profitable price $p_k = \bar{c} + z \times SE$ for the current shipment request. Once this request arrives at its destination through the planning agent's optimized route, the second pricing agent will then gather information on its cost c_k , which allows us to derive its deviation $\delta_k = |p_k - c_k|$. The second pricing agent then stores this request's origin, destination, time window, demand, and cost information to its real-time outcomes for further use.

We want to point out that the goal of our pricing system is not to have a large revenue $p_k - c_k$ but to guarantee a certain robustness level of remaining profitable while having a low deviation for each request. Therefore, in assessing performances of the pricing system, the desirable outcome is to have low total deviations and low per-pound prices.

5 Results and Discussion

We present a simulation-based experiment using a PI-LTL hyperconnected freight logistics network based on freight zones from the FAF dataset, and we focus on 8 zones in Georgia and Florida. Besides 8 hubs derived from the 8 zones, the PI-hyperconnected freight logistics network utilizes relay transportation and includes 30 transportation arcs that are less than 5.5 hours, such that drivers can return to their based hub abiding the driving regulations. We consider a time horizon of 48 hours with hourly planning instances and derive commodity requests with varied assumptions in three scenarios as shown in Table 1. For robustness of our results, we generate 100 cases as historical data and 30 cases as testing cases for each scenario. In this experiment, the target profit robustness is 90% in all cases of each scenario, which can be easily changed to adapt different goals.

Table 1: Comparison between setups of three scenarios

Scenario	Number of Cases	Percentage of LTL Flow	Volume Upper Bound	Per-Truck-Mile Cost	Per-Pound Transload Cost
1	100/30	1%	1/3 Truckload	\$2	\$0.04
2	100/30	1%	1/3 Truckload	\$1-\$3	\$0.02-\$0.06
3	100/30	5%	Full Truckload	\$1-\$3	\$0.02-\$0.06

In the first scenario, we assume the PI-LTL network handles 1% of all LTL shipment flows (10% of the entire shipment flow), which is approximately 500 to 600 full truckloads in a 48-hour time horizon. From the estimated LTL shipment flows handled by the PI-LTL network, we randomly generate individual requests with less than 1/3 of a full truckload and time windows between the shortest travel time plus 4 hours and one day for creating feasible yet time-sensitive requests. To our best knowledge, this time window interval is tighter than most industrial standards, including large and established logistics providers like UPS and USPS. As we consider no cost fluctuations in the first scenario, in each case, each traveling arc has the same per truck cost, derived from 2023 trucking operational cost analysis of ATRI and the 2024 annual freight trucking rate report of Uber Freight. Besides, each shipment request also has the same handling cost on each traveling arc in each case.

In the second scenario, the PI-LTL network handles the same amount of LTL shipment flows, and requests and their specifications are randomly generated with the same logic. However, we introduce uniform cost fluctuations, so, in each case, the same traveling arc might have different per-truck cost and different handling cost for the same request. This scenario applies our pricing agents in more practical cases where full pricing information is not disclosed, such that, in testing cases, the pricing agent will estimate cost with historical cost information from different network status.

In the third scenario, the PI-LTL network handles 5% of all LTL shipment flows, which is approximately 2500 to 3000 full truckloads in a 48-hour period. The request generated can now take up to full truckload. The cost also fluctuates between each case, following the logic of the second scenario. This scenario resembles cases when the PI-LTL network gains more market share and breaks the traditional concept that LTL shipments only take up to 1/3 of a full truckload, which are resembled by the previous two scenarios. Figure 3 compares the total shipment flows in each scenario, with scenario 1 and 2's shipment flows on the left, and scenario 3's shipment flows on the right.

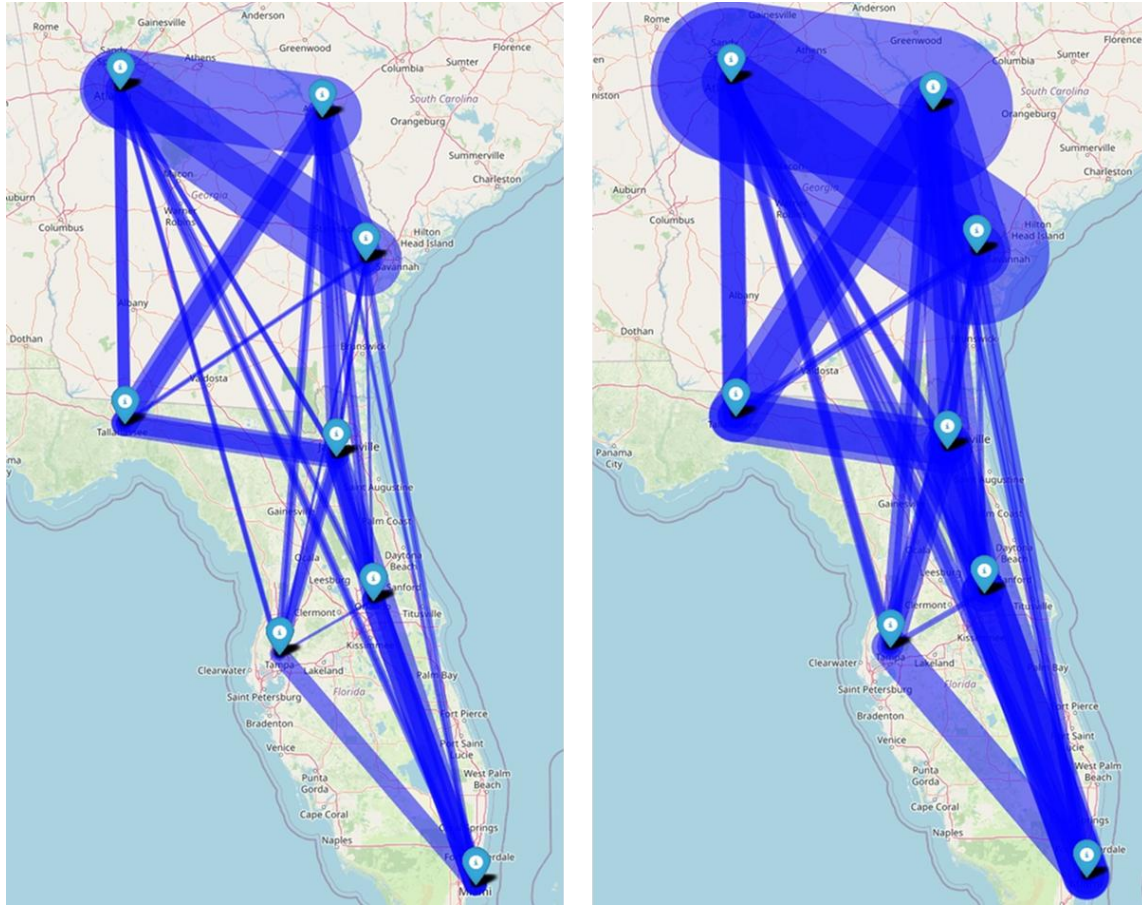


Figure 3: Comparing Total Shipment Flows Between Scenario 1 (left), 2(left), and 3 (right)

Table 2 compares the computed results of each scenario with three key performance indicators (KPIs): total deviation, per pound deviation, and average price per pound. Total deviation accounts for each case's sum of deviations of all shipment requests' estimated price from the optimized price; per pound deviation accounts for each case's total deviation divided by the total shipment weight; average price per pound accounts for each case's total price estimation divided by the total weight. As we have multiple cases for each scenario for robustness of our result, we analyze each KPI in lower quartile (25%), median, and upper quartile (75%) at the case level.

Table 2: Comparison between results of three scenarios

Scenario 1			
KPIs	Lower Quartile	Median	Upper Quartile
Total Deviation	58320	67689	74861
Per Pound Deviation	0.11	0.12	0.14
Average Price Per Pound	0.53	0.54	0.56

Scenario 2			
KPIs	Lower Quartile	Median	Upper Quartile
Total Deviation	75601	84794	109198
Per Pound Deviation	0.14	0.16	0.20
Average Price Per Pound	0.53	0.55	0.57

Scenario 3			
KPIs	Lower Quartile	Median	Upper Quartile
Total Deviation	336353	476058	593327
Per Pound Deviation	0.13	0.18	0.22
Average Price Per Pound	0.52	0.53	0.53

Comparing scenario 2 to scenario 1, adding uncertainties to the PI-LTL network increases the value of all KPIs, which can be expected as uncertainties will negatively impact our pricing system's prediction. Comparing scenario 3 to the previous two scenarios, due to the increment in request numbers and total volume, the total deviation inevitably increases. However, scenario 3's per-pound average price is below scenario 1 and 2's counterpart. This comparison suggests that our PI-LTL network exhibits an economy of scales. A potential interpretation is that, as our PI-LTL system attracts more shipment requests of larger volumes, the system can have a larger volume of historical knowledge for pricing estimations and explore more consolidation opportunities, the prediction error and prices will be driven down.

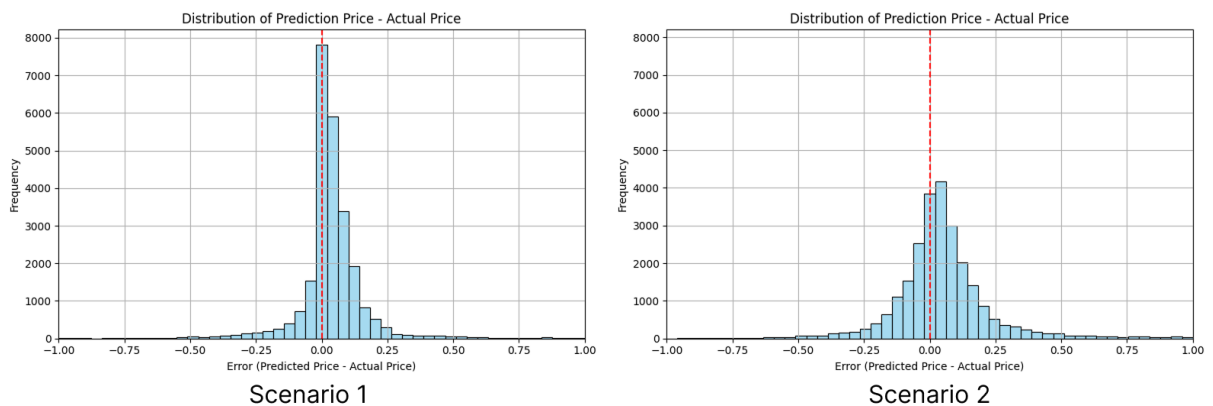


Figure 4: Histograms of Distributions of Pricing Errors Between Scenario 1 and Scenario 2

Figure 4 compares the distribution of pricing errors (prediction per-pound price minus the actual per-pound price) between scenario 1 and 2. As scenario 2 introduces uncertainty, less counts of shipment requests' prices are accurately predicted as in scenario 1. However, as shown in scenario 2's histogram, more shipment requests are on the nonnegative half, indicating our system's success in assuring profitability facing uncertainties.

6 Conclusion

Our study has three main contributions. First, it proposes a PI-LTL hyperconnected freight logistics system with open asset sharing, smart in-hub consolidation strategies, and hyperconnected relay transportation. Second, it provides a paired dynamic pricing system, as a part of a more advanced LTL operating system, to estimate price based on each shipment request's specifications, historical data, and current real-time outcomes. Third, it conducts a simulation-based experiment in a test bed of Georgia and Florida with real-life industrial data.

This research also opens several avenues for future work. The first direction is to consider a specific profit-splitting strategy to distribute profits fairly among the carriers involved in each shipment request's fulfillment. The second direction is to develop more advanced machine learning models to predict prices with faster response time and higher accuracy. The third direction involves considering a differentiation between premium requests and normal requests with different pricing tiers, such that premium requests are guaranteed to arrive on time with extra cost, and normal requests are less expensive but may have risks of arriving late.

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Freight In Urban Transit: challenges and enablers

Najat BARA¹, Olivier Labarthe¹, Walid Klibi^{1,2}, and Onur Ozturk³

1. The Centre of Excellence for Supply Chain Innovation & Transportation (CESIT),
Kedge Business School, Bordeaux, France
2. Physical Internet Center, Supply Chain & Logistics Institute, Atlanta, United State
3. Telfer School of Management, University of Ottawa, 55 Laurier Avenue East, Ottawa,
Ontario K1N 6N5, Canada

Corresponding author: najat.bara@kedgebs.com

Abstract: Freight on Transit (FOT) is a promising solution for urban logistics, involving the transportation of goods in urban areas using public transit vehicles or infrastructure. While FOT offers competitive advantages for urban logistics, the literature indicates a reluctance among public and private stakeholders to adopt this strategy. This paper aims to enhance the acceptability of FOT among stakeholders. It has three main objectives. First, it reviews the literature to identify the primary challenges associated with the implementation and success of FOT. Second, it provides a framework that positions FOT in the context of Hyperconnected City Logistics (HCL). Third, it proposes a mixed-integer linear programming model to estimate, in the context of HCL, the potential capacity of urban public transport networks to integrate freight mobility. The model is applied on the case study of the City of Bordeaux, and the first results are presented.

Keywords: Freight On Transit, Freight Urban mobility, Hyperconnected City Logistics.

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

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

1 Introduction

We refer to middle-mile delivery as the intermediate stage where goods are moved from the outskirts of the city (e.g., production plant, distribution center, airport...) to a micro fulfillment center near their final destinations. The latter can be retail shops, production plants, offices, hospitals, schools, restaurants, construction sites, or the customer's home. Urban retail activity is divided between independent retailers, supermarkets and chain stores, and e-commerce (Strale, 2014). Middle-mile delivery has become an emerging research area with increasing interest from scholars and practitioners. This growth is due to the increasing urbanization, sustainability concerns, innovation, e-commerce, change in customer behavior, and Covid 19 crisis. It should be timely, profitable, and sustainable to be competitive. The rapid growth of e-commerce is particularly a major reason for the great attention that has been received on the topic of sustainable urban logistics. One the main problem of e-commerce is the inefficiency of

the delivery vehicle load factor. There is a significant fragmentation of orders. First, delivery is the core business of e-commerce retailers. They adopt just-in-time strategies and go up to same-day delivery. To be competitive, e-commerce retailers may carry out deliveries regardless of the truck or vehicle load factor (Iwan et al., 2015). Second, since e-commerce is a B2C business model, individual customers usually order a small quantity of products, while expecting fast delivery. In addition, B2C entails dispersed destinations for a delivery vehicle. Another problem of the e-commerce supply chain is the high percentage of returns. In most countries, over half of all online shoppers have returned an online purchase (Schöder et al., 2016). For all these reasons, e-commerce presents a real challenge for urban logistics.

Many solutions for urban logistics are discussed in literature, some of which are implemented or tested. They suggest new sustainable organizational and business models for urban freight transportation (Crainic and Montreuil, 2016). In the literature, measures proposed for urban logistics include space and time access restrictions of vehicles, last-mile delivery optimization, integration of new infrastructure (underground transport and environment-friendly vehicles), Urban Consolidation Centers (UCC), new information and communication technologies, public-private collaboration (Russo and Comi, 2020), and crowdshipping (Feng et al., 2021). In this paper, we investigate the solution of moving goods by using the spare capacity of public transit infrastructures. Integrating freight transport with passenger transport is a long-standing practice for long-distance haulage. Its effectiveness has been already demonstrated. In the last two decades, several studies have been conducted on the implementation of the same principle in urban areas. Cochrane, (2016) talks about Freight on Transit (FOT), we adopt the same term in this paper. Other terms can be found in the literature: freight on public transportation, cargo-hitching, and passenger and package sharing (Elbert and Rentschler, 2021). Cochrane (2016) defines FOT as the “operational strategy where public transit vehicles and/or infrastructure are used to move freight” in urban areas.

FOT is related to multiple stakeholders including passengers, shippers, carriers, public authorities, regulators, transport orchestrators, and vehicle manufacturers. The literature shows a certain reluctance among these public and private stakeholders regarding the implementation of FOT. This paper aims to present an illustration so that concerned stakeholders may investigate to what extent FOT is feasible and profitable in their context. It has four main objectives: *i)* review the literature on FOT strategy to identify its key challenges and link it to the concept of Hyperconnected City Logistics (HCL). *ii)* Propose a multi stakeholder-centered framework, highlighting gaps in the literature. *iii)* Develop a model-driven decision support system to estimate the freight-carrying capacity of transit networks, and *iv)* validate the proposed model using the case of Bordeaux in France.

The rest of this paper is organized as follows. The second section reviews the literature, reports on the main FOT challenges and provides the framework. The third section presents the flowchart of the mathematical model. Section four presents the first results of the case of Bordeaux. Section five contains a conclusion.

2 Literature review

In this section, we first review the main FOT success stories and their characteristics. Second, we describe a set qualitative studies aiming to evaluate the feasibility of FOT in some specific context. Third, we review FOT-related prescriptive models.

2.1 FOT projects driven by real case experimentations

In this first sub-section, we present examples of FOT implementation. A first successful example is Dabbawala system in Mumbai, India. Many hot lunch boxes which are prepared in workers houses are delivered to them by thousands of delivery men using suburban trains. In New York and Zurich, subways and tramways are used to transport garbage and bulky waste respectively. From 2007 to 2017, Monoprix successfully used the RER (Regional Express Rail) line to transport goods from its warehouses to Bercy station in Paris (about 30 kilometers). Volkswagen in Dresden, used a tramway to transport spare parts between its distribution center and a factory in downtown Dresden. In 2007, a pilot project was studied in Amsterdam to transport goods from distribution centers to Amsterdam center using tramway.

Table 1 shows that consolidating enough volume is a necessary condition for FOT success. Monoprix and Cargo tram projects had enough volume to fill train capacity. New York and Zurich projects deal with wastes which are “no value” products with no traceability or competitiveness issues, consolidation was straightforward. Dabbawala example shows that the used symbol system is very effective. Concerning City Cargo in Amestaredam, the project failed due to financial constraints and the resistance of different actors to collaborate which limits volume consolidation.

Table 1: FOT experiments

Project	Volume to be transported	FOT configuration	Status
Dabbawala, Mumbai, India	Consolidation of deliveries from different origins toward different destinations	Mixed passenger and freight train	Successful
Garbage Subways New York	Consolidation of wastes from different metro stations toward the processing unit	Dedicated train	Successful
Crago Tram Zurich	Consolidation of wastes from different tram stations toward the processing unit	Dedicated train	Successful
Monoprix (Paris)	Large volume of products are consolidated in Monoprix warehouses	Dedicated train	Successful
Cargo Tram Volkswagen Dresden	Large volume of products are consolidated in Volkswagen distribution center	Dedicated train	Successful
City Gargo Amsterdam	Consolidation of deliveries from different origins toward different destinations	Dedicated train	Canceled

2.2 FOT studies

In this section we review FOT related research studies. We first presented a set of qualitative studies. Second, we review FOT based prescriptive models.

2.2.1 FOT qualitative studies

This section reviews examples of papers dealing with qualitative studies about FOT. Pietrzak and Pietrzak (2021) use a literature review, the documentary and Delphi methods to evaluate the integration the transport of freight in the city of Szczecin in Polish. They distinguished between two different configurations of tram networks: uni and bi-directional trams. The identified challenges concern the decrease of capacity allowed to passengers and the lack of UCC.

Villa and Manzon (2021) investigate the use of FOT to transport e-commerce deliveries. They highlighted volume consolidation and door-to-door delivery as the main challenges.

For the case of Brussels, Strale (2014) emphasizes that FOT challenges concern volume consolidation, lack of knowledge regarding spare capacity, investment costs to adapt facilities and transshipment operations.

Cochrane et al. (2016) are interested to the city of Toronto in Canada. They evaluated 5 strategies:

- The first strategy, Air Rail Mail, involves transporting parcels by train between Toronto's Pearson Airport and Union Station downtown. This point-to-point delivery operates during peak traffic hours. Challenges highlighted by the Delphi survey include the rail lines' capacity to accommodate additional freight trains and the investment costs needed for infrastructure upgrades to handle loading, unloading, and parcel reception.
- The second strategy, called Paper Train, was meant to run dedicated subway trains transporting newspapers and retail products. Products would be delivered to subway stations during night-time. The first reported difficulty concerns the capacity of the subway lines. The second one concerns the suitability of the products as "paper products are being phased out". The third difficulty is related to the time of delivery night deliveries would result in little congestion relief, and trucks and subways would likely have the same reactivity during the night.
- The third strategy, called Mall Hall, consists of using the subway, during night-time, to run dedicated freight trains to supply retailers in large shopping malls downtown. Interviewees mentioned necessary investment costs to upgrade facilities, and minimum congestion and time reductions.
- The fourth strategy, called Liquor Line, would attach a trailer to the tramway to deliver kegs, cases of wine, and cases of liquor from 10 AM to 4 PM. Comments of participants were negative: the strategy would disrupt passenger service, it would be difficult for retailers to be present at the station at the right time, the tram would be too long, and the security of products wouldn't be guaranteed.
- The fifth strategy was to use the train network to deliver low-priority mail and packages throughout GTHA. Packages would be deposited by users at commuter rail stations in automated mailboxes called "packstations". The contents of the "packstations" would be removed by station attendants and placed into special compartments on trains traveling to the downtown core. Couriers would meet trains at Union Station and take packages to a sorting hub where they would be sorted and placed in a container bound for the appropriate commuter rail station. The containers would be loaded back onto the mail compartments of the trains before making the return trip outside of the city. A station attendant would meet the train at the suburban end, retrieve the appropriate container and place it in a holding area until a courier arrived to deliver packages to final suburban destinations on trucks the following morning. Two main difficulties are mentioned regarding this strategy, the lack of space in the Union Station and the volume which would not be sufficient to justify investment in additional staff and "packstations".

2.2.2 Prescriptive methods

In the last decade, literature also has presented FOT-related quantitative studies. Most of the presented papers deals with train scheduling in case of FOT (Ozturk et al. 2018; Behiri et al. 2018; Li et al, 2021...). Delle Donne (2021) presents a mathematical model-based approach to design an FOT system. Labarthe et al., (2024) developed an optimization-based decision support system to assign the transport of a set containers to a set prescheduled trips in the context of hyperconnectivity. Their model integrates different modes of transport and considers constraints related to multi-mode synchronization and resource capacity. Table 2 presents a grid of analysis of the reviewed papers. They generally deal with FOT regarding a limited number of stakeholders. The main FOT challenge considered concern transshipment operations. For instance, Labarthe et al., (2024) consider synchro modality concept. Regarding capacity constraints, papers generally assure feasible conditions and consider capacity as a given constraint. Table 2 presents a synthesis of examples of prescriptive studies about FOT:

Table 2: FOT prescriptive models

Authors	Problem	Modelling method	Decision level	Transportation time	Economic criterion	Satisfied demand	Carbon emission	Stakeholder	Challenge dealt with	Capacity constraints
Ozturk and Patrick, (2018)	Train scheduling	Optimisation	Operational	*				Orchestrator Operator		Given as a constraint
Behiri et al., (2018)	Train scheduling	Optimisation	Operational	*				Orchestrator Operator		Given as a constraint
Li et al., (2021)	Train scheduling	Optimisation	Operational		*			Orchestrator Operator		Given as a constraint
Labarthe et al., (2024)	Train scheduling	Optimisation	Operational	*				Orchestrator Operator	Transshipment	Given as a constraint
Delle Donne., (2023)	Network design maximizing the satisfied demand	Optimisation	Strategic			*		Public authorities		Given as a constraint

3 FOT in Hyperconnected city logistics

The Physical Internet (PI) has been introduced as a solution to the Global Logistics Sustainability Grand Challenge (Montreuil et al., 2013). It is based on interconnectivity of the logistics systems. When applied to cities, PI enables the appearance of Hyperconnected City Logistics (HCL) (Crainic et al., 2023). In this section we discuss FOT in the context of HCL to highlight their complementarity and position the challenges of FOT regarding HCL principles. Crainic et al. (2023) present a framework that synthesizes a set of HCL principles and means. We rely on the same framework to build our framework which is FOT oriented.

The first HCL principle integrated into our framework is the network of stakeholders perspective. It categorizes stakeholders into four main clusters: demand generators, transport providers, legislative bodies, and citizens. The second principle focuses on mobility networks, emphasizing seamless and synergized urban flows of both people and freight, in line with the Freight on Transit (FOT) concept. The third and fourth principles address service and resource networks. These principles promote shared use and hyperconnectivity of resources, aiming to enhance facility and resource utilization. This is achieved through the consolidation of freight, irrespective of the underlying business transactions. They also emphasize the importance of efficient transshipment operations. Notably, both volume consolidation and effective transshipment are key challenges in implementing FOT. The fifth principle concerns cyber-physical networks, which facilitate the integration of data, decisions, and contracts across physical, digital, financial, and legal domains. Finally, the sixth principle highlights the role of governance networks, advocating joint steering and coordination among urban authorities, corporate stakeholders, citizens, and urban planners.

In addition, the framework of Crainic et al, (2023) provides a set of means to implement the above principles. The first is open sharing, which is based on the openness of facilities and complete share of relevant information which is required to allow the consolidation of freight flows. The second means is open flow consolidation based on leveraging standard, smart and modular containers. The smartness of π -containers of PI strengthens the willingness of different stakeholders to collaborate in an integrated logistics system as they would deal with containers instead of the products. The third means is open live monitoring. One of the fundamental prerequisites toward openness is live monitoring of the state, and the performance of different logistics facilities and different logistics operations. Reliable and effective information systems should be implemented to ensure confidentiality of different transactions and continuous improvement of performance indicators. Participants no longer must share their product information with competitors. In addition, they will have real-time visibility of their goods.

The framework in figure 1 positions FOT regarding the framework of Crainic et al, (2023). The left side of the framework lists the main FOT challenges (ch), each associated with a number. As in HCL, FOT is related to multiple stakeholders. The framework classifies the FOT challenges according to the most concerned stakeholders. It should be stressed that HCL considers FOT via its principle of mobility networks. Besides, the rest of HCL principles are

promising enablers for successful implementation of FOT. Indeed, the framework highlights the positive relation between HCL means and FOT challenges.

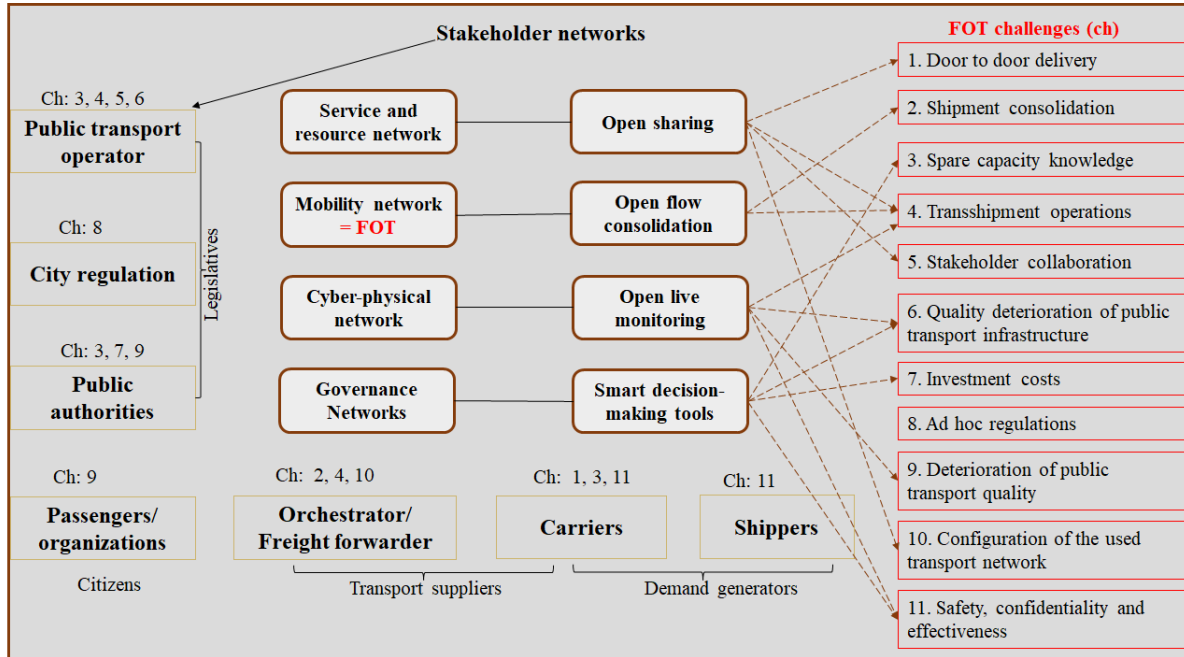


Figure 1: FOT framework

4 Mathematical model of potential capacity estimates

In the rest of the paper, we deal with the challenge of estimating the capacity of a public transport network to integrate freight mobility. We assume the context of set of open networks based on HCL, in which shipments can be consolidated without any competitiveness issues. We are interested in urban mobility of freight regardless of the owner and the business transaction that generated it. We first describe the problem in first sub-section and further we present the problem formulation in sub-section two.

We are interested in a physical system characterized by the following components: Path (or Route): A sequence of stations through which a tramway train travels. Tramway Train: The physical vehicle used for transportation. Trip: The completion of a journey at a specific time. Different trips may utilize the same tram. Trolley: A wheeled transport device. In the context of freight transport by tram, a trolley represents the indivisible unit of demand considered in the following model.

This study focuses on dimensioning of the tramway network to transport goods flow, expressed in trolleys. We distinguish between intermediate stations and termini which are located at the end of tram lines. We consider that loading is only possible at termini (figure 2).

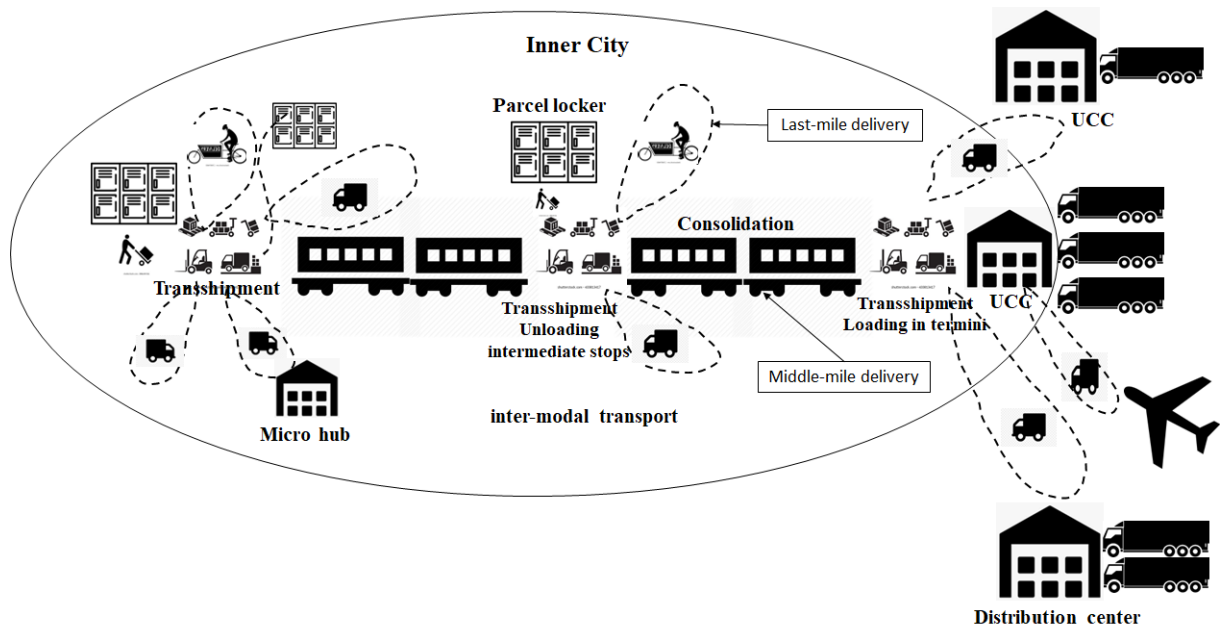


Figure 2: extract of urban logistics network

Two types of tramway trips can be used for transporting goods: mixed trips and dedicated trips. Mixed trips are already scheduled for passenger service (denoted as VM), with unused residual capacity (in trolleys) that can be utilized for freight transport. Dedicated trips (denoted as VD) refer to tram sets available in the depot not used for passenger transport.

Figure 3 presents a flowchart of the model. The right side of the figure describes the main inputs of the model. They concern the characteristics of the urban transport network and characteristics of the freight demand. The model estimates the share of the satisfied demand per mode of transport and evaluates each scenario based on costs and CO₂ emissions.

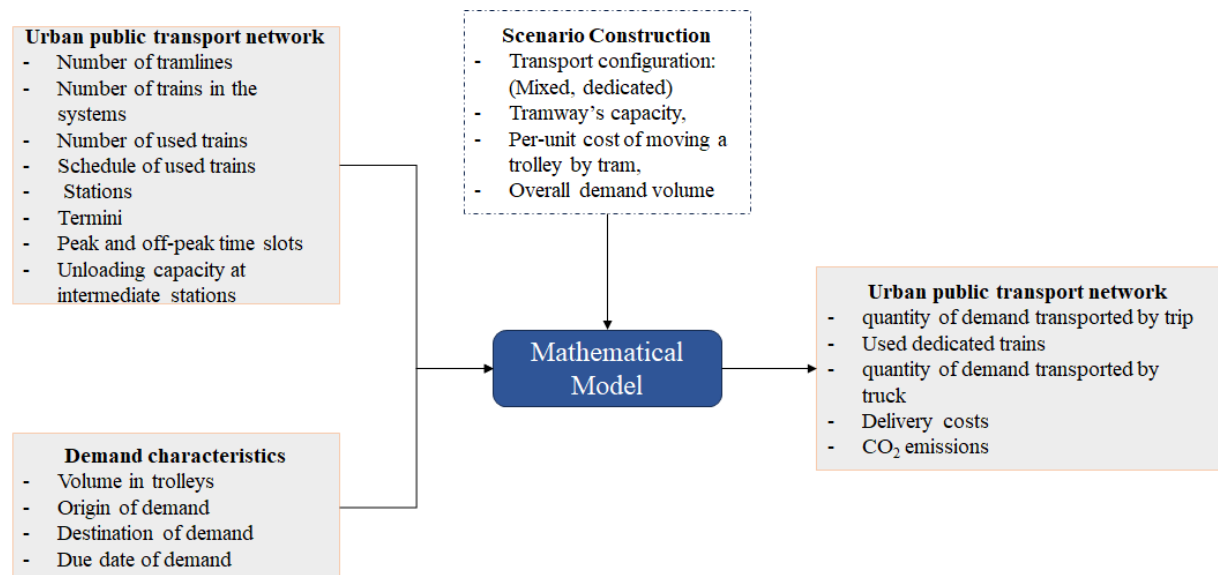


Figure 3: mathematical model flowchart

5 Case study of Bordeaux

Transporting goods through Bordeaux has become increasingly challenging due to the rising restrictions on truck traffic. At the same time, the city boasts a dense and well-integrated public transport system, comprising four tram lines, an extensive metropolitan bus network, river

shuttles, and shared mobility services for bikes and cars. Despite its relatively small footprint, Bordeaux has a high population density, making it a prime candidate for enhancing shipment consolidation strategies. As a leading hub for e-commerce in France, the city generates strong demand for efficient urban logistics solutions. Additionally, since Bordeaux's entire public transport network operates at street level, logistics operations are simplified, eliminating the need for vertical goods transfers between different transport layers.

5.1 Instance and scenario generation

The information required to define the instances is obtained from previous studies in Bordeaux. Details on the network and the streetcars in circulation are provided by the operator of public transport in the Bordeaux metropolis area.

To assess how different factors influence the proportion of freight transported via the tramway network, multiple scenarios are designed. These scenarios are constructed around four critical parameters: the transport configuration: (e.g., mixed-use trams versus freight-dedicated trams), the tramway's capacity, the per-unit cost of moving a trolley by tram, and the overall demand volume.

5.2 Results and analysis

5.2.1 Analysis of transport configuration

Figures 2 and 3 describe the evolution of costs and emissions per day per transport configuration.

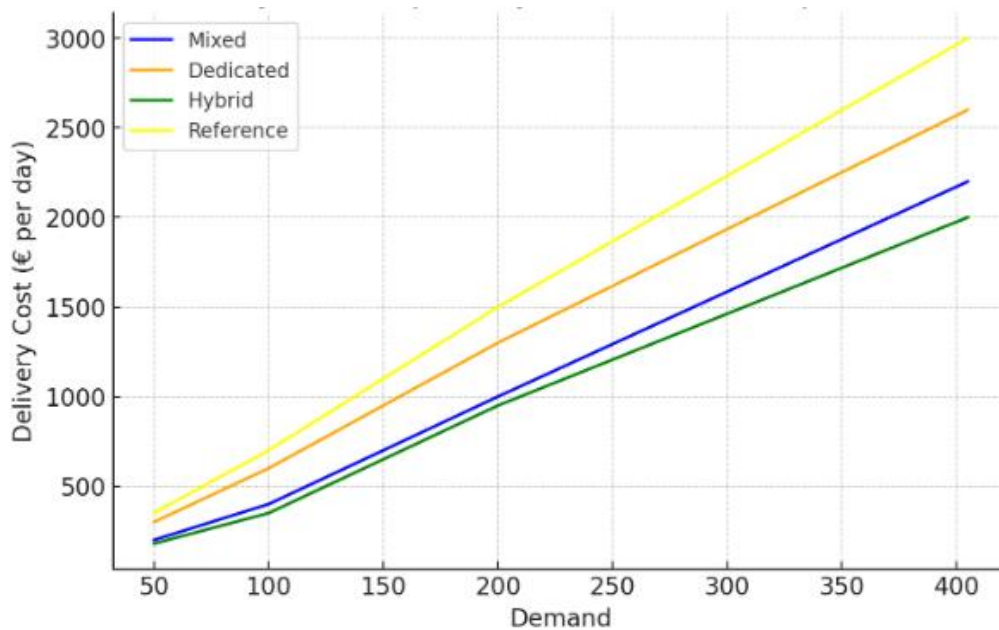


Figure 4: Delivery cost according to transport mode and demand

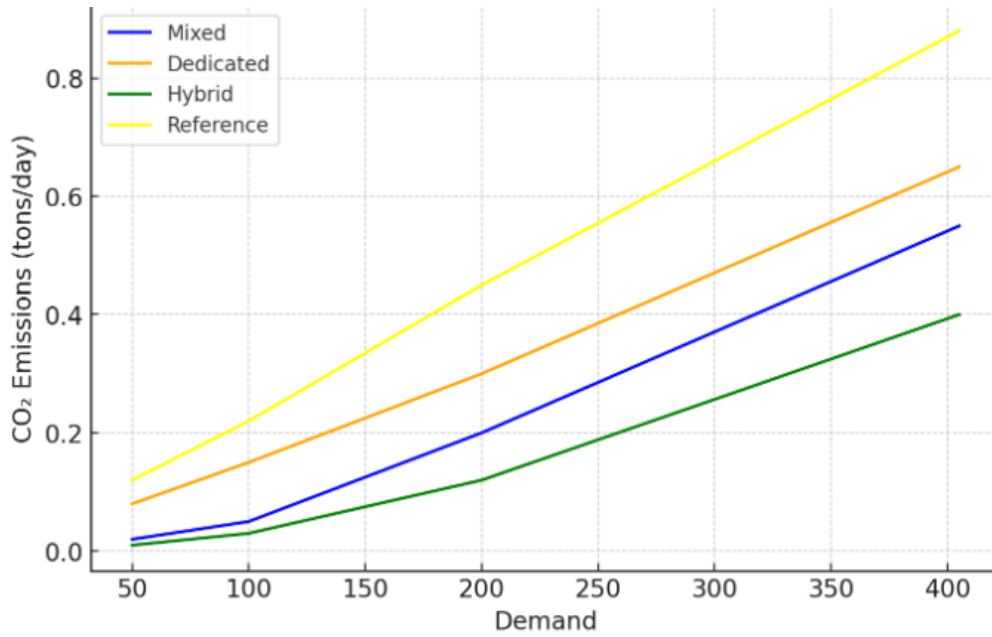


Figure 5: CO₂ emissions according to transport mode and demand

Several conclusions can be drawn. The first is that an entirely mixed solution is always more attractive than an entirely dedicated solution (both economically and ecologically). Despite this finding, it can also be observed that with higher demand (200-405 trolleys per day), a hybrid solution becomes much better than either mixed or dedicated solutions. This means that, although mixed trips are more attractive than dedicated trips, their use should not be neglected to achieve optimum efficiency.

5.2.2 Impact of demand

The results show that a very large quantity of demand can be transported by tramway. With a demand of 50 or 100 trolleys per day, the tramway is a more cost-effective method of transport than the truck. More specifically, almost all demand is carried by mixed trip. This means that a very significant proportion of demand in the hyper-center could be transported by tramway.

As mixed trips have no fixed opening costs, their utilization seems to be prioritized. Nevertheless, their capacity is limited, and as demand rises, their utilization rates fall in almost proportion to demand, indicating an inability to use more of the residual mixed-trip capacity.

When demand exceeds this threshold, the remaining trolleys are transported by truck or dedicated trips. This trend seems to validate that the dedicated tramway has the potential to be used and is more cost-effective than the truck if enough demand is available to justify its use. Some requests could therefore be pooled and transported together by a dedicated trip, while the last remaining requests were routed by truck.

5.2.3 Impact of capacity

When it comes to capacity, its influence is most evident in scenarios involving mixed trips. In these cases, the number of trolleys transported per trip doubles under optimistic capacity assumptions. Hybrid solutions also experience a notable rise in mixed trip usage. This, in turn, leads to a comparable reduction in costs and emissions—ranging from 10-15% for hybrid solutions and 25-30% for mixed solutions. Conversely, in dedicated freight solutions, the impact of capacity per trip remains minimal.

Conclusion

This paper has three main contributions. First, we reviewed the literature to explore the challenges of FOT implementation and success. Second, we present a framework that summarizes the main challenges of FOT implementation. It classifies them according to relevant stakeholders. Third, we present a mathematical model to estimate the potential capacity of a public transport network to integrate freight in the context of PI. The first results of the case study of the city of Bordeaux are presented.

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Master Assembly Scheduling Optimization of Project-Driven Hyperconnected Manufacturing

Zhihan Liu¹, Jihye Jung¹, Wencang Bao¹ and Benoit Montreuil^{1,2}

1. Physical Internet Center, Supply Chain & Logistics Institute, H. Milton Stewart School of Industrial and Systems Engineering, Georgia Institute of Technology, Atlanta, GA, USA

2. Coca-Cola Material Handling & Distribution Chair

Corresponding author: zliu929@gatech.edu

Abstract: Hyperconnected manufacturing is emerging to address the increasing demand for agility, resilience, and product-specific manufacturing methodologies suitable for various practical scenarios where traditional centralized, large-scale facilities are inadequate. This study explores a hyperconnected manufacturing network—aligned with Physical Internet principles—that supports a geographically dispersed, project-driven assembly system necessitating the delivery of multiple complex products within strict timelines. We develop an optimization model for early-stage planning and decision-making, based on a real production system from the industry. The proposed model schedules production within mobile assembly factories while minimizing total production resource costs. It also incorporates realistic constraints associated with various resource types, such as workloads across product categories, parts arrival schedules, workforce continuity over resource commitment periods, and specified inventory levels. A comparative analysis evaluates the baseline schedule that directly relates to the products' demand at the project site against a set of optimized project schedules generated from our proposed formulation. This assessment examines the effectiveness of the designed optimization model on decision-making for PI factories. The findings provide insights for practitioners aiming to enhance master assembly scheduling to achieve a cost-efficient, PI-enabled hyperconnected manufacturing.

Keywords: Physical Internet, Hyperconnected Manufacturing, Master Assembly Scheduling, Distributed Manufacturing, Mobile Manufacturing, Multi-Skilled Workforce

Physical Internet (PI) Roadmap Fitness: ☑ PI Nodes (Customer Interfaces, Logistic Hubs, Deployment Centers, Factories)

Targeted Delivery Mode-s: ☑ Paper, ☑ In-Person presentation

1 Introduction

Over the past several decades, scholars in supply chain and operations management have increasingly explored adaptive manufacturing paradigms that can meet contemporary market expectations for rapid, low-cost fulfillment with minimal delivery variability and extensive product customization. In the work done by Christopher and Towill (2000), lean and agile capabilities have emerged as complementary imperatives: lean practices secure structural cost efficiency, while agility enables firms to capture volatile, short-lived demand fluctuations. More recently, researchers have highlighted mobility—the ability to share assets and reconfigure capacity across spatially dispersed production sites—as a further source of competitive advantage, promising heightened capital efficiency and resilience (Stillström and Jackson, 2007). A noteworthy, well-structured solution is offered by Marcotte and Montreuil (2016), who introduced the concept of hyperconnected mobile production, defined as a manufacturing paradigm in which firms dynamically scale their global

capacity by routing reconfigurable, plug-and-play production modules through open, multiple-party fabs distributed across regions.

In this study, leveraging the principles of the Physical Internet, we focus on a hyperconnected manufacturing network that serves clients needing the assembly of sets of large, complex products for distributed projects, each at a specific site and according to a precise just-in-time delivery sequence aligned with the project schedule. Each project may require different types and specific quantities of products. Production for a project occurs in a factory within the hyperconnected network that is as close as possible to the delivery site and is available during the designated production period.

Once assembled, a product can be staged or shipped directly to the project site. The hyperconnected assembly factories, distributed across the market territory, can be dynamically assigned to multiple projects sequentially and concurrently as needed. Each factory may contain one or more assembly lines or cells operated at a cadence established by a determined takt time (e.g., 2 hours), driving the progression from one assembly station to the next, all the way to product completion. The factory may rely at each station on combinations of multi-skilled humans, robots, and automated equipment to complete the assembly of the products.

In each project, the ownership and maintenance of the selected building that houses the contracted factory, the activation and operation of the factory to assemble the products, the logistics of staging and delivering products to the sites, and the clients requesting the products for their projects can involve distinct companies interconnected to realize this project, aligning with one of the key visions of the Physical Internet – universal interconnectivity (Montreuil, 2011).

Our paper introduces and evaluates the performance of a model that enables the optimization of master assembly scheduling for the hyperconnected assembly factory engaged for a specific project. This schedule outlines a sequenced list of products to be assembled, detailing the type of each product in the sequence and the takt time for starting and completing each product. The goal is to ensure dynamic availability of products to meet the product-to-site delivery schedule of the project, adhere to the planned availability of the parts needed for assembling each product, and complete the assembly of all products at minimal resource costs, including personnel hiring and robot operating expenses.

The remainder of the paper is structured as follows: In Section 2, we provide a concise review of the relevant literature. In Section 3, we formally describe the master assembly scheduling problem within hyperconnected manufacturing networks. In Section 4, we present our modeling methodology for optimizing the master assembly schedule. In Section 5, we detail our experimental design, followed by a report and analysis of our computational results. Finally, in Section 6, we summarize our key contributions and insights, discuss the current limitations of our research, and suggest avenues for further exploration in this exciting thread focused on realizing products through hyperconnected networks in the Physical Internet.

2 Literature Review

In the design of a production system, the concept of takt time is often used to manage the cadence of the process. This concept refers to the maximum time interval a product—or any of its subproducts—can occupy during each production phase. The takt time is often derived from analyses of the desired production throughput, based on market factors such as inventory cost, consumption rate, and market seasonality. Through comprehensive takt time planning, the goal is to develop an optimized production schedule and workforce assignment that maintain a continuous production flow at a steady rate (Frandsen et al., 2015; Vatne et al., 2016).

Complementing this focus on a pace-driven manufacturing plan implemented in regional facilities, the research is based on the concept of a fractal: a set of collective processing units that can handle

any product type. The fractal paradigm aligns with hyperconnected, distributed, and mobile production, as these concepts aim for increased flexibility and agility. Utilizing the fractal concept, managers can easily adjust the number of highly modularized and standardized fractal centers to respond to market fluctuations or operational disruptions, thus fine-tuning the production pace (Montreuil, 1999). From an operational-dynamics perspective, the fractal approach significantly enhances flexibility and robustness, while from a life-cycle perspective, it allows for straightforward capacity expansion—advantages that are challenging to replicate in traditional product- or process-oriented factory designs (Montreuil, 1999; Venkatadri et al., 1997).

This research builds upon the framework proposed by Bao et al. (2024), which presents a modular-design methodology for fractal centers within hyperconnected assembly factories and their connection with other parties in the PI network. Their work, grounded in Physical Internet (PI) principles, concentrates on the microscopic scale—specifically, material handling and assembly operations occurring inside an individual fractal center. Our contribution stems from a shift in analytical focus from the previous work of Bao et al. We emphasize project-level master assembly scheduling throughout the entire duration of a single project.

Furthermore, optimization-based approaches have been proposed for optimizing physical internet systems, while the domain mainly covers the discipline of transportation and logistics. For example, Sarraj et al. (2014) propose an optimization formulation for the assignment of containers to transportation means to demonstrate the advantages of the PI. Toth and Vigo (2014) propose sequential optimization and simulation for transportation networks by validating the cost efficiency of the PI-based system. Our study contributes to the discipline of PI by exploring the further capability of optimization in the PI-based production and manufacturing, efficiently deriving a production schedule that minimizes total cost while remaining consistent with the modular, fractal-center production paradigm.

3 Problem Description

3.1 Motivation

As established in the introduction and literature review, this study is built upon the concept of hyperconnected manufacturing networks designed to support a wide range of geographically distributed assembly factories. Each assembly factory within the network operates under a business model that imposes several structural and operational constraints. Additionally, the production in each facility is driven by takt time and is operated by either multi-skilled manual labor or multi-functional autonomous robotic units. The takt-time-driven assembly approach ensures that one unit of product is completed at each takt interval over the long term, with production activities executed by a consistent workforce (either human workers or robots) throughout a given resource commitment period.

Regarding material flow into the assembly facility, each facility is linked to a single storage area designated for the inventory of all parts. Since multiple product types are scheduled for production throughout a project's duration, and each product type entails distinct workloads and inventory space, the system experiences significant variability in resource demand. Additionally, due to the inherent limitations in dynamic workforce management and additional storage rent, it becomes crucial to smooth the fluctuations in resource and inventory requirements over the production timeline. This practical challenge serves as the primary motivation for our optimization efforts.

We note here that the problem is examined under a set of simplifying assumptions. It is assumed that exactly one product will be launched for production in the facility every other takt time, and all products remain in the factory for the same number of takt times, implying that they progress through the same sequence of stations according to the pace of takt time within the assembly factory. We also assume that parts are procured periodically with a constant period. The workforce is maintained

within a workforce commitment period. All time-related elements within the system, such as task durations, start times, and delivery times of parts, are modeled as deterministic to thoroughly outline the entire assembly workflow. The earliest allowable start takt time of a product indicates the time this product can start only after, and not before, while the latest start takt time of a product implies that the module will be moved out of the finished product inventory to the project site at this takt time plus the number of takt times each product occupies.

3.2 Defining the Problem

Objective. At the level of an individual facility within the manufacturing network, production capacity is predefined based on the facility's business model (Bao et al., 2024). This includes the physical size of the facility and the quantity and types of equipment available. As a result, the costs associated with facilities and equipment are considered fixed based on the desired production capacity at each location. Given these factors, the focus of the current optimization effort shifts toward minimizing resource costs incurred by humans and/or robotics. Specifically, resource cost is computed by aggregating the workload requirements across all skills/functions, weighted by the cost associated with each resource type, which is capable of a class of skills/functions. Although we perceive the resource costs associated with human labor or robotics as the same, inherently, resource costs for human labor are tied to daily salaries, while those for robotics depend on lease, energy, and maintenance costs calculated on a daily basis. The set of skills affects the daily salary of a human and the daily operating cost of a robot, indicating the differentiation in resource costs among various worker and robot types.

Key Decisions. To achieve the minimization of resource costs, the primary decision variable under our control is the production schedule, which can be further detailed as the takt time phased product assembly sequence. In this context, cost efficiency can be achieved by establishing a schedule that promotes balanced workloads across different skills/functions within a resource commitment period and ensures that the products assembled at any takt time correspond to workloads that do not significantly differ from those at nearby takt times. With a set of product types that vary in complexity, the model aims to distribute complex products to prevent workload peaks at certain takt times caused by a consecutive sequence of complex products, thus avoiding the need for a larger workforce throughout the entire resource commitment period.

Constraints. Several operational constraints must be imposed on the production schedule for practical purposes. The interdependence between the manufacturing process and upstream or downstream project activities represent one of the primary constraints. For instance, certain groups of products must be manufactured consecutively because they either need to be physically attached after assembly or must be delivered to the project site as an aggregated unit. Additionally, the start time for assembling each product is limited by a specific time window: the earliest start time reflects the earliest availability of required parts for that product, while the latest start time is determined by the necessary availability of assembled products to meet the product-to-site delivery schedule required by the client. Precedence relationships may exist between pairs of products to reflect the business decisions made based on the inherent technical product demand precedence considerations.

Problem Inputs. Below is a collection of inputs to the decision-making process and our optimization model to capture the objectives, variables, and constraints illustrated above. The inputs are categorized under the relevant components of the target production system:

- **Product Unit:** Product type of such product, physical volume (ft^3) for the aggregation of all parts of such product, physical volume of the finished product, earliest/latest allowable start times, and groups for nearby production, if applicable. Products of the same product type have an identical assembly process.
- **Workloads:** The aggregated workloads of each skill, of each relative takt time, of each product type.

- Skills/Functions: Mappings from required skills/functions to worker types/robotic types.
- Worker Type/Robotic Type: Estimated resource utilization percentage, hourly resource costs.
- Resource commitment periods: Period ID, the set of consecutive takt times that fall in this period, and the length of this period. The periods are defined as input to this model and allowed to be of different lengths.
- Inventory: Maximum capacities for parts and product storage, and parts order interval.
- Products Precedence: Directed pairs of products with lags if applicable.
- Global Parameters: the number of takt time any product will spend in the assembly process, the project start time, and the takt time duration.

Problem Outputs. Below are the desired outputs from the problem, which we expect to have a set of optimized values of these outputs once we solve the proposed model:

- The master assembly schedule: the assembly start time of all products
- Optimized quantity required for each human worker type or robotic type in each resource commitment period.
- Total skill workload and aggregated worker-type workload at each takt time.
- Total resource costs.

4 Methodology

4.1 Nomenclature

This section presents the notations and the detailed definitions of them, covering the sets, parameters, and decision variables that compose our optimization model. Specifically, we separate the decision variables into two different groups: the primary variables and the auxiliary variables. The set of auxiliary variables can be determined directly from the primary variables with the defined equations, that is provided as part of the constraints in the following section.

Sets and Indices.

P	Set of products that will be manufactured for the target project, indexed by p .
G	Set of product groups of products that need to be scheduled nearby, indexed by g .
P_g	Set of products in group $g \in G$, indexed by p .
H	Set of resource commitment periods, in which the same workforce will be employed/deployed, indexed by h .
T	Set of takt times that the target project will be active, indexed by τ .
T_h	Set of takt times within the resource commitment period h .
S	Set of skills that is required to accomplish all the tasks within the project, indexed by s .
W	Set of worker types/robotic types who equip the partial required skills, indexed by w .
O	Set of parts order arrival points, where $O = \{0, \theta, 2\theta, \dots\} \subseteq T$ and indexed by o .
Z	Set of precedence relationships, where $(p, q) \in Z$ indicates product p must start before q .

Parameters.

l	Number of takt times every product spends in the assembly process.
l_h	Number of takt times in the resource commitment period h .
\underline{t}_p	Earliest allowable takt time when product p may start to be assembled.
\bar{t}_p	Latest allowable takt time when product p may start to be assembled.
d_{p,q}	Smallest allowable number of takt times between the start time of product p and the start time of product q .
w_{p,k,s}	Workload required by skill/function s at step k of product p . Step k represents the relative takt time k , which indicates the step or phase over product p 's entire assembly process.

u_w	Estimated utilization rate of worker type w .
c_w	Cost of employing/deploying one resource of type w .
v_p^{parts}	Physical volume of all parts required for product p .
v_p^{fin}	Physical volume of finished product p .
v^{parts}	Maximum allowable parts inventory volume.
v^{fin}	Maximum allowable finished products inventory volume.
$\omega(s)$	Worker/robotic type assigned to skill/function s .
θ	Fixed interval (in takt times) between parts orders' arrival time.

Decision Variables.

$Y_{p,\tau}$	Binary; 1 if product p starts at time τ , 0 otherwise, for $p \in P$ and $\tau \in T$.
T_p	Integer; Actual start time of product $p \in P$.
$N_{w,\tau}$	Integer; Number of resources of type w needed at time τ .
$\bar{N}_{w,h}$	Integer; Peak number of resources of type w employed/deployed in resource commitment period $h \in H$.
$W_{s,\tau}$	Real; Total workload for skill s at time τ .
$W_{w,\tau}$	Real; Total workload for worker type w at time τ .
\bar{c}_h	Real; Induced resource cost in the resource commitment period h .
I_o^{parts}	Real; Total parts delivered at the ordering point o .
I_τ^{fin}	Real; Inventory of finished products at time τ .
T_g^{\min}	Integer; Minimum start time among all products in group $g \in G$.
T_g^{\max}	Integer; Maximum start time among all products in group $g \in G$.

4.2 Optimization Model

Equations (1) – (17) represent the objective function and the associated constraints with the notations introduced in the previous section.

$$\min \quad Z = \sum_{h \in H} \bar{c}_h l_h \quad (1)$$

$$s. t. \quad \sum_{\tau=\bar{t}_p}^{\bar{t}_p} Y_{p,\tau} = 1 \quad \forall p \in P \quad (2)$$

$$\sum_{p \in P} Y_{p,\tau} \leq 1 \quad \forall \tau \in T \quad (3)$$

$$T_p = \sum_{\tau \in T} \tau \cdot Y_{p,\tau} \quad \forall p \in P \quad (4)$$

$$T_p + d_{p,q} \leq T_q \quad \forall (p, q) \in Z \quad (5)$$

$$T_p \geq T_g^{\min} \quad \forall g \in G, p \in P_g \quad (6)$$

$$T_p \leq T_g^{\max} \quad \forall g \in G, p \in P_g \quad (7)$$

$$T_g^{\max} - T_g^{\min} = |P_g| - 1 \quad \forall g \in G \quad (8)$$

$$I_o^{\text{parts}} = \sum_{p \in P} v_p^{\text{parts}} \cdot \sum_{\tau=o+1}^{o+\theta} Y_{p,\tau} \quad \forall o \in O \quad (9)$$

$$I_{\tau}^{\text{fin}} = \sum_{p \in P} v_p^{\text{fin}} \cdot \sum_{\tau \in T: \underline{t}_p + l - 1 \leq \tau < \bar{t}_p + l} Y_{p,\tau} \quad \forall \tau \in T \quad (10)$$

$$I_o^{\text{parts}} \leq v^{\text{parts}} \quad \forall o \in O \quad (11)$$

$$I_{\tau}^{\text{fin}} \leq v^{\text{fin}} \quad \forall \tau \in T \quad (12)$$

$$W_{w,\tau} = \sum_{s \in S: \omega(s)=w} W_{s,\tau} \quad \forall w \in W, \tau \in T \quad (13)$$

$$N_{w,\tau} \cdot u_w \geq W_{w,\tau} \quad \forall w \in W, \tau \in T \quad (14)$$

$$N_{w,\tau} \leq \bar{N}_{w,h} \quad \forall w \in W, h \in H, \tau \in T_h \quad (15)$$

$$\bar{C}_h = \sum_{w \in W} c_w \cdot \bar{N}_{w,h} \quad \forall h \in H \quad (16)$$

$$W_{s,\tau} = \sum_{p \in P} \sum_{l'=1}^l w_{p,l',s} \cdot Y_{p,\tau-l'+1} \quad \forall s \in S, \tau \in T \quad (17)$$

Equation (1) represents the objective function that minimizes the weighted sum of peak costs for each resource commitment period, where the weights are defined by the number of takt times for each resource commitment period. Because changing the workforce deployment on a daily basis adds a great burden for operations management, and we need to find feasible solutions, we decided to adopt the common industrial assumption that we will hire the peak workforce we must need for a resource commitment period. Equations (2) and (3) work jointly to assign the production of each product to a specific takt time. Equation (2) guarantees every product to be assigned to one takt time within its allowable window, while Equation (3) prevents the assignment of more than two products to a single takt time.

Equations (4) – (8) are the constraints that schedule the production based on the precedence and the group information provided to the model. Equation (4) links binary scheduling variables to the continuous start time variable by computing the production start time of each product. Equation (5) enforces the required lag time between products if the precedence applies to the pair of products. Equations (6) – (8) ensure that all products in the same group are scheduled consecutively of any order, without any gaps. Specifically, Equations (7) and (8) let production begin within the time window given to each of the product groups.

Equations (9) – (12) define the relationship between the variables that are relevant to the inventory of parts and finished products. Equation (9) captures the total volume of parts ordered at delivery times, covering all products that start to be assembled from this ordering takt time up to the next ordering takt time. Equation (10) tracks the inventory of finished products that remain unshipped, where each product is assumed to be shipped at its latest allowable start time plus the number of takt times every product spends in the assembly process. Equations (11) and (12) follow to ensure that parts orders do not exceed warehouse capacity at the delivery moment and to control the total volume of finished goods stored before shipment.

Equations (13) – (17) represent the constraints about workload and the associated resource costs.

Equation (13) computes the total workload for each skill/function at each takt time of all products under the assembly process. Equation (14) ensures that the available capacity provided by the hired workers/deployed robotics is at least the required workload. Equation (15) ensures the capture of the actual number of resources needed during that resource commitment period. Lastly, Equation (16) calculates an actual resource cost in a resource commitment period by multiplying the actual

number of resources needed during the resource commitment period by their resource cost rates. This directly inputs into the objective function we defined by Equation (1). Equation (17) is used to calculate the intermediate variable of workload by takt time and skill for a sequence of products, which is then fed into Equation (13). Note that all the variables used in this optimization model are greater than or equal to 0.

5 Computational Experiments

5.1 Experiment Settings

This study investigates five experimental scenarios based on the proposed optimization formulation and mock-up data from MiTek Inc., our collaborative industrial partner in research on Physical Internet-inspired hyperconnected distributed construction. In this case, products correspond to building modules. In the first experiment, the optimization process is bypassed, and the default product sequence, defined by the order in which products are demanded at the project site, is adopted as the fixed production schedule. In contrast, the second to fifth experiments introduce flexibility into the scheduling of products, allowing the optimization model to adjust the production sequence within the bounds defined by each product's earliest permissible start time. The distinction among Experiments 2 to 5 lies in the degree of scheduling flexibility permitted. The objective of these experiments is to evaluate the benefits of relaxing the production sequence constraints, measured through key performance indicators, including total resource cost, and the workforce allocation plan across resource commitment periods.

In Experiments 2 to 5, scheduling flexibility is governed by a parameter referred to as the *Permitted Time Span for Re-sequencing*, as presented in *Table 1*. This parameter defines the length of the takt time intervals within which the model is allowed to freely re-sequence the start times of products. For example, in Experiment 2, a value of 16 indicates that within each block of 16 takt times, the model may determine the optimal production sequence for the corresponding 16 products. To incorporate a fair comparison, all other decision attributes are the same, including resource commitment period, order arrival period, etc.

The experiments are conducted using a dataset comprising 128 products categorized into 15 distinct product types. These products are characterized by their large size and high complexity. Although all product types are processed through a common set of stations under a generally similar production process, variations arise due to differences in task inclusion and task duration across product types.

Table 1: Experiment Setting

Experiment	Sequence Flexibility	Permitted Time Span for Re-sequencing	Optimization Applied
Experiment 1	None (Fixed to project site demand order)	0	No
Experiment 2	Low	16	Yes
Experiment 3	Moderate	32	Yes
Experiment 4	High	64	Yes
Experiment 5	Free (No earliest allowable start time)	128	Yes

5.2 Results

After these 5 experiments have been processed through the optimization model, the output results are gathered from each scenario, in terms of total resource cost, and size of workforce for each resource commitment period. *Tables 2 and 3* illustrate the resource cost and workforce size for each resource commitment period and experiment.

Table 2: Experiments' Resource Cost(\$) over Resource Commitment Periods

Resource commitment period	Experiment 1	Experiment 2	Experiment 3	Experiment 4	Experiment 5
H1	230,723.20	222,083.20	222,083.20	222,083.20	222,083.20
H2	235,043.20	222,083.20	222,083.20	222,083.20	222,083.20
H3	226,403.20	222,083.20	222,083.20	222,083.20	222,083.20
H4	79,241.12	72,409.12	61,041.12	61,041.12	47,377.12
Sum	771,410.72	738,658.72	727,290.72	727,290.72	713,626.72

Table 3: Experiments' Workforce Size over Resource commitment periods

Resource commitment period	Experiment 1	Experiment 2	Experiment 3	Experiment 4	Experiment 5
H1	36	34	34	34	34
H2	37	34	34	34	34
H3	35	34	34	34	34
H4	35	33	28	28	24

The 5 experiments reveal how optimization reduces both resource cost and workforce requirements while maintaining feasibility across the takt-based production schedule. In the baseline scenario (Experiment 1), the total resource cost is highest at \$771,410.72, with the workforce peaking at 37 workers in a single resource commitment period. This reflects a default sequencing of products that does not consider optimization for labor smoothing.

As we introduce optimization in Experiments 2 to 5, in comparison to Experiment 1, we observe the following improvements:

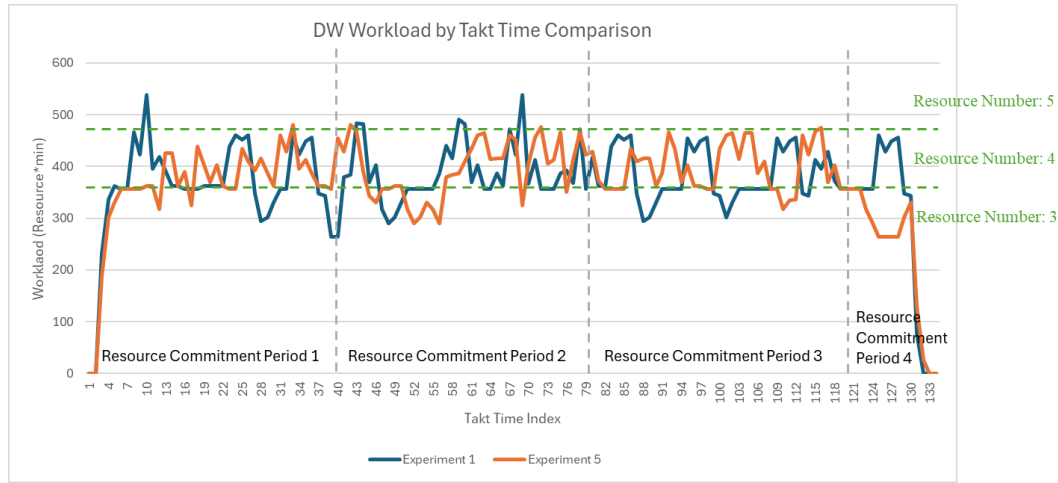
- Total resource cost drops to \$738,658 in Experiment 2, then to \$727,290 in Experiments 3 and 4, and finally to \$713,626 in Experiment 5. They represent a saving of 4.25%, 5.72%, 5.72%, and 7.49% in terms of resource cost.
- Workforce size becomes more uniform, reducing peak employing/deploying needs. While the default requires up to 37 workers, optimized scenarios limit this to 34 or fewer.

The most significant labor and workforce reduction occurs in the resource commitment period H4, where costs drop from \$79,241.12 (Exp. 1) to \$61,041.12 (Exp. 3 & 4), then to only \$47,377.12 (Exp. 5). The total required workforce size drops from 35 to 24. This suggests that the optimization effectively reduces the peak required number of resources during the resource commitment period H4 compared to the default case. For H1 to H3, the resource cost is improved from experiment 1 to experiment 2 and remains unchanged up to experiment 5. This indicates that allowing resequencing in a narrower takt time span has reached the boundary of the resource cost reduction we could gain out of resequencing for those periods.

Despite the implications of the experimental results, the reduced resource costs and decreased workforce variation, facilitated by a more relaxed takt time span for resequencing, offer additional advantages. First, the decrease in peak workforce size simplifies resource planning by alleviating the challenges of deployment, onboarding, and daily management. Second, the lower and more consistent resource costs allow for easier budgeting and financial control. Third, the more uniform distribution of workload across takt times encourages operational smoothing, which diminishes the chances of bottlenecks and excessive inventory accumulation. Finally, the significant reduction in both resource costs and workforce demand during the final resource commitment period (H4) indicates that optimized schedules not only provide a timeframe for handling products with less workload, but also contribute to a more efficient project ramp-down, helping to prevent underutilized labor near the project's end. In this study, we defined a total of 10 resource types, and here we would like to use the worker type DW to illustrate the different outcomes. A comparison of the workload of DW resource

type by takt time between the default baseline schedule and the optimized schedule from Experiment 5 demonstrates how effectively the optimization balances the workload, as illustrated in Figure 1.

Figure 1: DW Workload Fluctuations Comparison



The grey dashed line breaks the overall project takt time into four resource commitment periods, while the green line breaks the required workforce size of DW into five (upper area), four (area between two green lines), and three (lower area). From the figure, it can be seen that the experiment 5 schedule avoids many workload peaks for DW that originally exist, through resequencing the products, potentially saving costs for the resource type DW.

6 Conclusion

This study presents a master assembly scheduling optimization framework for project-driven scenarios in a hyperconnected manufacturing network, aiming to minimize peak resource costs while adhering to constraints on parts availability, finished product inventory, product precedence, product grouping, etc. By integrating reasonable parameters and constraints into a mixed-integer programming (MIP) model, we demonstrate that intelligent resequencing of products can lead to significant reductions in total resource costs and smoother workforce allocation across resource commitment periods. Comparative experiments show that even slight flexibility in product scheduling yields measurable operational benefits.

However, several limitations remain. First, the model assumes fixed task durations and deterministic workloads, which may not reflect real-time variability in production environments. Second, logistics and material handling activities are abstracted into inventory constraints that capture only the physical volume of objects, omitting potential conflicts in shared spaces and operating cross-interference with assembly activities. Third, the current model operates at a single project level without accounting for dynamic interactions between multiple projects or demand uncertainty. Future research could extend the model by incorporating stochastic demand and multi-project coordination. Additionally, integrating logistics resource scheduling alongside production resources would offer a more holistic view of master assembly planning.

This work contributes to the vision of the Physical Internet (PI) by exploring the “realizing” aspect of the overall PI key verbs in a hyperconnected manufacturing network. The proposed model supports the PI principle of dynamic adaptability by enabling flexible resequencing that aligns with the cost efficiency objective while accommodating practical constraints. As PI manufacturing nodes are expected to operate with high interoperability, our optimization framework establishes the foundation for master assembly scheduling that can be integrated at the node level, facilitating scalable and responsive hyperconnected networks.

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Implementation of Hyperconnected Mobile Supply Chains For Large Scale Networks

Julien Maurice, Simon Soonhong Kwon and Benoit Montreuil

Physical Internet Center, H. Milton Stewart School of Industrial & Systems Engineering, Georgia Tech, Atlanta, GA, USA

Abstract

Traditional supply chains, designed for economies of scale, often lack the flexibility needed to respond to fluctuating demand, limiting their performance in terms of cost, sustainability, and reconfigurability. Mobile and module production concepts, such as containerized manufacturing and Hyperconnected Mobile Production, have emerged as promising alternative, enabling dynamic, local deployment of plug-and-play production modules. While prior research has highlighted the potential of such systems, most remain confined to small-scale or single-tier networks.

This paper investigates the design and performance of a Hyperconnected Mobile Supply Chain (HMSC), a multi-tier, Physical Internet enabled network of networks comprising mobile production units, open certified facilities and suppliers. We develop a multi-objective mixed-integer programming model to optimize facility locations, production capacities, supplier assignments and module relocations. A tailored metaheuristic approach ensures the generation of high-quality nondominated solutions. We benchmark the HMSC against traditional and hybrid supply chain networks across a comprehensive set of key performance indicators. Preliminary results show that large-scale HMSCs offer significant advantages in cost, adaptability and sustainability, paving the way for more resilient and responsive supply chains.

Keywords

Hyperconnected Mobile Production, Multi-tier networks, Modular Capacity, Large-scale Network Design, Metaheuristic

1. Introduction

In an era of increasing volatility, uncertainty and complexity, supply chains are under growing pressure to become more agile, resilient and sustainable. However, traditional supply chain networks, designed to capitalize on economies of scale, remain largely static, prioritizing stability and cost-efficiency over adaptability. This rigidity often leads to significant inefficiencies in production allocation, transportation, inventory management, and ultimately, customer responsiveness when faced with fluctuating demand or disruptive events.

To overcome these limitations, mobile and modular production systems have emerged as a promising alternative. These systems offer dynamic, reconfigurable manufacturing capacity that can be deployed closer to demand regions, drastically reducing lead times and operational costs. Industry leaders such as Bayer and Procter & Gamble have demonstrated the value of such solutions through initiatives like the F3 factories project, a public-private European program aimed at developing and implementing mobile containerized production in the chemical sector. Results indicated improvements in profitability, responsiveness, and time-to-market while simultaneously reducing environmental and logistical burdens. These outcomes highlight the potential for broader applications across various industries.



Figure 1: Implementation of The F3 Factory project

A particularly relevant application domain is modular construction, which has attracted increasing attention due to its ability to accelerate project timelines, reduce weather-related delays, enhance safety, and lower material and energy usage through offsite production in controlled environments [1] [2]. However, the sector still relies heavily on fixed-location production facilities, resulting in capacity limitation and high transportation costs, especially for geographically dispersed projects. These challenges make mobile, reconfigurable production systems especially valuable in this context.

Despite growing industrial interest, the large-scale deployment of mobile production systems across multi-tier supply chains remains largely unexplored. To the best of our knowledge, existing literature rarely addresses the interaction between multiple mobile production networks, an essential consideration when supply chains are viewed as ecosystem of interdependent actors.

This paper addresses this research gap by investigating the Hyperconnected Mobile Supply Hain (HMSC) – a network of networks of interoperable, mobile production units, embedded in a multi-tier structure. We propose a large-scale implementation framework of the HMSC and use a metaheuristic-based optimization model to minimize both total cost and environmental footprint for strategic network design.

The rest of this paper is structured as follow: Section 2 reviews relevant literature on mobile and hyperconnected mobile production. Section 3 introduces the HMSC framework. Section 4 provides a mathematical methodology used to model and solve the problem. Section 5 presents a case study in the modular construction industry, assessing the performance of the HSMC relative to traditional static networks. Finally, Section 6 concludes with insights and directions for future research.

2. Problem Description

The concept of Hyperconnected Mobile Production, introduced by [3] builds on the principles of the Physical Internet to create a modular, mobile containerized production framework designed to meet the growing need for fast, flexible, and cost-effective manufacturing. Among the various strategies proposed to address global supply chain challenges, this approach emphasizes on-demand, near-market production, enabled through modularity, standardization, and digital connectivity.

At the core of this paradigm is a network of open, certified production facilities, also referred to as open fabs. These geographically distributed facilities are designed to host mobile production modules (either standalone or in combination) which can be rapidly deployed, reconfigured or relocated. The modules are designed to be plug-and-play and interoperability, minimizing transition time and operational disruption. By leveraging hyperconnected transportation networks, these facilities are integrated with suppliers and demand regions, enabling localized and responsive manufacturing that dynamically adapts dynamically to market needs.

This work extends the concept by modeling a network of interacting Hyperconnected Mobile Production systems, referred to as a Hyperconnected Mobile Supply Chain (HMSC). This network-level approach aims to coordinate multiple modular production nodes across space and time, accounting for supplier availability, facility capacities, relocation costs and dynamic demand pattern. [4]

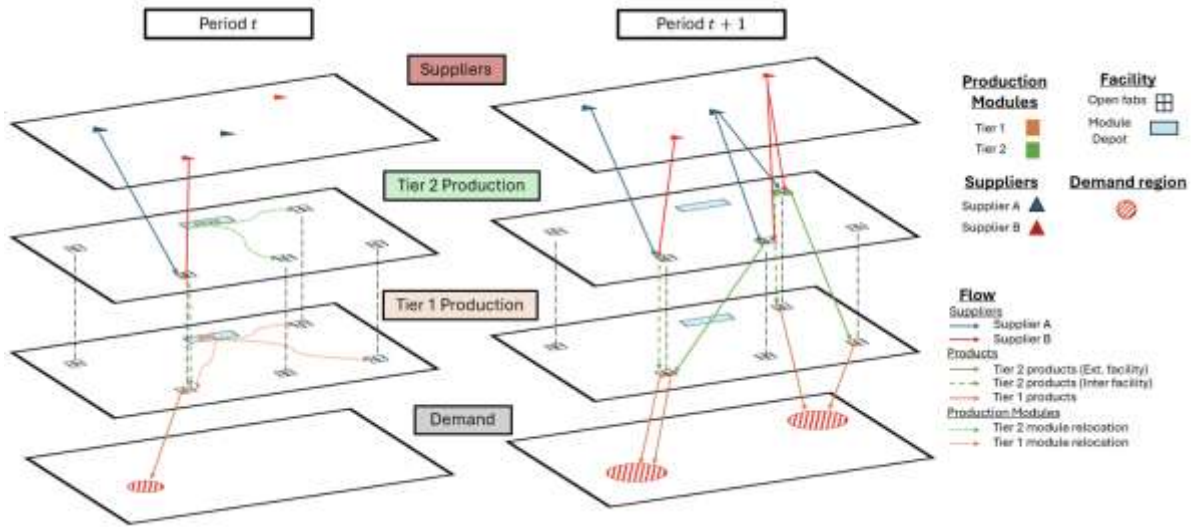


Figure 2: Illustration of HMSC over two periods of time

At each period, mobile production modules can be activated, operated, relocated between facilities, sent to storage or deployed from storage based on system needs. The deployment strategy balances the trade-off between localizing production to minimize logistic costs and consolidating production to benefit from economies of scale across tiers. This coordination across multiple layers of the network reflects the ecosystem logic of the Physical Internet and serves as the foundation of the proposed framework.

We consider a deterministic, multi-tier supply chain setting, in which the demand for a given product in each market region α during period t is known in advance. The supply chain consists of four tiers. Adopting a bottom-up perspective, the first tier is the set of market regions where demand originates. The second tier, referred to as tier-1 production, is responsible for producing the products required by markets, utilizing shipments from the third tier. The third tier, or tier-2 production, oversees consolidating inbound components received from suppliers to outbound shipment destined to tier-1 facilities. The fourth and last tier is the supplier network, providing components needed for production.

Within this setting, given a set of candidate facilities F and a set of projects to be realized, the main decisions to be made for each period t , include:

- Activating or deactivating open facilities.

- Deploying production capacity across both production tiers.
- Relocating production modules between facilities.
- Selecting appropriate suppliers for tier-2 facilities.
- Assigning customer markets to active tier-1 production facilities.
- Assigning active tier-1 production facilities to active tier-2 production facilities.

Motivated by the Physical Internet's objectives of addressing the economic, environmental and social unsustainability of traditional supply chains by redefining physical objects mobility, storage, realization, supply and usage, we considered a multi-objective optimization framework. Our goal is to simultaneously minimize both the induced cost (production, transportation, relocation and facility leasing) and environmental footprint of the Hyperconnected Mobile Supply Chain. These objectives are evaluated as functions of facility location choices, capacity deployment strategies, and the dynamic movement of mobile production modules with the HMSC.

3. Related Research

The concept of mobile manufacturing was first introduced by [5] as a strategy enabling manufacturing companies to rapidly respond to changing environments and evolving customer needs. This concept promotes flexible, reconfigurable and geographically mobile production, allowing the relocation of production units with minimal penalties in time, cost and performance. The *Factory-in-Box* project marked the first practical implementation of mobile manufacturing across five distinct industrial settings. In all demonstrators, the configuration and location of the production unit could be adapted, highlighting the broad applicability of mobile manufacturing across various sectors.

Building upon this foundation, the European *F3 Factory project* [6] was launched. Driven by industry leaders such as Procter & Gamble and Bayer, this initiative validated the economic benefits of mobile manufacturing in the chemical industry. As a self-containing production unit, mobile factories allow companies to rapidly respond to fluctuating demand, thereby increasing agility and profitability. [7]

Extending the concept, [8] introduced the concept of Mobile Supply Chains, an evolution of Distributed Manufacturing System to enable localized production, faster deployment of production capacity and improved service level. However, most of the literature on Mobile Supply Chains focus on Vehicle Routing Problems [8] [9] [10] and single-tier network. [11] [12]

In parallel, [13] introduced the concept of the Physical Internet, a paradigm shift aimed at reimagining how physical objects are realized, transported, handled, stored, supplied, and used to meet economic, environmental and social sustainability. Within this framework, [3] proposed the concept of Hyperconnected Mobile Production, which leverages core Physical Internet principles of modularization, resource sharing flow consolidation, standardization and interoperable protocols, to enable dynamic and localized manufacturing. This approach relies on a network of "open certified production facilities" and plug-and-play mobile production modules, to deliver on-demand production capacity close to market needs.

While Mobile Production and Hyperconnected Mobile Production show considerable promise, their implementation in large-scale, multi-tier supply chain networks remain largely underexplored. Previous studies have predominantly focused on small-scale, single-tier networks. [14] proposed the first model addressing the Mobile Modular Production and Inventory Problem. Motivated by industry's development, their work explored production and inventory decisions but limited to a single-tier network. [15] proposed a multi-objective tactical network design model for the Hyperconnected Mobile Production, targeting cost and environmental impact minimization. However, their model relied on a predefined network of open fabs and lacked tractability required to solve large-scale instances.

4. Methodology

Solving the proposed problem at large scale is computationally challenging due to the complex interdependence between decisions, time periods and network layers. Traditional exact optimization methods often become intractable as the problem size increases, especially when multiple conflicting objectives are considered.

To address this challenge, we adopt a metaheuristic optimization approach, which provides high-quality, near-optimal solutions within reasonable computational time. Specifically, our method builds upon the Non-dominated Sorting Genetic Algorithm II (NSGA-II) introduced by [16]. This algorithm efficiently explores trade-offs between objectives by maintaining a diverse population of candidate solutions that evolve over successive generations.

The algorithm operates by applying a series of evolutionary operators, that are the selection, crossover, mutation and replacement, to evolve the population. As illustrated in Figure 3, the current population P_t and the offspring Q_t are merged to form R_t , which is then sorted into Pareto fronts based on dominance relationships. Solutions from the best fronts are selected to form the next generation P_{t+1} , with crowding distance mechanism used to preserve diversity among individuals within the same front.

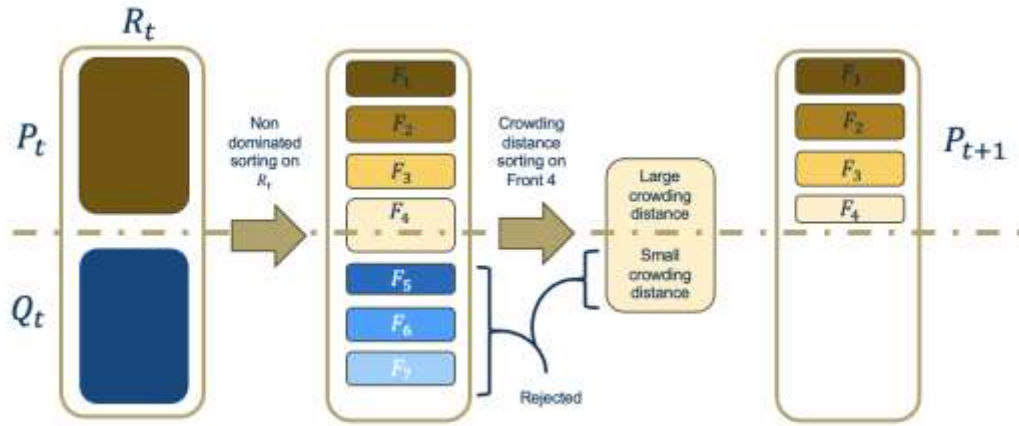


Figure 3: NSGA-II procedure adapted from [16]

Through repeated iterations, the population gradually improves, converging toward a well distributed approximation of the Pareto-optimal front. For brevity, the detailed algorithmic steps follow the standard NSGA-II procedure and are omitted.

To implement this metaheuristic in our context to capture the set of decisions required for the strategic network design of Hyperconnected Mobile Supply Chain, we define a problem-specific chromosome representation, encoding:

- Facility activation and deactivation decisions
- Production Module deployment and relocation
- Supplier selection strategies
- Project-to-facility assignment mappings
- Tier-2 to tier-1 facility assignment mappings
- Suppliers-to-tier-2 facility assignment mappings.

This encoding captures temporal dynamics and multi-tier interactions, enabling the algorithm to evaluate the performance of each network configuration with respect to total cost and carbon footprint.

5. Results

In this section, we explore the large-scale implementation of the Hyperconnected Mobile Supply Chain (HMSC) within the context of modular construction, leveraging data obtained through an ongoing research collaboration with an industry partner.

To evaluate the proposed approach, we consider a realistic, large-scale modular construction scenario, during which 159 construction projects must be delivered across continental USA. The network includes a pool of 398 candidate facility locations and 20 critical component suppliers (with other components assumed to be instantly available and thus excluded from the model).

We considered three different scenarios:

- Base Scenario: Six fixed tier-1 and two fixed tier-2 production facilities. No mobility is allowed.
- Hybrid Scenario: Six fixed tier-2 production facilities, while tier-1 can be selected from the 398 candidate locations, enabling mobility only at tier-1.
- HMSC Scenario: Full implementation of the Hyperconnected Mobile Supply Chain framework, as introduced in Section 3, with mobility at both tiers.

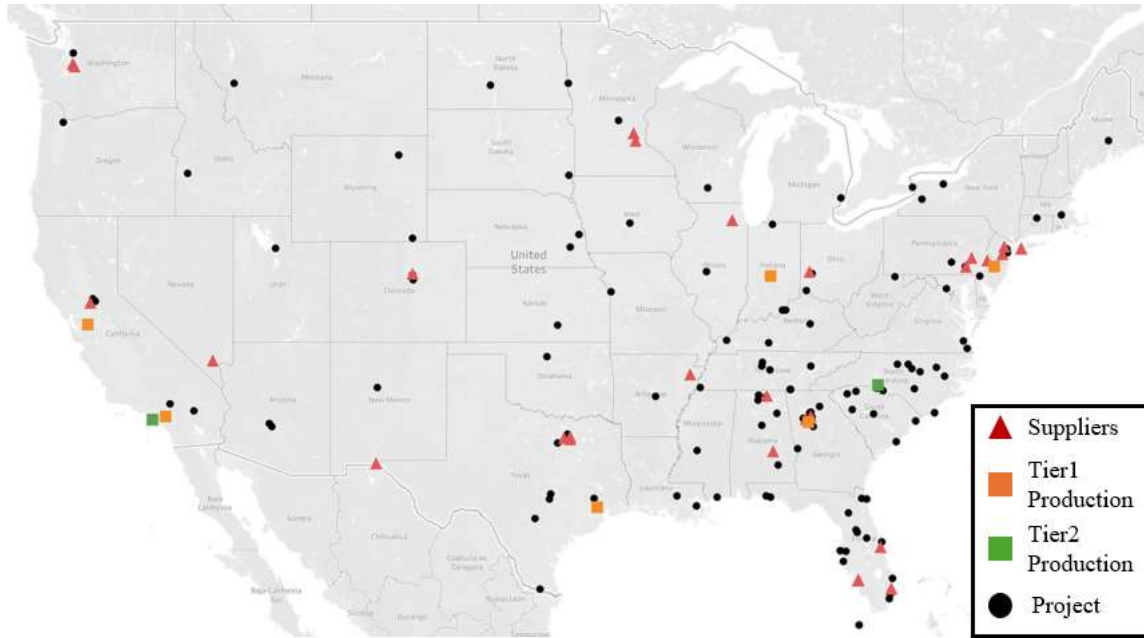


Figure 4: Visualization of the set of projects (159), suppliers (28) and fixed multi-tier Modular Construction Network

To assess the performance of the proposed HMSC framework, we defined the following key performance indicators (KPIs):

- Total supply chain cost
- Total supply chain carbon footprint
- Average relocation distance of mobile production modules (both tier-1 and tier-2)
- Active facility lease duration
- Average deployed capacity at active facilities (both tier-1 and tier-2)
- Average distance between project and assigned tier-1 facility
- Average distance between active tier-1 facility and assigned tier-2 facility

This set of KPIs enables a comprehensive assessment of both economic and environmental dimensions, and more broadly, offers insights into the practical viability of mobile production large-scale production environments.

For the implementation, we utilized Pymoo, a Python based multi-objective optimization package offering state-of-the-art single and multi-objective optimization algorithms, as well as visualization and decision-making features related to multi-objective optimization. [17] Due to the mixed-variable nature of our problem, the algorithm was configured with a *Two-Point Crossover* operator, a *Bitflip Mutation* operator, and *MixedVariableSampling* to accommodate the combination of binary and discrete decision variables. Duplicate elimination was enforced during mating and selection using *MixedVariableDuplicateElimination*.

Table 1: KPIs comparing the three Supply Chains settings

	Scenario			Improvement		
	Base	Hybrid	HMSC	Base	Base	Single Tier
				Vs	Vs	Vs
				Single Tier	HMSC	HSMC
Total SC Cost (\$)	\$2.8B	\$989M	\$569M	64.7%	79.7%	42.4%
Total SC CO ₂ (metric tons CO ₂)	162,350,062	101,773,805	41,785,510	37.3%	74.2%	58.9%
Avg. relocation distance tier 1 (miles)	/	324.39	334.7	/	/	-3.2%
Avg. relocation distance tier 2 (miles)	/	/	333	/	/	/
Avg. leases duration (months)	8.3	3.69	4.6	55.5%	44.6%	-24.66%
Avg. deployed capacity Tier 1 (mod/day)	16	8.8	8.74	45%	45.3%	0.68%
Avg. deployed capacity Tier 2 (mod/day)	36	27.20	8.85	22.4%	75.4%	67.4%
# Project > 250 miles from Tier1	114	0	0	100%	100%	0%
Avg. Distance tier1-Project (miles)	532.95	149.83	151.13	71.8%	71.6%	-0.9%
Avg. Distance tier2-tier1 (miles)	463.26	830.41	256.49	-79.2%	44.6%	69.1%

The results in Table 1 show that HMSC configuration outperforms both the Base and the Hybrid scenarios in terms of total Cost, CO₂ emissions, average deployed capacity at both tiers, and the average distance between tier-2 and tier-1 facilities. The Hybrid scenario with mobility allowed at only one tier already shows significant performance gains, eliminating long project -to-facility distances and reducing costs and emissions by over 60%. However, only the full HMSC configuration achieves optimal efficiency across both tiers simultaneously, demonstrating the benefits of full mobility and coordinated deployment across the network

In contrast, the Base scenario, while assumed to fulfill all project demands, may not be realistic in real-world setting due to its high levels of deployed capacity and long transportation distances. With 114 projects located over 250 miles from a tier-1 facility, this configuration is likely impractical for efficient large-scale modular construction.

6. Conclusions

In this work, we studied a large-scale implementation of Hyperconnected Mobile Supply Chain (HMSC) in the context distributed modular construction. Our results demonstrate the potential of this solution to design cost-effective and environmental supply chains networks, even when involving complex intricate multi-tier production structures.

The proposed model highlights the value of introducing mobility and modularity across production tiers, enabling responsive deployment of capacity and reducing both global costs and carbon emissions across the entire supply chain.

Future work will focus on exploring alternative metaheuristic algorithms, such as large neighborhood search (LNS), to further enhance solution quality and convergence speed. Additionally, we aim to refine the cost and carbon modeling by incorporating non-linear cost functions and emission factors to better capture real-world dynamics and trade-offs. Finally, we plan to extend the current work by integrating disruption scenarios and stochastic demand, developing a new stochastic formulation for the Hyperconnected Mobile Supply Chain framework to study the impact of operational uncertainties.

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Resource Pooling in Hyperconnected Warehouse Networks

Yaxin PANG¹, Walid KLIBI^{1,2}, and Olivier LABARTHE¹

1. The Centre of Excellence in Supply Chain and Transportation (CESIT), Kedge Business School, France
 2. Physical Internet Center, Supply Chain & Logistics Institute, Atlanta, United States
- Corresponding author: yaxin.pang@kedgebs.com

Abstract: *This paper investigates the potential of hyperconnected warehouse networks under the Physical Internet framework to address pressing challenges faced by logistics service providers, including labor shortages, escalating costs of advanced automation, and demand volatility. We propose a new paradigm—the hyperconnected warehouse network—where geographically proximate warehouses pool resources (e.g., labor, machinery) and share real-time demand data to enable dynamic, cost-efficient resource deployment. To operationalize this concept, we first formulate a tactical resource allocation problem and develop a mixed-integer linear programming model that minimizes total costs, incorporating expenses related to resource utilization, resource transfers, and workforce preference mismatches. The proposed model focuses on the intranet within one stakeholder, i.e., logistics service provider, which is a fundamental step towards hyperconnected warehouse network. Illustrative examples showcase the benefits of warehouse intranet in operation and cost efficiency.*

Keywords: *Physical Internet, Pooled Warehouse Network, Resource Pooling, Workforce preference, Sustainability, Resource Deployment*

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

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

1 Introduction

The COVID-19 pandemic has significantly accelerated global digital e-commerce growth (Hu et al., 2023), a trend projected to persist, with global sales expected to reach \$6.56 trillion by 2025 (Institute of Supply Chain Management, 2025). This expansion has intensified pressure on supply chains, especially warehouses, which play a pivotal role in meeting these demands by enabling efficient storage, retrieval, and distribution of goods. Recent survey data from supply chain leaders across North America and Europe reveals that 76% of organizations are confronted with workforce shortages, with warehouse operations emerging as one of the most severely impacted sectors (Supply Chain Brain 2024).

Traditional warehouses employ dedicated resources, such as labor and forklifts, to fulfill client orders but confront hyperconnected challenges. Rising e-commerce demand has intensified labor shortages, compounded by the sector's physical demands, while growing inventory volumes and order frequencies heighten pressure on limited storage capacity. Companies

increasingly adopt automation technologies, such as human-robot collaboration, or expand facilities to address space gaps, see e.g., Figure 1. However, these solutions demand significant financial investments, creating trade-offs between improved efficiency and cost-effectiveness. Additionally, dynamic nature of demand complicates planning. This opens avenues for collaboration—for example, firms with seasonal demand can share capacity with companies facing complementary peaks. Concurrently, sustainability has grabbed increasing attention for warehouse stakeholders to achieve a social sustainable warehouse system (Ali et al., 2023).

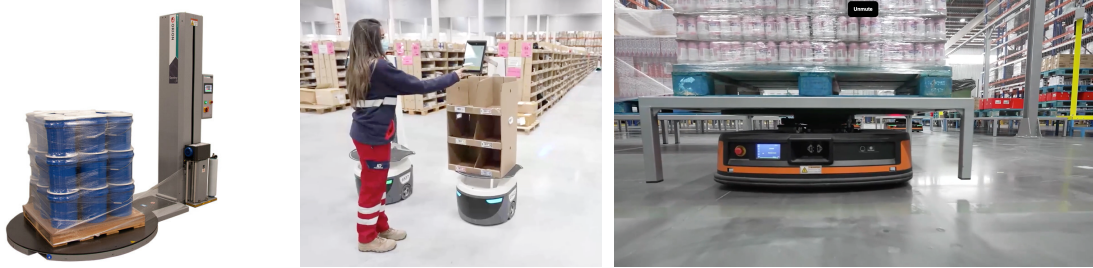


Figure 1: Wrapping machines to pack orders (left, source: Orion), human worker and order-picking robots in warehouses (middle, source: ID Logistics), and autonomous mobile robots (right, source: ID Logistics)

To address these challenges, we propose hyperconnected warehouse networks under the framework of Physical Internet (PI). PI is conceptualized as a global, open, and hyperconnected logistics paradigm that connects humans, objects, networks, and the main stakeholders (Montreuil, 2011). At its core, goods are seamlessly transported, managed, and stored through standardized, modular protocols and shared infrastructure. Within the PI vision, warehouses can be re-designed as hyperconnected nodes within geographically clustered networks. An hyperconnected warehouse network enables resource pooling such as labor, machinery, energy, and storage, information sharing, and interoperable operations among all participating actors. This solution enables adaptive resource deployment through dynamic allocation strategies and holds great potential to not only improve operational efficiency but also advance sustainability by reducing resource wastes.

Resource pooling strategies have been proposed to better align supply and demand. While prior research has focused on inventory pooling in warehouse, Jamili et al. (2022) showcases the benefits of sharing labor and storage space with different clients in a single warehouse. However, little attention has been paid to resource pooling within geographically clustered warehouse networks. Such networks, composed of facilities with diverse clients and demand patterns, may enable mutually beneficial resource sharing and improve utilization rates and supply-demand alignment. However, implementing these networks introduces operational complexities, such as coordinating mobile resource deployments and managing workforce adaptability.

This study aims to investigate the opportunity of hyperconnected warehouse networks and whether such collaborative frameworks align with LSPs' economic and sustainable interests. The contributions of this research are twofold. First, it pioneers the exploration of hyperconnected warehouse networks—a novel paradigm that integrates geographically proximate warehouses through pooled resources, infrastructure, and real-time data exchange—thereby advancing the PI framework by operationalizing interconnectivity within localized logistics systems. Second, we provide a tool which facilitates analyzing the impacts of strategic resource pooling on cost efficiency and operational performance in warehouses. This is achieved by solving a tactical resource deployment problem within an hyperconnected warehouse network. A mixed-integer linear programming (MILP) model is proposed to address the allocation of three critical resources: human labor (accounting for workforce location

preferences), wrapping machines, and autonomous mobile robots, to fulfill orders with minimized total resource allocation costs. The proposed model can also serve as a decision-making tool to find the most cost and operation-efficient resource allocation plan under a specific demand scenario across the network.

This paper is organized as follows. Section 2 reviews the literature relevant to the problem and positions the paper. Section 3 gives detailed description of the studied problem. Section 4 presents the proposed MILP model. Section 5 presents illustrative examples and results. Finally, the conclusion and future direction are discussed.

2 Literature review

Physical Internet (PI) seeks to establish a seamlessly hyperconnected logistics ecosystem to optimize resource allocation and enhance operational efficiency (Wu et al., 2025). It fosters mutual benefits and envisions strengthened coordination and collaboration for the stakeholders within the network (Wu et al., 2025; Zijm and Klumpp, 2016). Over the past decade, PI has garnered significant attention in both academia and industry. One key research focuses on integrating logistics resources and services to enable innovative models such as shared freight, e.g., (Thompson et al, 2020) and collaborative warehouses (Jamili et al. 2022). These novel models enhance operational flexibility, improve goods transportation efficiency, and elevate logistics performance (Ballot, 2018; Suzuki and Kraiwuttianant, 2024). Collaborative transportation, for instance, has been extensively studied: Chabot et al. (2018) demonstrated that collaborative transportation can bring important benefits to the companies, such as by synchronizing their shipments. Labarthe et al. (2024) proposed on-demand urban delivery model and showcased evaluates its operational feasibility and economic and sustainability benefits.

Despite these advancements, warehouses—critical PI nodes for inventory management and order fulfillment—remain underexplored in adapting to this transformative logistics paradigm. While collaborative resource-sharing are not novel in warehouse research, scholarly attention has predominantly focused on inventory pooling, a strategic practice of using shared inventory to fulfill multiple sources of demand (Alptekinoglu et al. 2013). Numerous research investigated its impacts including cost savings, disruption mitigating, and sustainability improving. The studies suggests that inventory pooling generally enhances operational and cost efficiency, though it may depend on the conditions of the problem context, such as information quality.

Beyond inventory management, warehouse operations and resource allocation are pivotal to achieving rapid and efficient order fulfillment. Extensive research has focused on optimizing internal warehouse processes, such as order-picking routes, storage location assignments, and resource allocation (e.g., workforce, robots, storage space) in non-collaborative settings. For instance, Tutam and De Koster (2024) studied human-robot collaboration in order-picking systems, proposing a model to minimize travel time by optimizing where human workers should interact with collaborative robots. Mokarrari et al. (2025) developed mathematical programming models to assign orders to pickers and design optimal routes, maximizing the number of orders fulfilled under resource constraints. These studies underscore the critical role of intra-warehouse efficiency in modern logistics.

Resource pooling has demonstrated significant benefits across diverse logistics systems, see e.g., Faugère et al. 2022; Xu et al.; however, its potential in warehouse resource management remains underexplored. Jamili et al. (2022) investigated collaborative resource utilization within a single warehouse, focusing on shared internal resources, i.e., order-pickers and dock doors. By developing an optimization model to allocate these resources while minimizing total

order tardiness across multiple users, the authors demonstrated measurable improvements in system performance. Extending this work, Jamili et al. (2025) evaluated the efficacy of different resource-sharing configurations, proposing a cost-minimization model that aligns strategy selection. The authors demonstrated that the strategy selection depends on the clients' characteristics such as demand rate.

While these studies underscore the advantages of resource pooling for multi-client operations within individual warehouses, extending collaboration to hyperconnected warehouse networks remains a promising yet nascent research topic. To our knowledge, Mathlouthi et al. (2015) are the first to consider “pooled warehouses”. They considered that all the storage facilities share their storage capacity to maximize the number of accepted requests while maintaining quality of stored products. The authors developed a simulation model and compared different storage allocation strategies among the actors. However, the impacts of hyperconnected warehouse networks on the system's performance regarding economic, operation, sustainability have not been studied yet. This study bridges this gap by introducing the concept of hyperconnected warehouse network and formulating a tactical resource allocation problem tailored to its unique dynamics, such as workforce preference, machine transfer constraints, and service level.

3 Problem statement

Logistics Service Providers (LSP) manage extensive warehouse networks to handle inventory storage and order fulfillment through transportation consolidation. This relies on finite resources such as labor, machinery, and energy, which are often statically allocated across individual facilities. This leads to several potential situations: either the resources deployed are beyond what is required to fulfill orders, leading to idle capacity and financial waste; or resources and demand are perfectly matched; or a lack of resources that degrades service level. We propose hyperconnected warehouse network (HWN) to address these issues.

Figure 2 illustrates a HWN involving multiple stakeholders. In HWN, resources are pooled among all the warehouses of multiple stakeholders, which aligns with the principle of Physical Internet. The HWN enables dynamic resource reallocation across facilities based on fluctuating demand scenarios in each warehouse. An elementary step for transforming towards hyperconnected Physical Internet is the implementation of Physical Intranet, which is a logistics framework implemented within the limits of a single organization (Shaikh et al.).

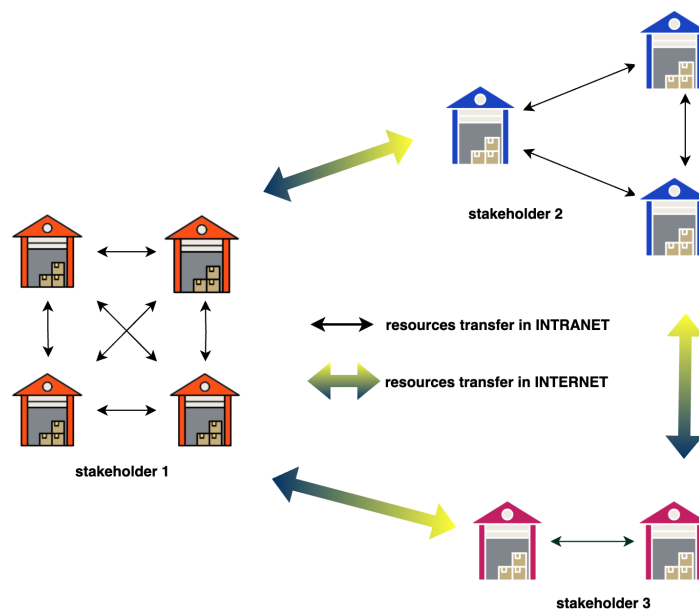


Figure 2: Hyperconnected Warehouse Network (example of three stakeholders).

This study starts from the impacts of Intranet within HWN (IHWN), i.e., we only consider one stakeholder. Particularly, we take human labor, wrapping machines, and autonomous mobile robots, as representative resources. We aim to analyze, from strategic level, the economic metrics of a resource-pooled warehouse network by solving a tactical resource allocation problem over defined planning horizons, such as daily or weekly cycles. Figure 3 depicts resource allocation patterns in dedicated warehouses (DeW) over a given planning horizon, where resource levels remain fixed within individual facilities despite fluctuating demand. In contrast, Figure 4 demonstrates the dynamic resource management enabled by an IHWN. Here, resources are pooled across the network and dynamically reallocated in response to real-time demand shifts, optimizing utilization rates while minimizing idle capacity.

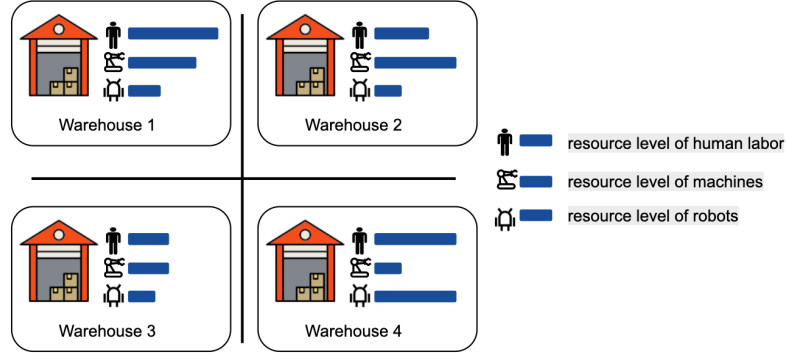


Figure 3: Resource Level in Dedicated Warehouses for One Planning Horizon.

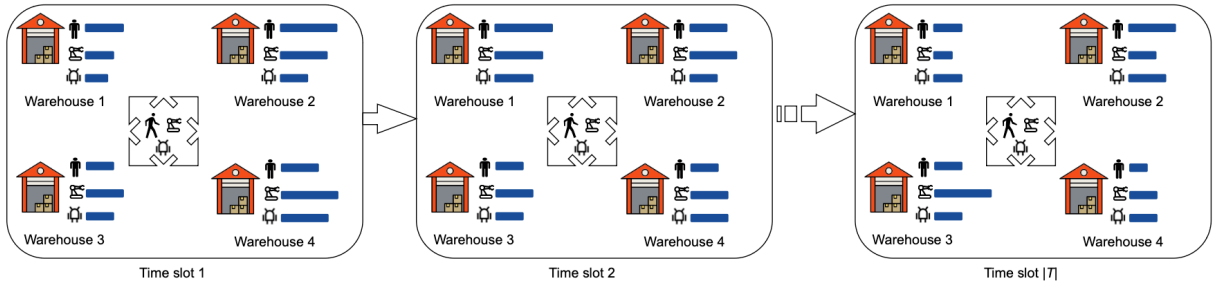


Figure 4: Resource Level of IHWN for One Planning Horizon.

We consider a network of warehouses pre-selected based on geographical proximity and operated by the same LSP. Each warehouse serves dedicated clients and must fulfill all demand within a predefined planning horizon \mathcal{T} , partitioned into discrete time slots $t \in \mathcal{T}$. We particularly focus on outbound operations, where orders must be prepared and dispatched during their assigned due time slot. Two order types are distinguished: regular orders, which require workers and autonomous mobile robots to retrieve pallets from storage, wrap them using a wrapping machine, and dispatch them to outbound vehicles; and pass-to-gate orders, which involve retrieval and dispatch by workers and autonomous mobile robots without wrapping.

The warehouse network pools three critical resources: human workers, autonomous mobile robots, and wrapping machines. Shortages of either resource will fail order fulfillment. At the tactical planning level, resource capacity for type $r \in \mathcal{R}$ is defined as the average number of orders processable per time slot t . Resources are allowed to be dynamically reallocated across the network during the planning horizon. To fully explore the potential of pooled warehouse network, we do not set restrictions on transfer frequency. However, relocations incur transfer costs (e.g., fixed vehicle costs, distance-dependent variable costs, and compensation for setup activities). Note that in this tactical problem, we assume any resource transfer within this localized network can be done during one time slot and thereby do not consider transfer time.

The resources are pooled but with different features. Machines and robots can be transferred among any warehouses. Workers, by contrast, bring human-centric complexities: their natural preference for a specific warehouse. This is shaped by commute convenience, workplace familiarity, or social ties and creates an inherent resistance to relocation. Assigning workers with preference of warehouse n to non-preferred warehouses i necessitates compensation costs $c_{i,n}^{pref}$.

Overall, the goal is to find an optimal tactical resource allocation plan for the pooled resources in the warehouse intranet, taking distance-related transferring costs between warehouses, workforce preference, and time-dependent resource availability into consideration. By incorporating warehouse-specific demand and network-wide resource availability constraints, the model minimizes total costs, which encompass fixed costs for resource utilization $r \in \mathcal{R}$ (e.g., per-unit costs of workers or machines), resource transfer costs (e.g., relocating workers or equipment between facilities), and worker compensation costs for preference violations.

4 Model formulation

Table 1: Description of notations.

Sets and Parameters	
\mathcal{W}	Set of warehouses, $i, j, n \in \mathcal{W}$
\mathcal{T}	Set of time slots, $t \in \mathcal{T}, t = 1, 2, \dots, \mathcal{T} $
\mathcal{R}	Set of resources, $r \in \mathcal{R}, r = 1: \text{worker}, r = 2: \text{wrapping machine}, r = 3: \text{autonomous mobile robots}$
$D_{i,t}^{Pass}$	Demand: number of pass-to-gate orders without wrapping operation at warehouse i due at time slot t
$D_{i,t}^{Wrap}$	Demand: number of regular orders requiring wrapping at warehouse i due at time slot t
p_n	Workforce preference parameter: total workers preferring warehouse n
f_r	Processing capacity of resource r (orders per time slot)
$c_{i,j}^{trans}$	Transportation cost per unit of resource relocated from warehouse i to warehouse j
$c_{i,n}^{pref}$	Cost of assigning a worker preferring warehouse i to warehouse n
c_r^{reso}	Unit cost of resource r
Decision Variables	
$y_{i,j}^{t,r}$	Integer, number of resource $r = \{2,3\}$ relocated from warehouse i to j at time slot t
x_r	Total number of resource $r = \{2,3\}$ required
z_n	Total number of required human worker with preference of n
$\beta_{i,n,t}^{worker}$	Integer, number of workers preferring warehouse n assigned to warehouse i at time slot t
$\beta_{i,t}^r$	Integer, number of resource $r = \{2,3\}$ assigned to warehouse i at time slot t

Table 1 describes the notations. The following mixed integer linear programming (MILP) model is proposed for the resource deployment problem in a pooled warehouse network:

$$\min \sum_{n \in \mathcal{W}} c_1^{reso} z_n + \sum_{r \in \mathcal{R} \setminus 1} c_r^{reso} x_r + \sum_{i \in \mathcal{W}} \sum_{t \in \mathcal{T}} \left(\sum_{j \in \mathcal{W}} c_{i,j}^{trans} \sum_{r \in \mathcal{R} \setminus 1} y_{i,j}^{t,r} + \sum_{n \in \mathcal{W}} c_{i,n}^{pref} \beta_{i,n,t}^{worker} \right) \quad (1)$$

s.t.:

$$z_n^{worker} \leq p_n, \forall n \in \mathcal{W} \quad (2)$$

$$\sum_{i \in \mathcal{W}} \beta_{i,n,t}^{worker} \leq z_n, \forall n \in \mathcal{W}, t \in \mathcal{T} \quad (3)$$

$$\beta_{i,t}^r - \beta_{i,t-1}^r = \sum_{j \in \mathcal{W}} y_{j,i}^{t-1,r} - \sum_{j \in \mathcal{W}} y_{i,j}^{t,r}, \forall i \in \mathcal{W}, r \in \mathcal{R} \setminus \{1\}, t \in \mathcal{T} \setminus \{1\} \quad (4)$$

$$\sum_{i \in \mathcal{W}} \beta_{i,t}^r \leq x_r, \forall t \in \mathcal{T}, r \in \mathcal{R} \setminus \{1\} \quad (5)$$

$$y_{i,j}^{|T|,r} = 0, \forall i, j \in \mathcal{W}, r \in \mathcal{R} \setminus \{1\} \quad (6)$$

$$\sum_{n \in \mathcal{W}} f_1 \beta_{i,n,t}^{worker} \geq D_{i,t}^{pass} + D_{i,t}^{wrap}, \forall i \in \mathcal{W}, t \in \mathcal{T} \quad (7)$$

$$f_2 \beta_{i,t}^2 \geq D_{i,t}^{wrap}, \forall i \in \mathcal{W}, t \in \mathcal{T} \quad (8)$$

$$f_3 \beta_{i,t}^3 \geq D_{i,t}^{pass} + D_{i,t}^{wrap}, \forall i \in \mathcal{W}, t \in \mathcal{T} \quad (9)$$

$$x_r, z_n, y_{i,j}^{t,r}, \beta_{i,t}^r, \beta_{i,n,t}^{worker} \in \mathbb{N}, \forall i, j, n \in \mathcal{W}, t \in \mathcal{T}, r \in \mathcal{R} \setminus \{1\} \quad (10)$$

Minimizing expression (1) corresponds to minimize the total resource pooling costs, defined in this paper as the cost of deploying resources in each warehouse, resource transferring cost, cost for preference mismatch. Constraint (2) calculates the total required workers. Constraint (3) limits the maximum available workers of each preference. Constraint (4) governs the flow conservation of each type of resource, ensuring continuity across each time slot. Constraint (5) calculates the total required resource of each type (except for workers). Constraints (6) avoids late transfer resources. Constraint (6) bounds the number of deployed workers to the network's pooled labor capacity. Constraints (7) - (9) guarantee that all the orders should be fulfilled. Constraints (10) defines the variables.

The model can be extended by accounting for demand uncertainty. This extension will leverage robust optimization techniques to find robust resource deployment plans that hedge against worst-case scenarios while balancing trade-offs between conservatism and operational efficiency (Ben-Tal and Nemirovski, 2002; Bertsimas and Simm 2003). The proposed nominal model is solved by commercial solver CPLEX.

Nominal model	Robust counterpart
Minimize $\mathbf{c}^\top \mathbf{x}$	Minimize $\max_{\xi \in U} \mathbf{c}(\xi)^\top \mathbf{x}$
subject to $\mathbf{A}\mathbf{x} \leq \mathbf{b}$,	subject to $\mathbf{A}(\xi)\mathbf{x} \leq \mathbf{b}(\xi), \quad \forall \xi \in U,$
$\mathbf{x} \geq \mathbf{0}.$	$\mathbf{x} \geq \mathbf{0}.$

Figure 4: Canonic formulations of nominal model and its robust counterpart.

5 Illustrative example

This section illustrates the proposed solution approach of resource pooling in IHWN. In this illustrative example, we first consider the four DeWs of stakeholder 1 without resource pooling, see Figure 3. Each warehouse needs to fulfill its orders with its own resources. We then consider a network of these four warehouses where resources are pooled and can be allocated adaptively based on the demand scenario at each warehouse. There are 7 time slots (e.g., day) in the tactical planning horizon, i.e., $|T| = 7$. We assume the demand per time slot at each warehouse follows a uniform distribution. Table 2 and Table 3 presents the number of orders, regular and pass to gate respectively. Three resources are pooled: human workers, wrapping machines, and automobile robots. The handling capacity per time slot of each resource is $f_r = [50, 100, 100]$, $r = 1, 2, 3$. Worker preference p_n is set as 45 workers for each warehouse based on the required resource level in DeW. Transfer cost between any two warehouses for per unit resource is set to 20 euros. Cost for mismatching per human worker is 20 euros. The fixed cost for using one human worker, one wrapping machines, and one mobile robot is 25000 euros, 50000 euros, and 15000 euros, respectively.

Table 2: Demand with wrapping operations (regular orders).

Warehouse	Demand:	Time slot 1	Time slot 2	Time slot 3	Time slot 4	Time slot 5	Time slot 6	Time slot 7
1	U[700,1200]	1122	726	798	751	1081	953	744
2	U[600,900]	868	662	746	680	684	685	679
3	U[500,1000]	607	673	920	669	633	876	965
4	U[300,500]	420	461	366	421	364	390	421

Table 3: Demand of pass-to-gate type.

Warehouse	Demand:	Time slot 1	Time slot 2	Time slot 3	Time slot 4	Time slot 5	Time slot 6	Time slot 7
1	U[300,400]	397	327	326	328	347	324	340
2	U[100,300]	221	198	104	154	182	196	265
3	U[100,300]	118	241	183	223	205	212	161
4	U[100,200]	114	196	198	150	178	170	169

We first evaluate the minimum resource levels required to fulfill orders in DeWs. In such systems, resource availability remains fixed throughout the planning horizon, necessitating that each warehouse provision resources based on its peak demand during the period. For example, Warehouse 1 experiences its maximum demand at time slot 5, with 1519 total orders (regular and pass-to-gate), requiring at least 31 human workers, 12 mobile robots, and 16 wrapping machines to meet this surge.

We implemented the proposed model for resource pooling in Matlab 2023a. By solving the model using commercial solver CPLEX, we obtain the resource allocation plan in IHWN. Table 4 compares resource requirements and total costs between DeWs and the IHWN. The results demonstrate that resource pooling reduces total costs by approximately 10% for the specific demand scenario, even after accounting for resource transfer expenses and workforce preference mismatches. This cost efficiency stems from adaptive, demand-driven resource allocation, which minimizes idle capacity and overprovisioning. Specifically, the pooled network achieves reductions of: 7 human workers, 1 wrapping machines, and 4 mobile robots. Similar experiments are carried out on stakeholder 2 and 3. Table 5 presents the total costs and resource required in the warehouse intranets for stakeholder 2 and 3.

Table 4: Resource required and total costs in the Intranet for stakeholder 1.

Warehouse	Human worker	Machine	Robot	Total costs
1	6	2	3	-
2	9	3	5	-
3	17	7	9	-
4	11	5	6	-
Total in Stakeholder 1_DeWs	43	17	23	4,740,000 euros
Stakeholder 1_IHWN	36	16	19	4,285,440 euros

These reductions highlight how adaptive resource pooling optimizes utilization across time slots, aligning capacity with real-time demand fluctuations while maintaining service levels. This illustrative instance first exemplifies the transformative potential of IHWN in optimizing

system-wide resource utilization, reducing resource requirements, and achieving cost-efficiency while preserving operational performance standards.

Table 5: Resource required and total costs for DeWs and IHWN.

Warehouses	Human worker	Machine	Robot	Total costs
Stakeholder 2_DeWs	103	40	53	5,375,000 euros
Stakeholder 2_IHWN	88	39	51	4,916,000 euros
Stakeholder 3_DeWs	80	35	41	4,365,000 euros
Stakeholder 3_IHWN	73	32	37	3,980,320 euros

Conclusion and future directions

This research proposes a new solution: hyperconnected warehouse network under the vision of Physical Internet, to deal with increasing tension between surging demand, high resource investment, and resource shortage such as labor and machinery. At the core of *Hyperconnected warehouse network*, resources are pooled and transferred across the networks to fulfill orders and improve efficiency at warehouses. This system enables bridging the gap between resource supply and demand dynamically with increased resource utilization rate and decreased resource deployment costs while maintaining service level. To analyze the effectiveness of such networks, we first study a tactical resource allocation problem under a specific demand scenario, considering resource transfer and worker preference, in warehouse intranets. We developed a MILP model to optimize resource allocation among the warehouses at each time period based on the demand. The proposed model balances the tradeoff between resource using cost and costs of relocation, and preference mismatch. The illustrative example preliminarily demonstrates the transformative potentials in cost and operational efficiency of resource pooling in warehouse Intranet, which is a critical step towards hyperconnected warehouse network.

For future work, we will further investigate the potential of hyperconnected warehouse network with multiple stakeholders. A robust counterpart of the model will be formulated to take the demand uncertainty into account and provide robust resource deployment plans.

This work also opens new research avenues, including the sustainability implications of resource-pooled warehouses. Additionally, future studies might explore methodological frameworks for clustering hyperconnected warehouse networks, balancing geographic proximity and resource compatibility, etc.

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Synchromodality Service Planning and Procurement in a Global Logistics Platform: A Bi-level Programming Approach

Xiangtianrui Kong¹, Tianai Gong¹, Lele Zhang^{2,3}, Russell G. Thompson⁴

1. Department of Supply Chain Management, College of Economics, Shenzhen University, Shenzhen, China
2. School of Mathematics and Statistics, The University of Melbourne, Australia;
3. ARC Training Centre in Optimisation Technologies, Integrated Methodologies, and Applications (OPTIMA), The University of Melbourne, Australia
4. Department of Infrastructure Engineering, University of Melbourne, Victoria, Australia

Corresponding author: kongxtr@szu.edu.cn

Abstract: With the evolution of global supply chains and trade patterns, synchromodality has emerged as a crucial logistics model to meet shippers' demands for reliability, flexibility, and security. However, existing global logistics digital platforms face challenges in balancing supply and demand, decision-making mechanisms, and multi-objective collaborative optimization, which hinder the efficiency of synchromodality. To address these issues, this paper proposes an optimal synchromodality service planning and procurement model based on bi-level programming. The upper level is the synchromodality routing planning (SRP) model, which optimizes transportation mode selection and routing to minimize total transportation time. The lower level is the winner determination problem (WDP) model for transportation service procurement through combinatorial auctions, using the O-VCG mechanism to select carriers to minimize total transportation costs. Numerical experiments demonstrate that the model reduces transportation time by 10.3% and transportation costs by 6.6%, validating its effectiveness. This model provides new insights and tools for theoretical research on synchromodality and the optimization of international logistics platforms.

Keywords: Synchromodality; Transportation Service Procurement; Bi-level Programming; Combinatorial Auction; O-VCG Mechanism

Conference Domain Fitness: Multi-Modal Transport; Data-driven Logistics Analytics; Global Logistics

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

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

I. INTRODUCTION

International logistics now faces demands for greater reliability, flexibility, and security (Giusti et al., 2019). Sychromodality is an emerging concept in the logistics field, focusing on improving the overall efficiency of transportation systems by integrating road, rail, sea, and air transport modes. It aims to achieve end-to-end resource integration and process coordination, providing demand-driven, efficient services (Tavasszy et al., 2017; Khakdaman et al., 2020). Unlike traditional multimodal transport, sychromodality emphasizes not only the diversity of transportation modes but also real-time decision optimization and cross-level collaboration, making it a key solution to the complexities of international logistics.

Currently, existing international logistics digital platforms for sychromodality (e.g., "YunQuNa") have established information matching mechanisms, enabling initial supply-demand connections between foreign trade enterprises and freight forwarders. While these platforms have improved transparency and shortened transaction chains, their functionality remains limited to information intermediation and has yet to address the deeper needs of sychromodality (Pfoser et al., 2016). Specifically, existing platforms face three major operational challenges:

First, current platforms struggle with imbalances in supply and demand matching. Due to seasonal fluctuations, geopolitical risks, and unexpected events, both international logistics demand and capacity are highly uncertain. Platforms' capacity allocation capabilities are insufficient, leading to risks of capacity shortages during peak periods, which can cause delivery delays and cost increases. During off-peak periods, resource idleness exacerbates operational cost pressures, severely hindering normal international trade.

Second, platforms face challenges in dynamically adjusting to capacity changes. Most existing platforms rely on historical data for static optimization, lacking real-time awareness and adjustment capabilities for capacity status (e.g., during traffic congestion). This not only leads to cargo delays and reduced shipper satisfaction but can also escalate local disruptions into systemic delays, significantly increasing overall transportation costs.

Third, existing platforms lack the ability for multi-objective collaborative optimization. They lack flexible parameter settings and customized solutions, making it difficult to achieve precise optimization based on shippers' varying priority preferences. Current algorithms often focus on single objectives, failing to provide truly optimal comprehensive solutions. Additionally, platforms' reliance on single models for universal optimization overlooks customers' personalized needs (Giusti et al., 2019), reducing shipper satisfaction and engagement.

Given these challenges, sychromodality has yet to be fully realized in practice. This study aims to further optimize the functionality of international logistics digital platforms in the field of sychromodality, thereby improving overall operational efficiency and service quality. This paper focuses on the tactical and operational levels of sychromodality (Steadieseifi et al., 2014; Behdani et al., 2016; Giusti et al., 2019). The platform leverages international logistics networks and resources to integrate transportation demands from foreign trade enterprises and capacity resources from freight forwarders, coordinating two internal departments: the planning department and the procurement department. The planning department (upper level) addresses tactical planning issues in sychromodality, optimizing multi-segment international logistics routing, determining transportation modes, transfer methods, and cargo volumes for each route to minimize total transportation time and ensure timely delivery. The procurement department (lower level) addresses operational planning issues in sychromodality, using combinatorial auctions to match freight routes with transportation service providers. Through reasonable pricing schemes, it minimizes total transportation costs, helping foreign trade enterprises better control costs and maximize profits.

In this context, the two departments must handle conflicting decision-making objectives (total time and total cost). How the platform coordinates and adjusts decisions between the two departments to provide optimal transportation and pricing solutions is a significant challenge. Therefore, this paper aims to address three main research questions: (1) At the tactical level, how can the planning department optimize international logistics synchromodal routing and cargo volumes to minimize total transportation time. (2) At the operational level, how can the procurement department design a combinatorial auction mechanism to foster appropriate competition among freight forwarders, select cost-effective transportation services, and design reasonable pricing schemes to minimize total transportation costs. (3) How can the platform synchronize tactical and operational levels, constructing appropriate methods for coordination and collaboration to simultaneously reduce conflicting performance indicators such as transportation costs and time, flexibly plan all transportation demands, and optimize overall transportation performance.

II. LITERATURE REVIEW

A. Synchromodality Planning

Regarding synchronization at different levels of multimodal transportation, this study explores the planning issues of Synchromodality at both tactical and operational levels. Most existing research focuses on single-level decision-making, with limited studies addressing the synchronization of planning across both levels. Van Riessen et al. (2017) used a Markov decision process to set price limits for transportation services at the tactical level, considering the available capacity of the transportation network at the operational level to optimize the expected revenue of transportation service providers. Van Riessen et al. (2021) extended this problem to Synchromodality networks, incorporating route re-planning to balance different priced transportation services and increase flexibility for providers. Xu et al. (2015) developed a stochastic integer programming model to address container capacity allocation (tactical level) with the goal of maximizing total transportation profit. The model considered different transportation modes and stochastic demand (operational level) and used a genetic algorithm to obtain optimal solutions. Giusti et al. (2023) addressed the multi-commodity, multi-service hub location problem (tactical level) by considering optimal commodity flow (operational level). They proposed a new mixed-integer linear programming formulation based on spatiotemporal network design, providing a reference for achieving synchronization in different environments.

Further, regarding planning models for Synchromodality, Behdani et al. (2014) designed a mathematical model for Synchromodality service scheduling. Using the Rotterdam port hinterland network as an example, they discussed the benefits of synchronized transportation services compared to individually planned services, although their model did not include mode switching. Giray et al. (2019) proposed a multi-objective mixed-integer programming problem to capture the characteristics of Synchromodality. The problem included objectives such as total transportation cost, total transportation time, and total CO₂ emissions, with computational results provided for real-world instances in the Marmara region of Turkey. Guo et al. (2020) studied a dynamic shipment matching problem in Synchromodality, where a centralized platform provides online matching between shipment requests and transportation services. They proposed a rolling horizon approach to handle newly arriving transportation requests and developed a heuristic algorithm to generate real-time solutions. Yee et al. (2021) proposed a decision support model for Synchromodality, modeled as a Markov decision process that allows for adjustments in transportation mode selection based on real-time information. They evaluated the value of Synchromodality planning compared to static planning, showing that synchronized planning is more valuable when penalties for delayed delivery are high. Zhang et al. (2022) proposed a mixed-integer linear programming model for the flexibility of transportation services in Synchromodality. The model considered both flexible and fixed services, simultaneously planning vehicle routes and demand routes. They designed an adaptive large neighborhood search heuristic, which reduced costs by an average of 14% compared to existing models in large-scale

instances. Unlike previous studies, this research considers the coordination of Synchronomodality routing planning (tactical level) and transportation service supply-demand matching (operational level) to optimize transportation time and cost, promoting more scientific and effective decision-making.

B. Transportation Service Procurement and Combinatorial Auctions

Define Regarding the optimization of resource allocation at the operational level of Synchronomodality, existing research primarily uses operational planning models. However, when selecting freight forwarders for fulfillment, there is a lack of incentives for appropriate competition among forwarders to encourage reasonable pricing and provide more cost-effective transportation services.

In recent years, auction mechanisms have gained attention for managing advanced logistics services due to their ability to fully and explicitly describe various characteristics through a set of rules and formulas. Research on auction-based transportation procurement has focused on developing effective auction mechanisms and algorithms to match supply and demand (Song and Regan, 2005; Figliozzi et al., 2007; Chen et al., 2009; Xu and Huang, 2014; 2015; 2017). Among these, the Winner Determination Problem (WDP) is critical, referring to the process of allocating transportation routes to suitable carriers in combinatorial auctions.

Regarding WDP models in transportation service procurement auctions, Ma et al. (2010) proposed a two-stage stochastic integer programming WDP model to reduce shippers' risks under transportation volume uncertainty. They demonstrated that the stochastic solution outperformed deterministic models based on average transportation volumes and solved medium-scale real-world cases within reasonable timeframes using commercial solvers. Extending Ma et al. (2010), Zhang et al. (2014) developed a sampling-based two-stage stochastic programming method to handle transportation volume uncertainty with continuous probability distributions. Remli and Rekik (2013) proposed a two-stage robust optimization for WDP under demand uncertainty, solving it using a constraint generation algorithm. Experimental results showed the effectiveness of the proposed method, and analysis highlighted the benefits of robust over deterministic WDP. Hu et al. (2016) studied transportation service procurement considering both price and transportation time, formulating a bi-objective integer programming model. Qian (2021) investigated the sustainability and responsiveness of WDP in transportation service procurement auctions with disruption risks. Qian (2020) studied the winner determination problem for fourth-party logistics (4PL) providers purchasing transportation services through combinatorial reverse auctions with bidder disruption risks. They combined mitigation strategies, including defense, reservation, and external options, to address disruptions and developed a new two-stage stochastic winner determination model.

Combinatorial auctions are suitable for transportation service procurement, allowing bidders to bid on combinations of items. Among WDP models, the well-known single-sided VCG combinatorial auction (Vickrey, 1961; Clarke, 1971; Groves, 1973) induces truthful bidding in reverse or forward auctions (Huang et al., 2013) and satisfies incentive compatibility (IC), individual rationality (IR), allocative efficiency (AE), and budget balance (BB). Huang et al. (2013) and Xu et al. (2014) were the first to apply single-sided VCG combinatorial auctions to transportation service procurement, improving the utility of both shippers and carriers. Their studies showed that O-VCG auctions minimize total transportation costs and encourage truthful bidding. This research builds on these studies, exploring the application of the O-VCG mechanism in Synchronomodality service procurement, integrating it with network design within a bilevel programming framework while ensuring IC, IR, AE, and BB properties.

In the above studies, since transportation routes are determined before the auction, flexibility in providing solutions based on real-time conditions is limited, hindering overall transportation performance optimization. In Synchronomodality, this increases operational costs, negatively impacting stakeholders' benefits. Therefore, this paper studies the design of combinatorial auctions for Synchronomodality services

from a platform perspective, using the O-VCG mechanism for allocation and pricing while coordinating Synchronomodality routing planning to optimize route selection.

C. Bilevel Programming

Bilevel programming has been applied in various fields, including economics and supply chain management. In logistics, research involving bilevel programming is limited, with scholars typically using bilevel logistics systems to study urban logistics. Barahimi et al. (2021) developed a bilevel programming model to determine link capacity increases in urban public transportation networks and proposed a particle swarm optimization (PSO) algorithm with dynamic parameters to solve the model. Ye et al. (2021) constructed a bilevel model considering elastic demand in urban multimodal transportation networks, determining the location and capacity of transfer infrastructure to promote multimodal travel and public transportation use. Amaral et al. (2015) studied effective urban logistics management, considering integration and distribution strategies with delivery time windows, and formulated a bilevel vehicle routing problem. The model was implemented using the AMPL mathematical modeling language, and case studies demonstrated its feasibility. He et al. (2013) designed a hybrid heuristic algorithm combining greedy algorithms, ant colony optimization, and neighborhood search for bilevel logistics systems, with case studies showing the feasibility and effectiveness of the approach. Masson et al. (2017) studied bilevel logistics systems using idle public transportation resources. The upper level aimed to transport goods using surplus bus capacity to multiple transfer points in city centers, while the lower level involved delivering goods to customers via urban tricycles. They proposed an innovative logistics system for congested cities and used an adaptive large neighborhood search algorithm to solve the model, with case studies demonstrating feasibility and effectiveness. However, no literature has applied bilevel programming to international logistics and Synchronomodality, though the methods used in urban logistics are worth referencing.

Despite significant academic attention, few bilevel programming models have been developed specifically for transportation service procurement. Yan et al. (2018) proposed a bilevel programming model for bid selection and winner determination in transportation service procurement auctions, developing a discrete PSO algorithm and analyzing the model and algorithm through numerical simulations. However, their model focused on the conflict and cooperation between carriers and shippers, while this paper delves deeper into the complex relationship between transportation routing planning and service procurement using bilevel programming.

Solving bilevel programming problems remains challenging for most existing optimization methods. Exact algorithms can only handle relatively small-scale problems, making heuristic algorithms attractive for providing satisfactory solutions within reasonable timeframes. Many studies have used heuristic algorithms to solve bilevel programming problems in various applications, overcoming numerous challenges. For solving bilevel programming models, scholars have designed algorithms based on model characteristics. Upper-level models have been solved using methods such as genetic algorithms (Zhang et al., 2019; Lin et al., 2023), simulated annealing (Liang et al., 2021), particle swarm optimization (Xu et al., 2015; Liang et al., 2017), and branch-and-bound (Long et al., 2010). For lower-level models in logistics, scholars have primarily used genetic algorithms (Zheng et al., 2017; Han et al., 2014) and simulated annealing (Xu et al., 2015).

Genetic algorithms are suitable for solving nonlinear, discrete, or complex-constrained bilevel programming problems, offering strong global search capabilities and high adaptability. Particle swarm optimization converges quickly, has simple parameters, and does not require differentiability, gradient information, or convexity of the search space, making it efficient for finding local optima in bilevel programming problems. This paper employs genetic algorithms and particle swarm optimization to solve the upper-level model and uses an integer linear programming solver for the lower-level model. Through

iterative coordination between the two algorithms, the bilevel programming model is optimized, ultimately yielding the optimal solution.

D. Review of Domestic and International Research Status

Based on the above review of domestic and international research, it is evident that there are still significant research gaps in the areas of Synchromodality routing, transportation service procurement combinatorial auctions, and bilevel programming methods in the context of international logistics. The specific gaps are as follows:

(1) Limited Research on International Logistics Scenarios: Most studies on Synchromodality routing focus on national or regional contexts, with very few addressing international logistics. Additionally, existing research primarily considers transportation routing and demand allocation, with almost no studies simultaneously addressing routing, capacity allocation, and pricing in Synchromodality. Furthermore, no studies have integrated international logistics Synchromodality with transportation service procurement combinatorial auctions.

(2) Lack of Bilevel Programming for Multi-Objective Optimization: While most research on multi-objective optimization in Synchromodality uses integrated optimization models, no studies have employed bilevel programming to link Synchromodality routing planning with transportation service procurement combinatorial auctions for multi-objective optimization. The two decision-making objectives (routing and procurement) often conflict, requiring coordination and cooperation across the system. This complex relationship is well-suited for bilevel programming, but no literature has deeply explored this approach in this context.

(3) Challenges in Solving Bilevel Programming Models: Building on existing research, this study designs a solution approach using genetic algorithms (GA) and particle swarm optimization (PSO) to solve the upper-level model, leveraging GA's strong global search capabilities and PSO's fast convergence and efficiency in finding local optima. The lower-level model is solved using an integer linear programming solver. Through iterative coordination between the two algorithms, the upper and lower levels of the bilevel programming model are optimized simultaneously, ultimately yielding the optimal solution.

III. PROBLEM DESCRIPTION

This study addresses the problems of Synchromodality routing and transportation service procurement from a bilevel programming perspective, based on an existing international logistics Synchromodality digital service platform. Different departments of the platform (planning and procurement) need to make decisions at both tactical and operational levels. In practice, decision-makers in these departments often face conflicting objectives. Transportation time and cost are the two most common factors in transportation planning problems (Lam and Gu, 2013). This study examines the relationship between planning at different levels in Synchromodality, where lower-level decisions are constrained by upper-level decisions, and it is crucial to incorporate lower-level decisions back into the upper-level decision-making process (Hofman et al., 2016). By analyzing the interplay between upper-level multi-segment transportation routing and lower-level capacity allocation, a bilevel programming model is constructed, as shown in Figure 1.

Upper Level (Tactical Level): The decision-maker is the platform's planning department (leader), which receives cargo transportation demands from foreign trade enterprises. The goal is to minimize total transportation time by constructing a Synchromodality Routing Planning (SRP) model and designing the transportation service network. Cargo departs from the origin node and passes through a series of nodes in the transportation network. Between nodes, multiple transportation modes are available based on infrastructure conditions. The model considers transportation service capacity and node capacity to select appropriate transportation modes and determine whether mode switching is needed at nodes. It also determines the cargo volume to be transported on each route. The routing decisions and cargo volumes

from the upper level serve as input parameters for the lower-level model, with decisions influenced by lower-level outcomes.

Lower Level (Operational Level): The decision-maker is the platform's procurement department (follower), which receives transportation services offered by freight forwarders. The goal is to minimize total transportation cost by constructing a Winner Determination Problem (WDP) model. For each transportation route decision made by the leader, the follower determines the actual carrier through a single-sided combinatorial auction. In practice, the transportation time provided by freight forwarders may change. In such cases, the lower level feeds the specific transportation time back to the upper level. If the termination conditions are not met, the upper level generates a new routing plan, which continues to influence lower-level decisions. This iterative interaction between the upper and lower levels ultimately determines the optimal transportation route, cargo volume, actual carrier, and transportation cost.

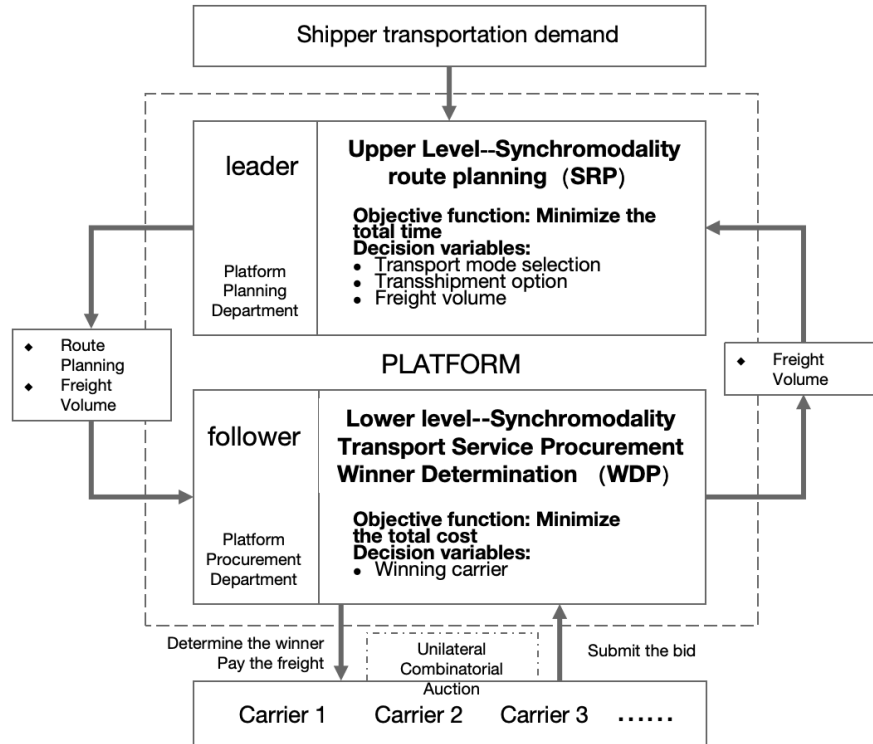


Figure 1: Framework of the Bilevel Model for the Synchromodality Digital Service Platform

A. (Upper Layer) Synchromodality route planning

At the end of each demand collection period, the planning department of the platform receives multiple transportation demands, each defined by the origin node, destination node, the number of cargo containers, and the time periods during which the cargo can depart from the origin. This paper takes a Synchromodality service network composed of rail, waterway, and road transport as an example. The cargo is transported by selected transportation services, each of which has a limited capacity. The subsequent nodes form service segments for the transport services. Therefore, a service may have one or more service segments, depending on the number of stop nodes.

When transporting goods using Synchromodality transport, the transfer time at nodes where the goods switch from one service to another must be considered. The transfer time is fixed for each transportation mode and node. Additionally, when a demand arrives, it is not always possible to immediately provide transport services, which results in waiting times at nodes. For any given node, trains at stations and ships at docks have specific operation time windows. During these windows, goods can be transshipped as soon

as they arrive with the vehicle. Road transport, due to its flexibility in departure and loading/unloading operations, can be treated as a transport mode without a fixed operation time window. Some nodes, such as railway stations and waterway ports, have limited throughput capacities. These nodes are subject to capacity constraints in the model, and such constraints are difficult to overcome, significantly influencing the selection of transportation routes. When the throughput capacity of a node cannot meet the demand for transport volume on the route, alternative suboptimal paths should be considered. For each transportation batch, the capacity of road, rail, or waterway transport is constrained. If a particular mode of transport has insufficient capacity to meet the volume requirements, the corresponding cargo volume should be transferred to other transportation routes or handled by other transport services.

B. (Lower Layer) Transportation Service Procurement One-Sided Combinatorial Auction

After collecting transportation demands during each cycle, the platform sets an auction time. In the lower-level decision-making, the platform's procurement department (cargo owner's agent) acts as the auctioneer, i.e., the buyer, procuring multiple units of transportation services for a specific segment of each route. Freight forwarders (hereafter referred to as carriers) act as bidders, i.e., the sellers, with certain carrying capacities, selling one or more transport service resources. Multiple carriers participate in the bidding process. The platform determines the optimal carrier by minimizing the total transportation procurement cost, solving the winner determination problem, and paying the freight charges to the carriers to complete the actual transportation task allocation.

This paper considers that in the final allocation, each carrier can only receive one bid (atomic bid) at most. It is assumed that if any carrier is removed, the total transportation capacity will still be sufficient. In the Synchromodality transport service procurement combinatorial auction, there is one platform (auctioneer) and n carriers (bidders). The auction is held in sealed price bidding form over a finite, discrete time period T . The set of carriers participating in the auction is denoted by $H = 1, 2, 3, \dots, n$, all of whom are risk-neutral. The bid b^h of carrier $h \in H$ can be represented as a vector $b^h = (B^h, p^h)$, where B^h is the set of route segments for which carrier h offers services in bid b^h , and p^h is the price proposed by carrier h per container for each transport segment. Each carrier $h \in H$ has a non-negative integer valuation (i.e., transport cost) for each route segment $z_\xi \in Z_\xi$, denoted as $c_h(z_\xi)$, which is private information to carrier h , and it is assumed that $c(\cdot)$ is non-decreasing. Each carrier is a rational, self-interested participant trying to maximize their net utility. It is assumed that the net utility u_h of each carrier h is quasi-linear, and the platform's utility is the difference between the reservation price and the payment price. Social welfare is the sum of the platform's and each carrier's utility.

IV. BILEVEL MODEL ESTABLISHMENT

A. Upper Layer Synchromodality Route Planning Model

Model Assumptions

- (1) Goods can only be transshipped once at each transfer node during the entire transportation process.
- (2) Goods can only choose one transportation mode between two adjacent nodes.
- (3) The transport distance and average transport speed between nodes for different transportation modes are known.
- (4) There is transfer time between different transportation modes at nodes, and the transfer time per unit cargo is known.
- (5) The maximum transport capacity between nodes and the maximum transshipment capacity at nodes are known.
- (6) After transshipment, goods are transported by the nearest departure service of the selected transport mode.

TABLE 1: Symbol Explanation

<i>Symbol</i>	<i>Description</i>
R	Set of transportation demands, $r \in R$
C	Set of intermediate nodes, $i, j \in C$
O	Set of origin nodes for cargo transportation, $o_r \in O$
D	Set of destination nodes for cargo transportation, $d_r \in D$
A	Set of arcs, $(i, j) \in A$ represents a transportation segment from node i to node j
K	Set of transportation modes, $k \in \{1, 2, 3\}$, where 1 represents road transport, 2 represents rail transport, and 3 represents waterway transport
TT_{ijk}	Transport time for mode k from node i to node j
TrT_{ikl}	Transfer time at node i for each container being converted from mode k to mode l
WT_{ikl}^r	Waiting time for transportation demand r at node i when transferring from mode k to fixed mode l
θ_{ijk}	Departure time period for transport from node i to node j using fixed mode k
S_{ijk}	First departure time for transport from node i to node j using fixed mode k
$Z_{ijk,\tau}^r$	If transportation demand r from node i to node j uses fixed mode k for the τ -th transport, it equals 1; otherwise, it equals 0
R_{ijk}	Transport capacity on the route from node i to node j using mode k
G_{ikl}	Transfer capacity at node i for converting from mode k to mode l
u_r	Cargo quantity for transportation demand r
d_{ijk}	Transport distance from node i to node j using mode k
v_k	Average speed of transportation mode k by carrier h

<i>Symbol</i>	<i>Description</i>
y_{ijk}^r	If transportation demand r from node i to node j is transported using mode k , it takes the value 1; otherwise, it is 0.
w_{ikl}^r	If transportation demand r at node i is transferred from mode k to mode l to node j , it takes the value 1; otherwise, it is 0.
f_{ijk}	The number of containers transported from node i to node j using mode k , which is a positive integer.
TA_i^r	The time at which transportation demand r arrives at node i .

Upper Layer Objective Function

$$\min F_1 = \sum_{r \in R} \left(\sum_{i \in C} \sum_{j \in C} \sum_{k \in K} TT_{ijk} y_{ijk}^r + \sum_{i \in C} \sum_{k \in K} \sum_{l \in K} TrT_{ikl} u^r w_{ikl}^r + \sum_{i \in C} \sum_{k \in \{2,3\}} \sum_{l \in \{2,3\}} WT_i^r w_{ikl}^h \right)$$

(1)

Constraints:

$$\sum_{k \in K} y_{ijk}^r \leq 1, \forall i, j \in C \cup O \cup D, \forall r \in R$$

(2)

$$\sum_{k \in K} \sum_{l \in K} w_{ikl}^r \leq 1, \forall i, j \in C, \forall r \in R \quad (3)$$

$$y_{(i-1)ik}^r + y_{i(i+1)l}^r \geq 2w_{ikl}^r, \forall i, j \in C \cup O \cup D, k, l \in K, \forall r \in R \quad (4)$$

$$\sum_{i \in C} \sum_{k \in K} y_{ijk}^r - \sum_{i \in C} \sum_{k \in K} y_{jik}^r = \begin{cases} -1, j \in o_r \\ 0, j \notin o_r, d_r \\ 1, j \in d_r \end{cases} \quad \forall r \in R \quad (5)$$

$$\sum_{r \in R} u^r y_{ijk}^r \leq R_{ijk} \quad \forall i, j \in C \cup O \cup D, k \in K \quad (6)$$

$$\sum_{r \in R} u^r w_{ikl}^r \leq G_{ikl} \quad \forall i, j \in C \cup O \cup D, k \in K \quad (7)$$

$$f_{ijk} = \sum_{r \in R} u^r y_{ijk}^r \quad \forall i, j \in C \cup O \cup D, k \in K \quad (8)$$

$$Z_{ijk,\tau}^r \in \{0,1\} \quad \forall i, j \in C \cup O \cup D, k \in K, \forall r \in R \quad (9)$$

$$\sum_{\tau} Z_{ijk,\tau}^r \leq 1 \quad \forall i, j \in C \cup O \cup D, k \in K, \forall r \in R \quad (10)$$

$$TA_i^r + w_{ikl}^r TrT_{ikl} u^r \leq (1 - Z_{ijk,\tau}^r)M + S_{ijk} + Z_{ijk,\tau}^r \cdot \tau \theta_{ijk} \quad \forall i, j \in C \cup O \cup D, k \in K, \forall r \in R \quad (11)$$

$$TA_i^r + w_{ikl}^r TrT_{ikl} u^r > (Z_{ijk,\tau}^r - 1)M + S_{ijk} + Z_{ijk,\tau}^r \cdot (\tau - 1) \theta_{ijk} \quad \forall i, j \in C \cup O \cup D, k \in K, \forall r \in R \quad (12)$$

$$TT_{ijk} = d_{ijk}/v_k \quad \forall i, j \in C \cup O \cup D, k \in K \quad (13)$$

$$y_{ijk}^r, w_{ikl}^r \in \{0,1\} \quad \forall i, j \in C \cup O \cup D, k, l \in K \quad (14)$$

Equation (1) represents the objective function for the platform's planning department (the leader), which minimizes the sum of transportation time, transfer time, and waiting time due to fixed departure times for rail and waterway transport at the nodes; Equation (2) ensures that only one transportation mode is selected between nodes; Equation (3) ensures that each node can only perform one transfer service at most; Equation (4) ensures the continuity of transportation; Equation (5) represents the flow balance constraint during transportation; Equation (6) ensures that the number of goods transported between nodes does not exceed the transport capacity of the route; Equation (7) ensures that the number of goods does not exceed the transfer capacity at the transfer nodes; Equation (8) represents the total quantity of goods transported between nodes; Equations (9) to (12) represent the departure time constraints for transportation modes at the nodes; Equation (13) provides the formula for calculating transportation time; Equation (14) defines the reasonable range of the upper-layer model's decision variables.

B. Lower Layer Transport Service Procurement Winner Determination Model

Model Assumptions:

- (1) All transportation services provided by carriers are homogeneous.
- (2) Carriers possess a certain amount of flat-rate transportation capacity or specific segment transportation capacity, allowing them to handle all cargo volumes on specific segments.
- (3) Each carrier submits only one bidding combination per round.
- (4) It is assumed that if any carrier is removed, the total transportation capacity remains sufficient.

TABLE 2: Symbol Explanation

Symbol	Description
Z	Set of optimal routes obtained from the upper-layer planning department, $z \in Z$
z_{ξ}	Set of segments for route z , z_{ξ}^+ is the total number of segments in route z , a positive integer
H	Set of carriers, $h \in H$

H^*	Set of winning carriers
B^h	Bid segment combination of carrier h, $(i_h, j_h) \in B^h$
p^h	Bid price per unit container by carrier h
B_{ij}^{hz}	If carrier h bids for route z segment (i, j) , the value is 1; otherwise, it is 0
F_{ijk}^{zh}	Carrier h's transportation capacity on route z segment (i, j) using mode k
PC	Total cost of the platform
BP	Reserve price of the platform

<i>Symbol</i>	<i>Description</i>
x^h	If carrier h wins the bid, the value is 1; otherwise, it is 0
s_h	The final payment price from the platform to carrier h

Lower Layer Objective Function

$$\min F_2 = \sum_{h \in H} \sum_{(i_h, j_h) \in B^h} p^h x^h f_{ijk} \quad (15)$$

Constraints:

$$F_{ijk}^{zh} \cdot x^h \geq f_{ijk} \quad \forall (i, j) \in z_\xi, k \in K, \forall h \in H, \forall z \in Z \quad (16)$$

$$\sum_{h \in H} B_{ij}^{hz} \cdot x^h \leq 1 \quad \forall z \in Z, (i, j) \in z_\xi \quad (17)$$

$$\sum_{h \in H} \sum_{(i, j) \in z_\xi} B_{ij}^{hz} \cdot x^h \geq z_\xi^+ \quad \forall z \in Z \quad (18)$$

$$p^h \geq 0 \quad \forall h \in H \quad (19)$$

$$x^h \in \{0, 1\} \quad \forall h \in H \quad (20)$$

Equation (15) represents the objective function of the platform's procurement department (follower), which minimizes the platform's transportation procurement cost; Equation (16) ensures that carriers have sufficient transportation capacity; Equation (17) ensures that each route segment is assigned to only one carrier; Equation (18) ensures that each route segment is assigned; Equation (19) is the bidding price constraint for carriers; Equation (20) sets the reasonable bounds for the decision variables in the lower layer model.

Auction Mechanism:

In order to encourage carriers to truthfully submit their bids (Huang and Xu, 2013), the O-VCG combinatorial auction mechanism is employed in the lower layer problem.

(1) Allocation Rule

According to the bilevel programming process, the platform conducts a combinatorial auction for multiple transportation routes simultaneously. In each round, bidding carriers can bid on combinations of multiple segments of various routes. Each carrier submits a sealed bid consisting of the segment combinations and bid prices.

The combinatorial auction begins with no carriers assigned, and the platform provides the transportation volume and initial asking prices for each route segment in the auction. The platform releases relevant information to participating carriers. Carriers base their bid combinations on the initial asking

prices and determine the bidding price for each segment combination. The platform's initial asking price is the maximum price it is willing to pay for each route segment, and it will not accept any bid above its reservation price. The platform then solves the winner determination problem to identify the winning bid combination and perform route assignment, aiming to minimize transportation procurement costs. This determines a preliminary set of winning carriers. After each round of the auction, the platform calculates the actual transportation time for the winning carriers and makes a provisional bid allocation. Based on the upper-layer route updates, the platform decides whether to end the auction process according to the bilevel programming iteration termination conditions. If the termination conditions are not met, the auction is repeated, continuing with the previous process. The auction continues until the termination conditions of the bilevel programming are satisfied.

(2) Payment Rule

Let π be the optimal value of the objective function (15). If carrier h is excluded from the auction, then π^{-h} is the optimal value of the objective function. The platform will pay the carrier:

$$s_h = \pi^{-h} - \left(\pi - \sum_{(i_h, j_h) \in B^h} p^h x^h f_{ijk} \right) = \pi^{-h} - \pi + \sum_{(i_h, j_h) \in B^h} p^h x^h f_{ijk} \quad (21)$$

Among them, $\pi^{-h} - \pi$ represents the bonus paid to carrier h , which signifies the value he contributes to the system by participating in the auction. If $x^h = 0$, carrier h is not awarded the bid, then $\pi^{-h} = \pi$ and $s_h = 0$; if $x^h = 1$, carrier h wins the bid, and the platform pays carrier h his bid p^h plus his contribution to the system.

To calculate the total cost of the platform:

$$PC = \sum_{h \in H} s_h = \sum_{h \in H} \left[\pi^{-h} - \left(\pi - \sum_{(i_h, j_h) \in B^h} p^h x^h f_{ijk} \right) \right] = \sum_{h \in H} \pi^{-h} - (n-1)\pi \quad (22)$$

BP represents the platform's reserve price. If $BP > PC$, the transaction is successful; otherwise, the transaction fails.

V. CASE STUDY

A. Model Solution

In the bi-level programming model proposed in this paper, the upper level aims to minimize transportation time, where the transportation time for each route segment is calculated based on the planned transportation lead time. Meanwhile, the actual transportation time of the winning carriers in the lower level can also be represented by their transportation lead time. Therefore, after the upper level passes the optimal transportation routing plan to the lower level, the lower level makes decisions and feeds back information such as the winning carriers and their actual transportation lead times to the upper level. This allows the upper level to gain more insights into the actual transportation scenario based on the winning carriers' transportation lead times and update the planned transportation lead times for re-decision-making. An iterative improvement strategy is adopted to determine the optimal transportation routes, volumes, and carriers under the two decision objectives.

The update formula for the transportation lead time is defined as:

$$v_n^{plan} = \alpha \cdot \overline{v_{n-1}^{actual}} + \beta \cdot v_{n-1}^{plan} \quad (23)$$

When the lower level feeds back the actual transportation times of the winning carriers in each iteration, the upper level needs to evaluate whether the difference between the actual transportation time and the previously obtained optimal transportation time meets the requirements. If the requirements are satisfied, the optimal result is obtained; otherwise, the upper level re-decision is triggered. The framework for solving the bi-level programming model is shown in Figure 2, and the main steps of the solution algorithm are as follows:

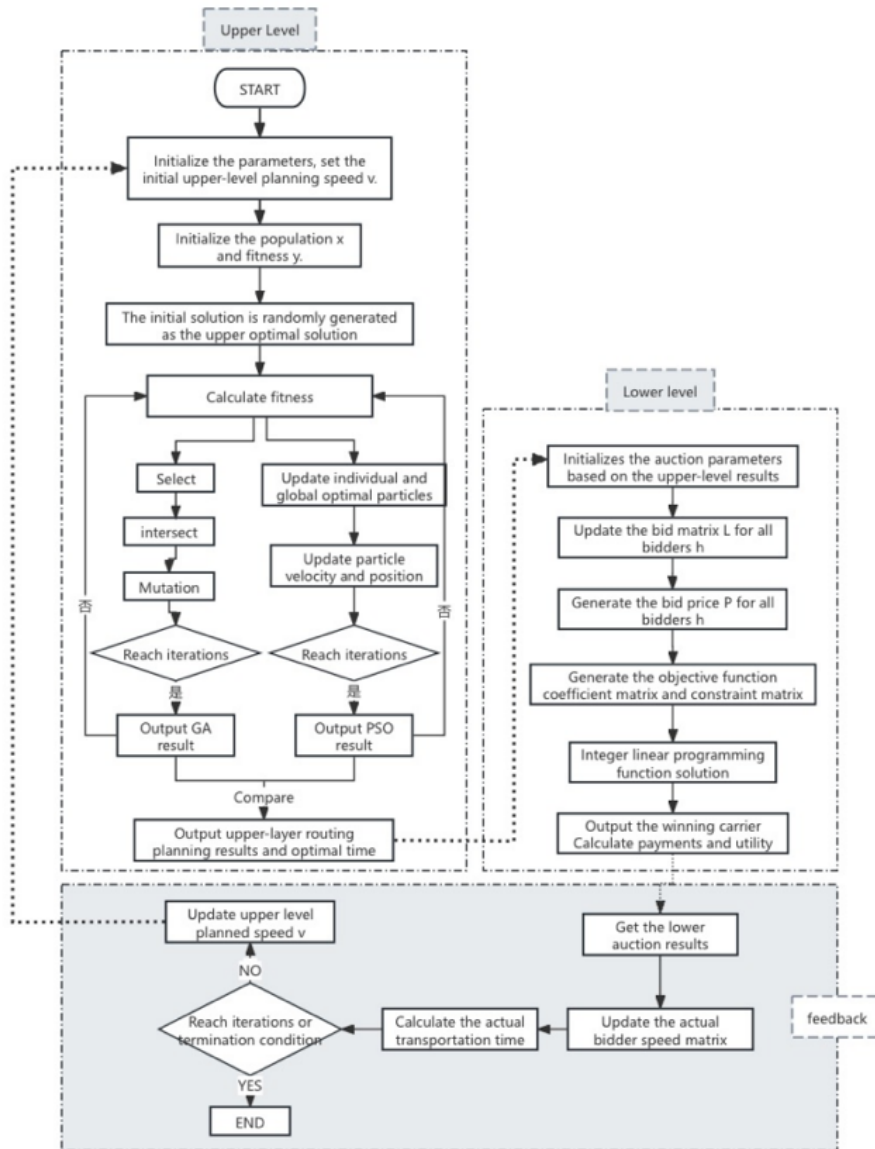


Figure 2: Framework Diagram for Solving the Bi-Level Programming Problem

Step 1: Input initial parameters and data, including the initial planned transportation lead time, transportation lead time weights, the number of carriers, carrier transportation capacities, etc. Set the number of iterations.

Step 2: Execute the upper-level optimization algorithm. Compare the results obtained using genetic algorithms and particle swarm optimization, select the better result, and output the initial transportation routing plan to the lower level. Calculate the current optimal transportation time for the upper-level iteration.

Step 3: Execute the lower-level auction algorithm, compute the auction results, determine the set of winning carriers and the optimal transportation cost, and update the actual transportation lead time matrix of the carriers.

Step 4: Run the lower-level feedback mechanism. Based on the winning carriers executing the transportation tasks, calculate the actual transportation time of the lower level using their actual transportation lead times.

Step 5: Check whether the iteration termination conditions are met. If satisfied, output the running time and related data; if not, update the planned transportation lead time in the upper level and repeat Steps 2–4 to start the next iteration.

Step 6: At the end of each iteration, output the minimum objective function value of the upper-level model, along with the objective function value and decision variable values of the lower-level model at that point.

B. Experimental Design

This paper considers the fluctuations in carriers' transportation lead times in real-world logistics scenarios. A random disturbance term is introduced into the carrier transportation lead time update formula to simulate the impact of unexpected events. The specific carrier transportation lead time update formula is as follows:

$$v_{n+1}^{actual} = v_n^{actual} + \gamma \cdot \sigma \cdot \eta \quad (24)$$

Here, γ is the disturbance intensity coefficient, controlling the overall strength of the disturbance; σ is the standard deviation of the random disturbance, controlling the fluctuation range; and η is a random number following the standard normal distribution $N(0,1)$, introducing uncertainty. Based on the impact of real-world scenarios on carrier capacity and transportation lead times, this paper simulates three different transportation scenarios by varying the above parameters. The correspondence between the parameters and the actual transportation scenarios is shown in Table 3:

Table 3: Description of Experimental Scenarios

Experimental Scenario	Parameter Values	Real-World Situation
Scenario 1: Stable Environment	$\gamma = 0.1$ $\sigma = 2$	Minor traffic delays and loading/unloading delays
Scenario 2: Moderate Fluctuations	$\gamma = 0.3$ $\sigma = 5$	Highway accidents, railway track maintenance, etc
Scenario 3: Severe Fluctuations	$\gamma = 0.5$ $\sigma = 10$	Typhoons causing shipping delays, heavy rain leading to road collapses, etc.

The experiments first verify the convergence of the model. Secondly, for logistics platform enterprises involved in international logistics, transportation costs and transportation time are key factors determining their market competitiveness. Currently, such enterprises still rely on traditional multi-objective optimization models to optimize these objectives. Based on actual transportation data from a logistics company, this paper sets up comparative experiments to analyze the changes in transportation plans generated by the synchromodal bi-level programming model and the traditional multi-objective optimization model, thereby validating the proposed synchromodal bi-level programming model and its solution algorithm.

C. Case Study data

In the actual business of the logistics platform enterprise, the international logistics transportation network starts from Changsha as the origin city for international Synchromodality transport, with Berlin, Germany, as the destination city. Considering various transportation corridors such as the Eurasian Land

Bridge, traditional sea transport, Gwadar Rail-Sea Intermodal, the New Western Land-Sea Corridor, and the ASEAN Corridor, the intermediate nodes include 25 cities, including Wuhan.

It is assumed that there are 10 twenty-foot containers to be transported from Changsha to Berlin, with 1-3 transportation modes (rail, road, waterway) available between each connected pair of city nodes.

The intermodal transport network for this case study is shown in **Figure 3**. The required data for the case study was collected from websites, official documents, and other sources. Some of the original data, or data after preliminary processing, is shown in **Tables 4 to 6**.

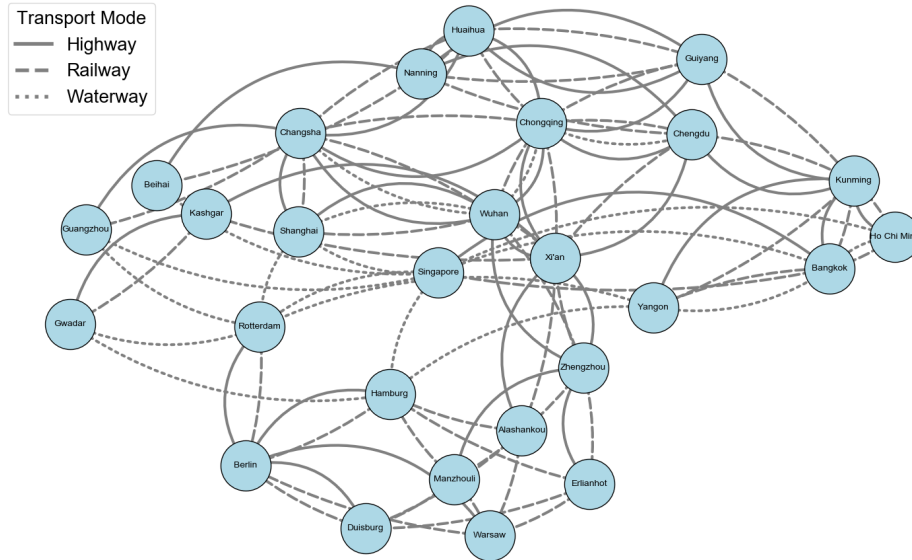


Figure 3: Synchromodality Transport Network Diagram

Table 4: Transport Distances Between Different Modes of Transportation for Selected Nodes

Segment	Rail (km)	Rail (km)	Rail (km)
Changsha to Guangzhou	706	670	—
Wuhan to Shanghai	1230	820	1043
Alashankou to Warsaw	6278	—	—
Kashgar to Gwadar	3352	3485	—
Shanghai to Rotterdam	—	—	19390
Kunming to Bangkok	1740	1890	—
Singapore to Hamburg	—	—	15858
Hamburg to Berlin	375	289	—

Table 5: Freight Rates and Speeds for Different Modes of Transport

Transport Mode	Freight Rate (CNY/container/km)	Speed (km/h)
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	Domestic Segment		Domestic Segment		
	Base 1	Base 2	Base 1	Base 2	
Rail Transport	440	3.185	0	3.211	35
Road Transport	0	9.185	0	10.131	43
Water Transport	0	1.784	0	1.070	28

The transfer of intermodal transport goods involves significant uncertainty, and there are fluctuations in the conversion between different transportation modes. Based on previous studies and practical considerations, this study sets the transfer time and costs (hours/container) for intermodal transport as fixed parameters according to different types, as shown in **Table 6**.

Table 6: Transfer Time and Costs for Intermodal Transport

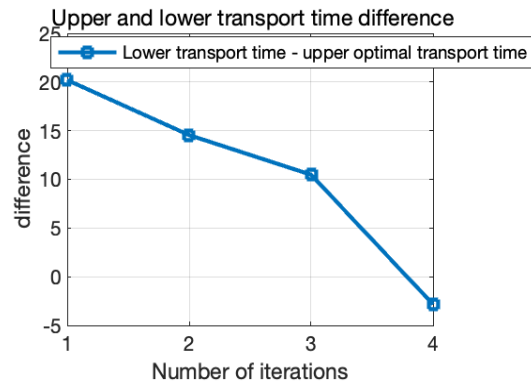
Transfer Mode	Transfer Time (hours/container)	Transfer Cost (CNY/container)
Rail to Road	0.8	195
Rail to Water	1.5	275
Road to Water	1.2	225

D. Numerical Experiment Results

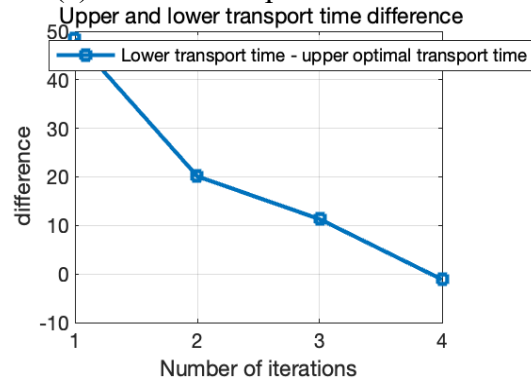
Convergence Analysis

The bi-level programming model was run under three different transportation scenarios, with a convergence threshold set at $\epsilon = 5h$. The difference between the upper-level optimal planned transportation time and the lower-level actual transportation time was output, and its variation is shown in Figure 4. The convergence of the bi-level iterations was analyzed.

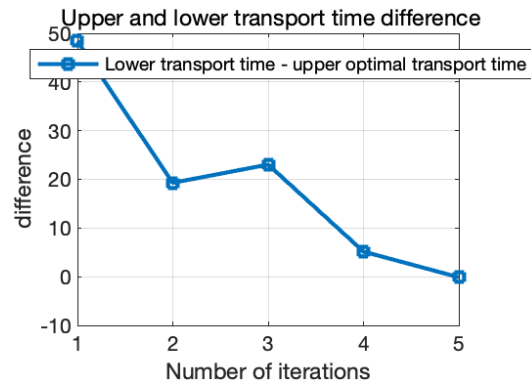
It can be observed that, across different transportation scenarios, the difference between the upper-level optimal planned transportation time and the lower-level actual transportation time tends to decrease as the number of iterations increases. This indicates that the bi-level programming iterations exhibit a certain level of convergence under the planned transportation lead time update formula proposed in this paper. Furthermore, the bi-level programming model achieves convergence within a relatively small number of iterations, which is reasonable. Since the logistics platform's lower level needs to conduct combinatorial auctions for transportation services, fewer iterations reduce the operational and organizational burden on the platform, making it highly suitable for the practical operations of logistics platform enterprises. Additionally, when carriers encounter significant fluctuations in transportation lead times, the difference between the upper-level optimal transportation time and the lower-level actual transportation time may suddenly increase. However, the bi-level programming model can quickly respond and adjust, continuing to converge thereafter. This demonstrates that the proposed bi-level programming model exhibits a certain level of stability and effectiveness even in highly volatile scenarios.



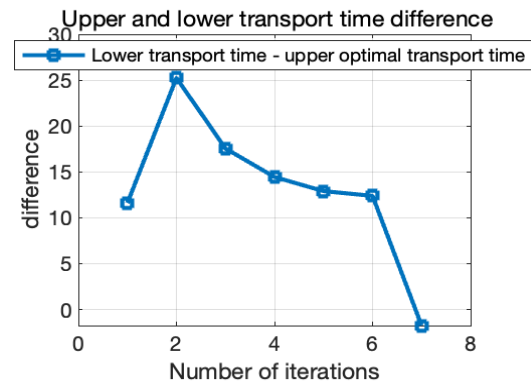
(a) Normal transportation scenario



(b) Scenario 1: Stable environment



(c) Scenario 2: Moderate fluctuations



(d) Scenario 3: Severe fluctuations

Figure 4: Iterative Convergence Diagram of the Bi-level Programming Model**Comparative Experiment Analysis**

The designed bi-level programming solution algorithm was applied to solve the example problem, and the results were compared with those of the multi-objective optimization model, as shown in Table 6. The case study was solved using the bi-level programming algorithm designed in this paper, and the results were compared with those of the multi-objective optimization model. The results are shown in **Table 6**. From the case results, it can be seen that compared to the multi-objective model, the bi-level programming model yields better results in terms of transportation time and cost for the same transportation plan, reducing transportation time and cost by 10.3% and 6.6%, respectively. This demonstrates that the bi-level planning model can achieve the optimal comprehensive benefit of Synchronomodality.

Table 6 Bi-level Planning Solution Results for Synchronomodality

	Model	Best Transportation Scheme	Transportation Time (hrs)	Transportation Cost (CNY)	Change
1	Bi-level Planning Model	Changsha-Wuhan-Xian-Alashankou-Warsaw-Berlin (Rail-Rail-Rail-Rail-Rail)	295	348090	The bi-level model reduces transportation time by 10.3% and cost by 6.6%.
2	Multi-objective Model	Changsha-Wuhan-Xian-Alashankou-Warsaw-Berlin (Rail-Rail-Rail-Rail-Rail)	329	372765	

VI. CONCLUSION

This study addresses the operational challenges faced by current international logistics digital platforms for synchronomodality by proposing a bi-level programming model for synchronomodal transportation. The model helps platforms provide transportation routes that effectively coordinate transportation time and cost, while utilizing the one-sided combinatorial auction O-VCG mechanism for pricing and allocation, achieving synchronization between tactical and operational levels.

First, convergence experiments on the model demonstrate that the bi-level programming model exhibits good convergence across different transportation scenarios. In stable environments, moderate fluctuations, and severe fluctuations, the model achieves convergence within a relatively small number of iterations. Moreover, in highly volatile scenarios, it can quickly respond to unexpected events and readjust to a stable state. This indicates that the synchronomodal bi-level programming model can effectively handle uncertainties caused by fluctuations in transportation lead times in real-world logistics, demonstrating strong adaptability and stability. Second, compared to traditional multi-objective optimization models, the synchronomodal bi-level programming model shows significant advantages in both transportation time and cost.

Through the construction and experimental validation of the bi-level programming model, this study provides an effective optimization method for international logistics digital platforms for synchronomodality. It not only significantly improves transportation efficiency and reduces transportation costs but also exhibits strong robustness and adaptability, enabling it to cope with complex real-world transportation environments. This study offers important theoretical support and practical guidance for the operational optimization of international logistics platform enterprises.

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A flexible operation organization of container terminals considering intermodal transport demand

Lingchong Zhong¹, Wenfeng Li², Wenjing Guo², Lijun He²

¹School of Intelligent Manufacturing and Materials Engineering, Gannan university of science and technology, Ganzhou, China

²School of Transportation and Logistics Engineering, Wuhan University of Technology, Wuhan, China

Corresponding author: zhonglc@gnust.edu.cn

Abstract: The operation organization of loading, unloading, and transshipment (LUT) is of great importance in managing, configuring resources, and scheduling container tasks for strengthening competitiveness in intermodal container terminals (ICTs). This study concludes the seven existing intermodal transportation LUT routes for sea-road, sea-rail, and road rail intermodal LUT methods in ports. In the past decade, container terminals usually operate container tasks based on a traditional operation organization by separating the 7 types of LUT routes. However, the traditional operation organization could not satisfy variable intermodal container transshipment simultaneously nor provide more choice of transshipment routes. A novel distributed parallel flexible operation organization with reentrant equipment (DPFOM_RE) for ICTs is constructed. Based on DPFOM_RE, ICTs can handle different intermodal container tasks at the same time with facility by multiple transshipment routes. The benefits for stakeholders and future directions for the proposed operation organization are discussed.

Keywords: Intermodal transport; Container terminal; Operation organization; Flexible operation; Reentrant equipment

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Introduction

Intermodal transportation is the movement of containers by a sequence of at least two transport modes (Crainic et al., 2007). Compared to unimodal transportation, intermodal transportation has the flexibility to use different modes considering the specific characteristics of containers (SteadieSeifi et al., 2014). In Europe, the growth of intermodal tonne-kilometer performance was 6.77% in 2021, with a 1.02% growth in the number of consignments transported (UIRR Report., 2021). A typical sea-rail application is the Eurasia Land Bridge, which connects Europe and China. It transports imported cargo from China and other far east countries. On its return from central Europe, the train transports European products, which are then loaded on feeder vessels to travel to China. Although the intermodal transportation brings convenience to global trade, it also brings great pressure to automated container terminals. Different intermodal containers need to be transferred to specific intermodal operation areas in container terminals, which makes the container transshipment process more

complex. A more intelligent decision system for automated container terminals in the context of intermodal (ICTs) is urgently needed.

ICTs are the key elements in intermodal transportation, managing the transfer from one transport mode to another. As shown in Figure 1, ICTs consist of yard operation areas in railway station (rail access area), internal trucks, yard operation areas (including yard crane handling area and containers storage area), check-in/out area (gate), external trucks (road access area), and berth operation areas (including quay crane handling area and truck transportation area). We can find that many blocks are used as yard operation areas; and they are regularly distributed at terminals and do not interfere with each other during work. For most of ICTs, the external trucks and rails have access to the ports, which is becoming a trend of terminals. The multiple intermodal containers are not only between vessels and road, but also between vessels and rails. These additional areas and access make the transshipment situations more complex.



Figure 1: An illustration of an intermodal container terminal layout.

ICTs are urged to find an integrated operation organization that can manage different areas and equipment better for more effective intermodal container transshipment. Recently, container terminals have been continuously working in three technology areas: automation, electrification, and digitalization; the most important being the development of automation and digitalization in container terminals, which has been enabled in part by operational organization (Zhou et al., 2022). Therefore, it is of great practical significance to study the novel operational organization of ICTs.

In ICTs, the operation of loading, unloading, and transshipment (LUT) is completed through the cooperation of different areas and equipment. The LUT is a complex operation process with multiple stages for containers transshipment. In general, the LUT process includes QC handling, IT horizontal traveling, and RC handling. Ordinary CTs only provide one type of transshipment route, which is regarded as the execution order of LUT process, for one type containers. However, at intermodal container terminals, there are more than one type intermodal containers (such as sea-road intermodal containers, sea-rail intermodal containers) to be meet at the same time. Only few studies have contributed to this research area. In the state-of-the-art study of Liu et al. (2020), three categories of container tasks including import, export and transfer container tasks were considered together.

To date, the existing operation organization of LUT process is based on the hybrid flow shop operation mode (HFSOM). The HFSOM is a production organization widely used in industrial manufacturing, which can only deal with one type of fixed production process at a time (Pinedo et al., 2008). The hybrid flow shop problem is, in most cases, NP-hard (Ruiz et al., 2010). In recent decades, the academia has analyzed some problems at CTs based on the

HFSOM. Lu et al. (2019) integrated QC handling and IT horizontal traveling as a two-stage hybrid flow shop scheduling problem. Chen et al. (2007), Sun et al. (2023) and Zhong et al. (2022) constructed three-stage LUT scheduling models which root from HFSOM. Although the HFSOM can integrate the processes with strong couplings well, it cannot simultaneously solve the flexible transshipment routes problem for various intermodal container tasks.

Based on the above considerations, we conducted a deep analysis from the following aspects. First, during loading, unloading, and transshipment, the distributed operation characteristics must be seriously considered for operation areas with homogeneous and heterogeneous equipment. Secondly, due to intermodal transportation, the types of intermodal containers and terminal operation areas will increase, followed by the diversification of transshipment routes. The new mode must be able to cope with transshipment for various tasks and provide sufficient flexible transshipment routes for multiple classes of containers. Third, the characteristics of critical equipment that occur many times during transshipment need to be properly defined to improve effective utilization.

Motivated by the above considerations, this paper proposes a comprehensive and effective novel LUT operation organization, named distributed parallel flexible operation mode with reentrant equipment (DPFOM_RE), with the following main innovations and contributions: 1) The seven types of LUT routes are concluded for the three intermodal methods for the first time. 2) The characteristics of hybrid LUT routes transshipment are extracted, including flexible LUT routes for variable intermodal containers, distributed multiple parallel operations for areas with homogeneous and heterogeneous equipment, reentrant equipment for the organization.

Related works

Traditional LUT operation organization

To date, the modeling and scheduling of LUT processes have been based on the HFSOM. Lu et al. (2019) studied a two-stage optimization problem on QC and RC scheduling in CTs. Sun et al. (2023) proposed a multi-resource collaborative scheduling optimization model, rooted in the principle of the blocking-type hybrid flow shop problem, with the objectives of minimizing the makespan of QC and the transportation energy consumption. Zhong et al. (2022) proposed a multi-objective optimization for integrated QC handling, IT traveling and RC handling operation considering no-idle QC operation in a container terminal. Lee et al. (2008) considered the comprehensive scheduling of QCs and RCs as a hybrid flow shop with sequence-dependent setup time. Xin et al. (2015) studied the joint scheduling of QCs, ITs, and automatic stackers, and introduced a hybrid flow shop scheduling model to represent discrete events.

In the above studies, the mathematical models of joint scheduling were all built based on the HFSOM. It can be seen that they abstract each operation stage of LUT as multiple parallel machines operation and assume that the LUT processes of all containers are consistent. However, this kind of study based on HFSOM ignores the distributed characteristics of equipment in all operation areas, and also ignores the diversity of LUT routes due to intermodal transportation.

Scheduling mode in distributed manufacturing

In practice, distributed manufacturing has been widely used in various types of industrial scenes, such as semiconductor wafer manufacturing (Dong et al., 2019), advanced computer-aided process planning (Mishra et al., 2012), production monitoring and scheduling in the distributed garment manufacturing environment (Guo et al., 2015). Many studies have been conducted on the scheduling of distributed manufacturing.

Wu et al. (2019) introduced the distributed flexible job shop scheduling to study the manufacturing problems of building materials and equipment manufacturing enterprises. There are also relevant researches that combine the distributed scheduling problem with other problems, such as the distributed problem with multi-factory manufacturing (Gharaei et al., 2018).

In particular, research on distributed job shop scheduling for factories began in the 1980s. Most of the studies focused on homogeneous factories or machines, and only a few studies discussed heterogeneous machines in heterogeneous factories. Researchers have made some progress on distributed heterogeneous parallel devices.

In most of the ICTs, there are at least two homogeneous pieces of equipment configured in each LUT operation area, and each stage operation area is divided into at least two parts, each of which has the same function and can work at the same time (Yu et al., 2021). However, few relevant researchers have considered resource allocation and job scheduling from the perspective of distributed scheduling, which makes the transshipment execution low and unbalanced between resources and consumption.

Reentrant operations

As important horizontal traveling equipment in ICTs, the trucks often interact with QCs and RCs. Therefore, most studies on trucks are conducted from the perspective of integrated scheduling. There are even more complex multi-stage integrated scheduling problems that simultaneously scheduled the QCs, ITs, and RCs in ICTs (Luo et al., 2020; He et al., 2015; Yang et al., 2018). In the models, the three types of equipment are assigned to container tasks, and the paths of ITs are planned at the same time.

In these models, the limited number of ITs requires the transportation of multiple container tasks (Luo et al., 2020). It can be seen that the current research on the vehicle path is limited to the closed-loop cycle between the endpoints of the two operation areas. However, it seldom considers how to use the non-circulating path to improve the utilization efficiency and turnover rate of ITs when more work areas have a demand for the internal truck.

Research gap

In the current research, the characteristics of distributed multiple parallel operations of ICTs have not been fully reflected in the traditional operational organization. The traditional organization cannot manage all different intermodal containers simultaneously, and the classification and definition methods for intermodal containers' LUT routes are not unified. Some critical equipment in ICTs may occur twice during LUT processing, and related studies have not researched this equipment.

Although the proposal and construction of the novel organization bring many challenges, for the intermodal transport network, the safe and efficient operation of ICTs can significantly improve the stability of container transportation. For ICTs, the change of operation organization can reduce effectively the waiting time of containers, and improve the competitiveness of terminals. For clients, the efficiency of ICTs can provide them with a reduction in logistics costs.

Construction of DPFOM_RE

LUT routes

Considering the combinations of intermodal transport, this section analyzes the transshipment routes (TR) during the process of LUT in ICTs. As shown in figure 2, the interaction diagram shows the traveling areas of ITs and external trucks (ETs) in some operation areas when the combination transport consists of sea, road, and rail. Among these operation areas, the yard

operation area is the most popular for ITs and ETs. The second popular area is the railway station. The types of intermodal containers' TR are shown in figure 4 - figure 6, the arrows in these figures indicate the flow direction of the containers.

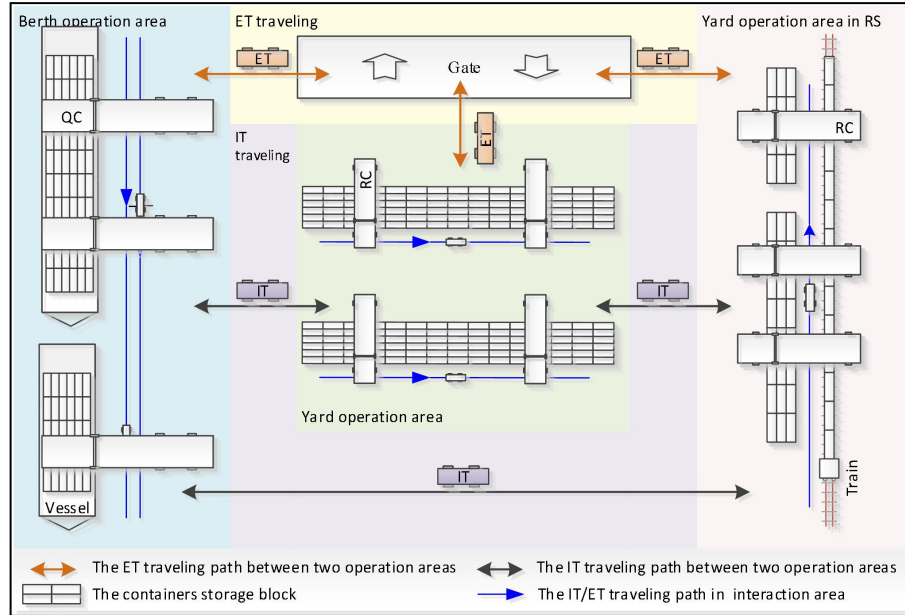


Figure 2: The interaction diagram among operation areas in an ICT.

For sea-road coordination, containers need to be transferred between vessels and ETs. Figure 3 shows two types of TRs for sea-road container (S-D container) tasks:

Type 1: If ETs are allowed to enter the berth operation area, the containers are handled by QCs between vessels and ETs directly. The TR is shown in figure 3 (a).

Type 2: The containers are first transported from the berth operation area to the yard operation area through ITs, and then carried to ETs by RCs in the yard, or the opposite LUT process. The TR is shown in figure 3 (b). It is worth noting that there is a temporary storage time Δt for containers in the yard.

The type 2 route is a standard TR in the actual operation of ICTs, alleviating the pressure on resources. For example, the excessive container transfer tasks may be limited by the quantities or capacity of the equipment. Therefore, some containers may be stored in the yard temporarily.

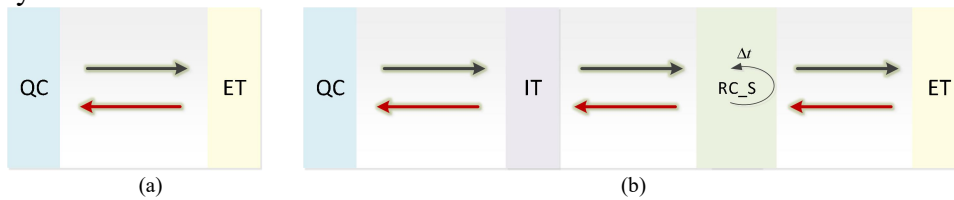


Figure 3: The TRs of sea-road containers. (a) Type 1 of TR; (b) Type 2 of TR

The LUT process between vessels and trains in the ICT is required for sea-rail intermodal containers. Figure 4 shows three types of TRs for sea-rail container (S-L container) tasks:

Type 3: If the railway connects to the berth operation area directly, the containers can be carried between the vessels and the trains by QCs without horizontal trucks travel. The TR is shown in figure 4 (a).

Type 4: Unlike type 3, if the train is not allowed to enter the berth operation area directly, the containers need to be transferred between the berth operation area and the railway station by the ITs. The TR is shown in figure 4 (b).

Type 5: The containers are first transported from the berth operation area to the yard operation area by ITs, and then stored in the yard temporarily. Until the railway station can

receive the containers, the containers will be transferred between the berth operation area and the railway station by ITs, or the opposite LUT process. It is worth noting that the storage time Δt is generated by the storage procedure in yard areas, and the transfer process of ITs has been completed twice. The TR is shown in figure 4 (c).

Likewise, some S-L containers will be stored in the yard areas temporarily. Therefore, there is a storage time Δt in type 5.

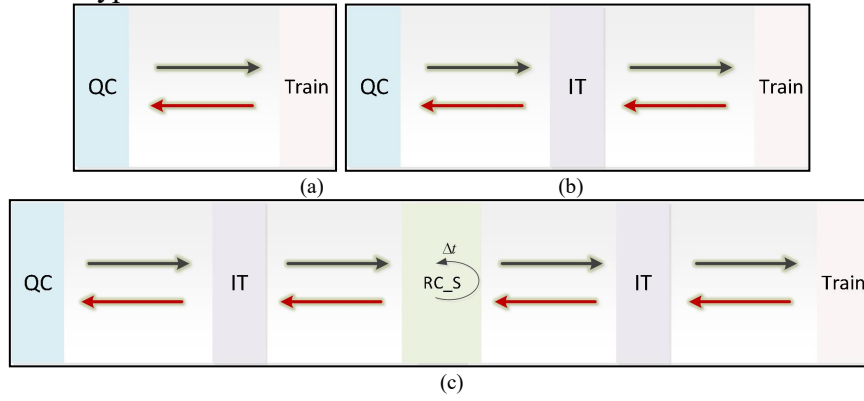


Figure 4: The TRs of sea-rail containers. (a) Type 3 of TR; (b) Type 4 of TR; (c) Type 5 of TR.

Sometimes, the same batch of intermodal containers in the railway station area is not only transported to vessels but also transported to ETs. For the sea-road-rail coordination, except for S-D container, and S-L container tasks, there are some road-rail container (D-L container) tasks. These D-L containers are transported between trains and ETs. Figure 5 shows two types of TRs for D-L container tasks:

Type 6: If the ETs have the access to enter the railway station area directly, the D-L containers are carried from the train to ETs by the RCs in the rail station directly without other transfer. In contrast, the transfer is from ETs to trains. The TR is shown in figure 5 (a).

Type 7: The containers are first transported from the rail station to the storage yard area by ITs, then stored in the yard temporarily until the ETs arrive at ICTs or the opposite LUT process. Similar to type 5, it is worth noting that Δt is generated by storage procedures in the yard. The TR is shown in figure 5 (b).

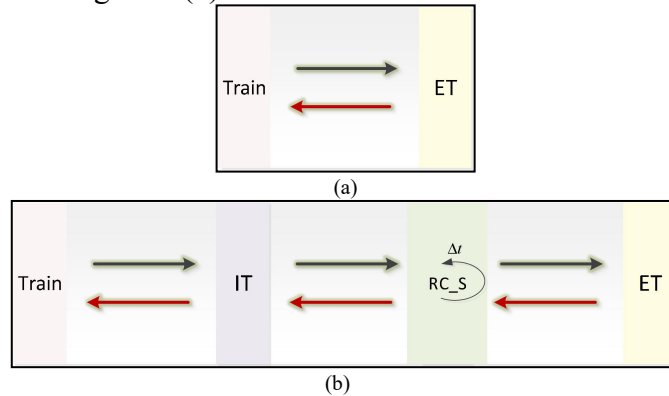


Figure 5: The TRs of road-rail containers. (a) Type 6 of TR; (b) Type 7 of TR.

In order to illustrate the flexible operation more clearly, the relationships between operational areas and container flows, and between each operational process, are shown in Fig. 6. The figure 6(a) shows important areas that are used during LUT, and the dashed double arrows indicate intermodal container flows between two different areas. It is noteworthy that two operation areas are related through IT/ET transport areas. The figure 6(b) gives the LUT process, which is divided into five common operational processes, and the seven colored double arrows link every two relational processes. The five common operational processes are QC handling, reentrant IT travelling, RC handling in storage yard, RC handling in the railway

station, and ET travelling. All of the types of TR are composed of these processes. Each TR can be represented by a combination of these links. The following are the combinations: Type 1 consists of link 5; Type 2 consists of link 1, link 2, and link 4; Type 3 consists of link 6; Type 4 consists of link 1 and link 3; Type 5 consists of link 1, double link 2, and link 3; Type 6 consists of link 7; Type 7 consists of link 3, link 2, and link 4.

In this subsection, we discuss various operation areas in ICTs. The S-D, S-L, and D-L containers are considered, and seven types of TR are defined, respectively. Each type of TR includes a unique LUT process, and each intermodal container can be assigned to at least two types of TR. Both of them reflect the flexible transshipment operation of the intermodal container tasks in ICTs. Finally, the flexible LUT route is defined as follows:

Definition 2 *The Flexible LUT route (FT)* means that each type of TR has a unique LUT process, and the TR assignment is flexible. Considering the distributed characteristics of equipment proposed in Section III. A and the limitations of equipment resources, each container is allowed to choose the appropriate TR type from the above definitions to complete the transfer. Before the transshipment start of each container, its selection of TR can be adjusted according to the current situation of resources.

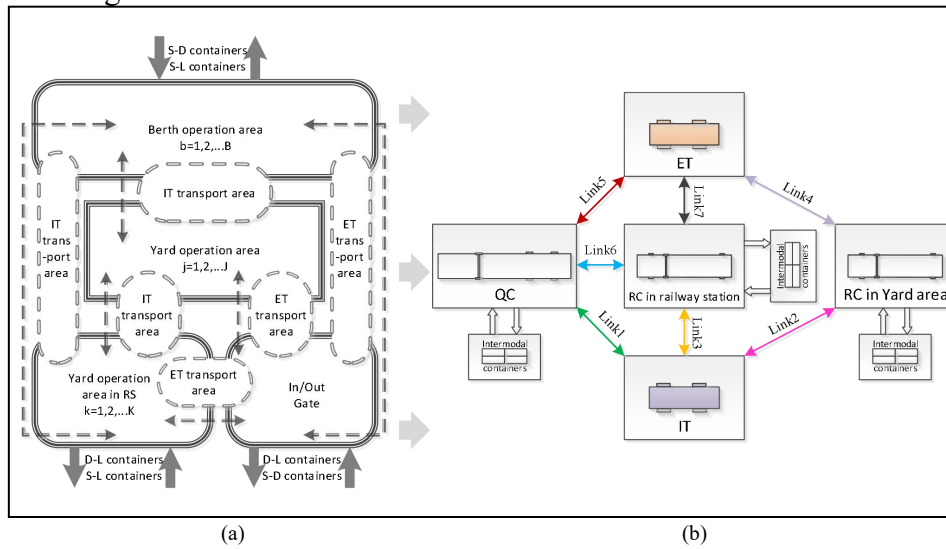


Figure 6: The flexible operational processes of LUT in ICTs.

Distributed multiple parallel operations

In this subsection, we take the sea-rail transshipment as an example to characterize the feature of distributed multiple parallel transfers of equipment.

As shown in figure 2, we can observe that a variety of equipment for different processes is distributed in multiple areas in batches, and the equipment can be used at the same time. This constitutes the distributed feature of heterogeneous transfer equipment. And in each distributed interaction areas, there are at least two sets of homogeneous equipment.

The feature of distributed configuration provides the basis of distributed parallel machine operation. It can provide the flexible operation with different scales or emergencies. Therefore, the distributed parallel machine operation is introduced to characterize the LUT. The k and s mean the total number of interaction areas in the operation area l and w , respectively. The n th machine exists in the interaction area j . The interaction area j exists in the operation area i . The definition of distributed multiple parallel operations is given below.

Definition1 *Distributed Multiple Parallel Operations (DMPO)* means that the homogeneous equipment is configured in distributed interaction areas, and heterogeneous equipment is configured in different operation areas. The transfer operations between different areas will not affect one another. In the face of changing tasks or uncertainty, the most suitable

equipment can be assigned to synchronize multiple tasks from distributed areas for LUT. Let S be a closed set, which means the operation area set. $S = \{So_1, \dots, So_i, \dots, So_n\}$, $|S| \geq 1$, $i=1, 2, \dots, n$, and So_i is also a closed set, which means the operation area i in ICT. The set $So_i = \{St_{i1}, \dots, St_{ij}, \dots, St_{im}\}$, $|So_i| \geq 2$, $j=1, 2, \dots, m$, and St_{ij} is also a closed set, means the distributed interaction area j exist in So_i .

Reentrant operations

As important horizontal transportation equipment of the ICT, the IT plays an important role during the LUT process. It can be seen from figure 2 and figure 6 that IT can travel in every operational area and execute twice within one type of TR. In addition, there is a temporary storage time Δt in type 2, type 5, and type 7 of TR. At the start time and end time of Δt , the container needs to be handled by RC. Therefore, the container is handled by RC at least twice during these types of TR. Based on the above factors, we define reentrant equipment:

Definition 3 *Reentrant equipment* (RE) can undertake multiple operation processes in a TR for a container. Let r_{ij} be a finite-dimensional vector, $r_{ij} = [r_{ij}^1, \dots, r_{ij}^Y, \dots, r_{ij}^Y]$, where the r_{ij}^Y is the Y th dimension in r_{ij} , $Y = |r_{ij}|$, $Y \in \mathbb{R}^n$. Elements $|w_{ij}|$ are extracted from r_{ij} and represented as the closed set w_{ij} , where $|w_{ij}| \geq 2$. Let $E = \{e_1, \dots, e_i, \dots, e_n\}$ be a closed set. If e_i is mapped to w_{ij} , then the e_i is RE.

In ICTs, RC and IT are REs. Then, another question comes. What effect will be triggered for the LUT when REs operating? To answer this question, we make the following analysis.

The number of operation processes assigned to REs will be increasing. Usually, the REs accept more instructions than ordinary equipment. The increasing instructions make that REs need to respond to the order and complete the previous transfer process in a timely manner. Additionally, if there is no idle equipment available to process the containers when the ITs arrive at the operation area, the ITs need to wait in the area. During this time, ITs continue to carry containers and cannot leave until the containers are unloaded by idle equipment.

Taking the above into consideration, it is necessary to account for the idle state of REs during transshipment and the potential strong coupling of space-time constraints that may arise when RE interacts with equipment in other operational areas.

Discussion

It can be seen from the above results that DPFOM_RE differs greatly from HFSOM in terms of the LUT process and performance. Further, we discuss the advantages, future work, and challenges of the novel organization from the following points.

Distribution. The intermodal container tasks are transmitted by the same LUT process based on HFSOM. Although the same type of equipment in ICTs is usually enough to complete the tasks, it can be challenging to handle, transfer, classify and store tens of thousands of containers simultaneously. With distributed operation organization, the DPFOM_RE distributes the container tasks to the equipment in different areas, which effectively relieves the pressure on the handling equipment.

Flexibility. In the intermodal container task, the choice of TR may be changed with the variety of the combination of intermodal. However, HFSOM cannot satisfy the flexible TR. For intermodal containers, the destinations of containers always depend on clients, which are diversified. Unlike the HFSOM, DPFOM_RE not only can provide the traditional TR to intermodal containers but also can meet other intermodal demands for clients. In addition, DPFOM_RE introduces the routes selection mechanism, which allows the terminal manager to choose the optimum TR. DPFOM_RE coordinates and utilizes terminal resources flexibly.

Complexity. The calculation of the TR combination of multiple intermodal container tasks is given above. Let $H \in \mathbb{R}^n$ be a closed set, let $H_{S-D}, H_{S-L}, H_{D-L} \in \mathbb{R}^n$ be a closed subset,

and $H_{S-D} \cup H_{S-L} \cup H_{D-L} \in H$, $H_{S-D} \cap H_{S-L} = \emptyset$, $H_{S-D} \cap H_{D-L} = \emptyset$, $H_{S-L} \cap H_{D-L} = \emptyset$. As we know, there are two types of TRs that can be selected by S-D container, thus there are $2^{|H_{S-D}|}$ TRs combinations for $|H_{S-D}|$ S-D containers. In a similar way, there are $3^{|H_{S-L}|}$ TR combinations for $|H_{S-L}|$ S-L containers and $2^{|H_{D-L}|}$ TR combinations for $|H_{D-L}|$ D-L containers. Therefore, the total number of TR combinations of container tasks is $2^{|H_{S-D}|} \cdot 3^{|H_{S-L}|} \cdot 2^{|H_{D-L}|} = 2^{|H|-|H_{S-L}|} \cdot 3^{|H_{S-L}|}$.

Stakeholders. It is always important for each carrier to complete the container tasks as soon as possible since that has a direct bearing on their profits. Similarly, for terminal operators, the operation efficiency of terminals is the key competitive indicator among peers. For shippers and logistics service providers, the resource loss generated during the LUT process is also worth considering (e.g., container wear). For customs agencies and their agents, the speed of customs declaration has an impact on the storage time of containers and then changes the choice of TR.

Conclusion

In this study, we propose an innovative LUT operation organization named DPFOM_RE, to enhance the containers transshipment in the context of intermodal transportation. The DPFOM_RE consists of distributed multiple parallel operation, flexible LUT route and reentrant equipment. The novel organization, which can cope with the variable demand of transshipment efficiently.

The DPFOM_RE can provide operation guidance to enhance the competitiveness of the terminals, and reduce the container wear, which are good news for shippers and logistics service providers. Additionally, the selection of TR can give a better advice to terminal operators to reduce the impact of customs declaration delay. This has a great attraction for customs agencies. For the terminal layout, the TRs can be used as references for designers during the initial design of terminals.

In the future, the types of TRs will become changeable with the development of ICTs and intermodal transportation modes. Therefore, it is significant to explore and expand the TR category library. Furthermore, a new direction of mathematical modeling and optimization based on DPFOM_RE for the ICTs' transshipment scheduling. The management framework based on DPFOM_RE provides new ideas for terminal managers.

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Resilient and sustainable transport networks: A novel decision-making framework for optimized logistics solution

Lukas Eschment¹, Irina Yatskiv (Jackiva)², Thomas Schüning^{1,3}, Kris Neyens⁴ and Walter Neu^{1,3}

1. Institute of Hyperloop Technology, University of Applied Sciences Emden/Leer, Emden, Germany
 2. TSI, Transport and Telecommunication Institute, Riga, Latvia
 3. School of Mathematics and Science, Carl von Ossietzky University of Oldenburg, Oldenburg, Germany
 4. Vlaams Instituut voor de Logistiek VZW, Berchem, Belgium
- Corresponding author: lukas.eschment@hs-emden-leer.de

Abstract:

*This research presents a novel multi-level decision-making framework for high-speed transportation technologies for industries and small to medium-sized enterprises. The proposed approach facilitates a stakeholder-centred selection of objectives, indicators, features, and performance criteria on the input side, and key performance indicator selection on the output side. The framework incorporates new developments in high-speed logistics transportation, such as hyperloop technology. Advanced technologies are included, thus creating an extended set of KPIs that current frameworks do not support, as they typically only consider existing modes of transport. The approach utilises the **Technique for Order Preference by Similarity to the Ideal Solution**, which considers a variety of impacts and weight parameters. Ultimately, it aims to bridge the gap between evolving political regulations and industrial adoption within the transport sector.*

Keywords: Hyperloop, MCDM, TOPSIS, Framework, Logistics, Physical Internet

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

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

1 Introduction

Resilience and sustainability have become increasingly important aspects of today's transport networks. Crises such as the conflicts in Ukraine or the Middle East, disruptions in key global shipping routes, extreme climate events, and a lack of truck drivers in Europe clearly demonstrate their impact on logistics and global supply chains. The shortfall in CO₂ reduction targets in transport calls for a fundamental rethink in how we design, manage, and improve transport and mobility systems to enhance sustainability and resilience.

Mario Draghi's Report on the Competitiveness of Europe forecasts a 79% increase in passenger demand globally and a doubling in freight volume. To ensure that Europe remains competitive,

he proposes a green and digital revolution in transportation as one of the main objectives. Alongside Artificial Intelligence (AI) and Big Data he outlines emerging innovations such as hyperloop as a very important contribution towards meeting the set goals. The report especially mentions the greater speed, efficiency and cost savings that are expected from hyperloop. (Draghi, 2024)

With new emerging modes such as hyperloop as well as innovations in sustainable fuels and electrified fleets, new approaches for decision-making are necessary to design and select the correct mode, as well as tools to be implemented in and expand transportation networks such as the TEN-T. This paper suggests a multi-level decision making framework (cf. Figure 1) supporting stakeholders in their choices. There is a particular emphasis on the business objectives and targets of logistics companies, making them central to the development of the hyperloop technology in the proposed framework. Integrating business objectives, technological characteristics and capabilities as well as policy requirements and further boundary conditions enables selecting and weighting of the relevant stakeholder metrics for high-speed transportation.

Building on previous research (Yatskiv et al, 2025; Duin, H. *et al.* 2025), the framework adopts a multi-criteria decision-making approach while integrating the latest advancements in high-speed logistics transportation, such as hyperloop. It incorporates technical parameters of emerging technologies as input, resulting in an expanded set of metrics and key performance indicators (KPIs) that go beyond those supported by existing frameworks, which typically only address current transport modes. The method applies the **T**echnique for **O**rder **P**reference by **S**imilarity to the **I**deal **S**olution (TOPSIS), leveraging features like impact and weight for improved decision-making. This paper outlines the fundamental structure of the decision-making framework, the implementation of the modified TOPSIS approach, and the specific adaptations made to incorporate constraints and industry-specific requirements. By including new technologies and innovative transport modes like hyperloop, the framework supports informed decisions for future transportation projects. This approach is specifically focused on freight logistics, thus clearly defining the scope of the research. Important dimensions like safety which is derived from policy requirements and technological characteristics is subsequently not included in this current iteration of the framework.

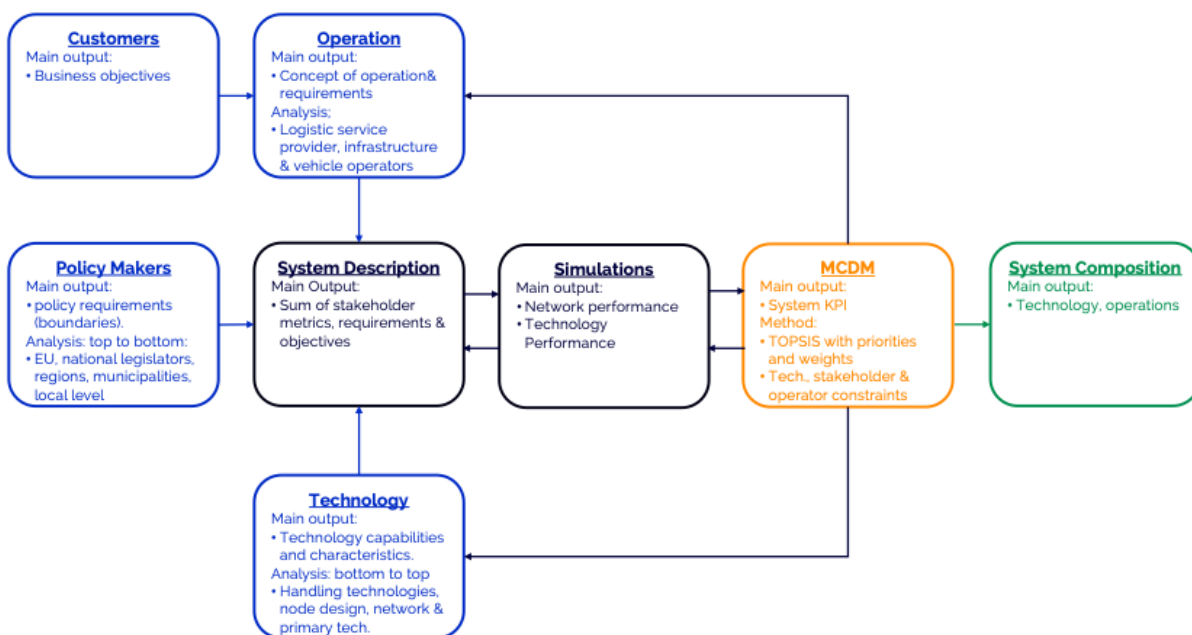


Figure 1: High-level overview of the proposed framework including stakeholders and categories.

A main goal of this research is to provide high-level guidance across many decision-making levels for a selected stakeholder group. The target beneficiaries of this new approach are industry stakeholders, from large-scale companies to small and medium sized companies (SMEs) with a special demand for robust, resilient and sustainable logistics. Emphasis is primarily placed on valuable freight with rapid added value that rely on fast logistics solutions. An application of this framework is planned after the system description and simulations are carried out.

2 Methodology

The research presented in this paper employs a multi-dimensional approach to decision-making within the context of resilient and sustainable transport networks. The methodology builds upon established multi-criteria decision-making (MCDM) techniques while extending them to address the specific challenges of incorporating emerging transport technologies such as hyperloop into existing logistics frameworks. To systematically evaluate and compare conventional and innovative transport solutions, a structured methodological framework has been developed that integrates the requirements, regulatory constraints and technological capabilities of multiple stakeholders, spanning from technology developers to policymakers and operators.

At the core of the approach lies TOPSIS, which has been adapted and enhanced to accommodate the complex, multi-level nature of transportation decision-making. TOPSIS represents an ideal foundation for the framework as it enables the effective handling of conflicting objectives, which are inherent in transportation network planning and optimization. The method allows for the simultaneous consideration of diverse criteria, making it particularly suitable for comparing heterogeneous transportation modes across multiple dimensions of performance. (Awasthi et al, 2011; Chatterjee and Lim, 2022)

2.1 Integration and Application

The multi-dimensional, multi-level structure enables the framework to capture the diverse requirements of all relevant stakeholders, support the evaluation of both established and emerging transport solutions and facilitate the selection and weighting of metrics and KPIs tailored to specific use cases and stakeholder needs.

By systematically mapping objectives, features, and performance criteria across these dimensions and levels, the framework ensures that decision-making processes are robust, transparent, and adaptable to future technological and regulatory developments.

2.2 Structure: Dimensions and Levels

This chapter details the multi-dimensional structure of the proposed decision-making framework for resilient and sustainable transport networks. The framework is designed to address the varying priorities, objectives, requirements and constraints of three key stakeholder groups (in the following called dimensions): Technology developers, operators, and policy makers. For each group, relevant levels and metrics are defined to ensure a comprehensive and stakeholder-centred approach to evaluating and selecting high-speed logistics solutions, including emerging technologies such as hyperloop:

- Technology developers: Focused on the technical capabilities and performance characteristics.
- Operators: Encompassing the objectives and performance of network operators, logistics service providers, and customers.

- Policy makers: Addressing regulatory and boundary conditions at the European, national, and local levels.

Each dimension is further subdivided into levels to capture the complexity and granularity of decision-making. The various levels of the three dimensions are listed below. Figure 2 shows the integration of the stakeholder metrics within the framework and the dimensions and multi-level structure.

Technology developers:

- Network & primary technologies: Assessment of core system architectures and enabling technologies as well as system compatibility and scalability (Hyper4Rail Project, 2024).
- Node design: Evaluation of node-level performance through simulations, focusing on throughput, resilience, and operational efficiency.
- Physical handling layer technologies: Analysis of process descriptions and the effectiveness of material handling systems.

Operators:

- Network operator: Metrics related to overall network performance, reliability, and utilization.
- Logistics service provider: Focus on vehicle fill rates, turnaround times, and delivery productivity.
- Customer: Emphasis on service quality, including on-time performance, cost efficiency, and environmental impact.

Policy makers:

- European union: Macro-level regulatory compliance, investment leverage, integration with existing modes and infrastructure (T-ENT), analysis of EU regulatory framework and sustainability targets.
- State/national level: National regulations and alignment with broader policy objectives.
- Local level: Regional economic output, local interests, and community impact such as noise exposure.

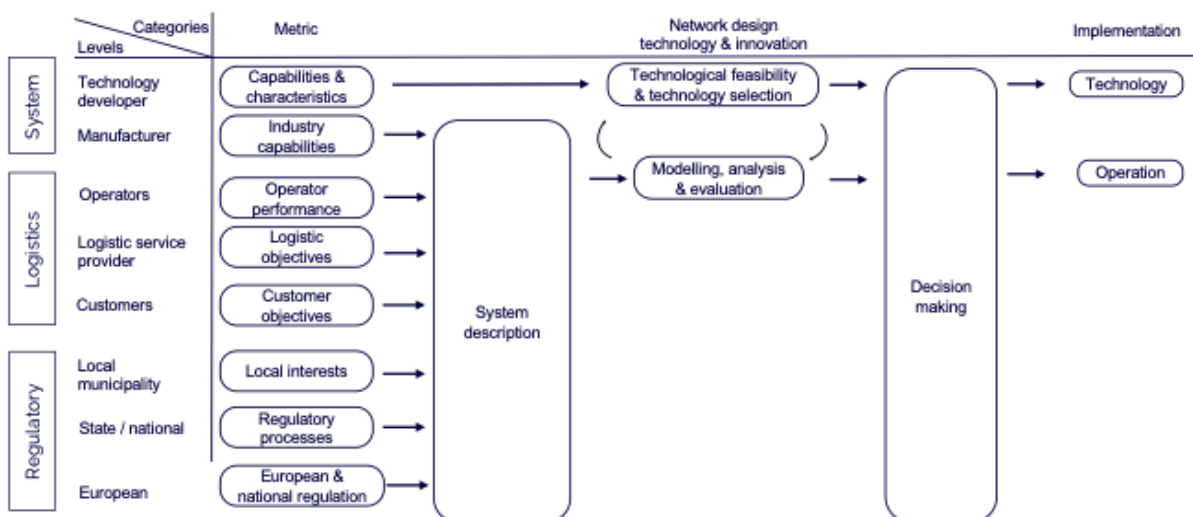


Figure 2: Stakeholder metrics integration into the framework.

2.3 Multi-level Decision Making with Constraints

The traditional TOPSIS method, while effective for many decision-making scenarios, requires significant adaptation to address the specific challenges of multi-stakeholder, multi-criteria transportation decisions involving emerging technologies. This framework implements a constraint-based TOPSIS approach that extends the conventional methodology to incorporate multiple levels of constraints and requirements beyond standard KPIs.

2.3.1 Theoretical Foundation and Adaptation

Drawing inspiration from the TOPSIS-inspired ranking method for constrained decision-making analysis (Chatterjee and LIM 2022), the approach is geared towards producing better compromised solutions in the event of conflicting objectives. In the traditional TOPSIS method, finding the appropriate weighting schemes and normalization criteria represents two complex tasks. Moreover, determining a positive ideal and negative ideal solution is crucial, as ranking can change due to the chosen ideal solution and normalization procedure. This approach therefore employs dynamic reference solutions according to the technological characteristics of possible top level hyperloop solutions. Furthermore, constraints are used during normalization and a feasibility check is carried out to only allow technologically feasible options with possible concepts of operations, validated through simulations. The general adaptations are shown in the following list:

1. **Option Set Generation:** Analytic calculations evolve candidate solutions from inputs (e.g., hyperloop technology compatibility) while respecting constraints like operations and node layout.
2. **Feasibility check:** Methods combine metaheuristics with TOPSIS to first generate feasible solutions and then rank them. This decouples constraint satisfaction from preference ranking, enhancing scalability.
3. **Dynamic Reference Solutions:** Traditional static ideals are replaced with context-dependent references derived from Pareto-optimal fronts or generated option sets. This aligns with real-world scenarios where “perfect” solutions are unattainable due to conflicting stakeholder priorities.
4. **Compromise Solution Identification:** TOPSIS ranks near-optimal solutions based on their distance from ideal coverage (all equations satisfied) and nadir coverage (minimal satisfaction) (Hu and Fang, 2015).
5. **Constraint Embedding in Normalization:** Normalization procedures account for constraint violations. For example, solutions exceeding a metrics limits receive penalized scores during normalization, ensuring infeasible options are systematically deprioritized.
6. **Adaptive Ideal Solutions:** Instead of static ideal values (e.g., for benefit-cost criteria), the method selects reference solutions from the Pareto front, ensuring realism in trade-offs (Chatterjee and LIM 2022).

The presented adaptation addresses these limitations by integrating elements from multi-objective constraint optimization. Therefore, the framework seeks to find a reference solution that better represents the near-optimal solution that optimizes conflicting objectives specific to transportation networks.

2.3.2 Implementation of the constraint-based TOPSIS model

The implementation follows a modified algorithm with the following key steps:

1. **Problem Formulation:** Define the decision matrix representing alternative technological solutions across multiple criteria.
2. **Constraint Integration:** Unlike conventional TOPSIS, our approach explicitly incorporates three categories of constraints:
 - Technological constraints (TRL levels, interoperability requirements)
 - Regulatory constraints (compliance with European, national, and local regulations)
 - Operational constraints (capacity limitations, resource availability)
3. **Normalization with Constraint Consideration:** The normalized decision matrix is used while accounting for constraint boundaries, ensuring that solutions violating fundamental constraints are properly penalized.
4. **Weighted Normalization with Stakeholder Priorities:** The weights assigned to different criteria reflect not only their relative importance but also their relevance to specific stakeholder groups as identified in the framework dimensions.

In general, the framework and decision-making concept highly values stakeholder-centric weighting. The novelty of this approach lies in the integration of a modified TOPSIS that can handle the specific requirements of multi-level decision-making for transportation networks.

3 Metrics

For each stakeholder and level, the framework establishes specific metrics to enable objective evaluation and comparison. These metrics are selected to reflect both traditional and innovative performance criteria, supporting the integration of new technologies and operational models. In the following tables a few of the selected metrics for the different dimensions and levels are shown.

Table 1: Policymaker metrics

European Union	State governments (national level)	Municipalities (local level)
Annual Public Investment: Capital expenditure on transport infrastructure Transport Volume: Total volume carried per hour European Regulation: Compliance with transport regulations Carbon Equivalent per ton: Environmental impact measurement of operations Infrastructure Resilience Index: Evaluates climate adaptation capacity with weighted scores for flood protection, heat-resistant materials, and redundancy Public-Private Investment Leverage Ratio: Compares private sector contributions to government transport spending	National Regulation: Compliance with transport regulations Freight Cost of GDP: Amount of freight transport Cost required per unit of economic output	Regional Economic Output: Economic benefits from transport activities Local Interests: Alignment with community priorities for transportation Local Noise Exposure: Noise levels from transport operations affecting local areas

Table 2: Technology developer metrics

Network level	Hub / Node level	Cargo interface
Network Resiliency: Ability to maintain operations during disruptions Annual cost of Maintenance Modelling, Analysis & Evaluation: Quality of operational simulation and planning Traffic Management and Control Measures: Effectiveness of traffic flow management systems Incident/ Disruption Detection: Speed and accuracy of detecting transportation disruptions	Station Throughput: Number of passengers or freight units processed per hour Station Footprint: Area the station occupies Station Capacity: Maximum number of vehicles that can be accommodated Transit Time within Stations: Time required for passenger/freight processing within Station Resiliency: Ability to maintain operations during disruptions Maintainability Index: Ease of performing maintenance on station equipment Station Complexity: Measure for the complexity of the Station infrastructure & operations	Technology Readiness Level: Measurement of technology maturity from 1-9 Technological Feasibility: Assessment of technical viability of proposed solutions Technological Boundaries: Limits of current technology capabilities Energy Consumption Rates: Efficiency of power usage for transportation system Handling Equipment Performance: Efficiency and reliability of material handling systems Maintainability Index: Ease of performing maintenance on material handling systems Cargo Transfer Speed: Time required to transfer cargo between the vehicle and the node System Adaptability: Capability to handle different cargo types and sizes Interoperability Maturity Level: Assesses compatibility between new technologies and legacy systems on 0-5 scale Interface Complexity: Measure for the complexity of the technological & operational complexity Manufacturability Reliability

Table 3: Operator metrics

Customer	Logistics service provider & station / vehicle operator	Network operator
On-Time Pickups: Percentage of pickups made within the scheduled timeframe On-Time Delivery: Percentage of deliveries completed within the promised time frame Cost per Unit: Total costs of transportation divided by the number of units shipped Cost per Ton: Transport cost reduced to one ton Carbon Emissions/Equivalent per Ton: Environmental impact measurement of air freight operations	Vehicle Fill Percentage: Measurement of how well vehicle load space is being utilized based on weight or pallet spaces Vehicle Turnaround Time: Average time elapsed between a vehicle arriving at a distribution center and its departure Cost per Vehicle: Transport cost calculated per vehicle Carbon Equivalent per Ton: Environmental impact measurement of operations Full Utilization Rate: Percentage of time the system is running in full capacity Delivery Productivity: Number of deliveries per vehicle per hour	Network Resiliency: Ability to maintain operations during disruptions Through-freight Share: Percentage of total freight demand passing through Routing Efficiency: Optimization of vehicle routes to minimize distance/time

Reliability Index: Ratio of total on-time arrivals	Terminal Occupancy: Percentage of terminal capacity in use
Average Transit Time: Total time for shipment movement from origin to destination	Station Efficiency: Average time for cargo loading/unloading at ports
	Container Dwell Time: Average time a container spends at the station before onward shipment

4 Results & Discussions

Current research highlights the importance of integrating resilience and sustainability in transport systems (Mitoulis et. al., 2023; López-Castro and Solano-Charris, 2021; Goodarzi et. Al., 2024; Mian et. al., 2023; Teixeira et. al., 2022) While there are efforts to involve industry stakeholders in KPI development, gaps remain-particularly regarding the comprehensive and standardized integration of KPIs for new and emerging transport solutions. Much of the existing research and practice still focuses on established modes and traditional performance criteria, underscoring the need for more adaptive and stakeholder-inclusive KPI frameworks. The suggested framework stimulates a new decision-making approach and performance criteria that are not covered by traditional methods, allowing for an extension of new innovative transportation solutions and tools for the integration into logistics applications. This research aims to fill the gap including metrics and KPI for these innovative and developing modes and solutions.

With a transport network analysis, focusing on the highlighted stakeholders, long term impacts of selecting novel transport modes and innovative solutions are examined. Technologies and systems such as freight handover, automation potential and requirements for intermodality are under investigation, modelled and simulated specifically for different modes, as with the introduction of new systems, additional interfaces are introduced.

As a result of this work, a new framework of technology selection and operations development for a high-speed logistics network is proposed through the combination of decision making and simulations. In future research the technological stack is further described and simulations are used to evaluate the system performance. A stack of KPI is used for evaluating the system and operational procedures provided by the framework and those could include cost, lifecycle performance, and particular emissions as well as throughput, service frequency, cargo volume, regulation (such as a carbon tax or prices on emissions) (compare for lifecycle performance and sustainability metrics; Wurst et. al. 2025). For the technological performance, KPI such as the following that arise from analytical models and simulations can be used: energy demand, maintenance and resource efficiency. For the output of the framework additional KPI such as emissions per unit, uptime, resilience, sustainability, stakeholder satisfaction, public perception and order fulfilment time are suggested as well.

5 Conclusion

The proposed decision-making framework outlines a structured way of solving problems and implementation of strategic decision-making. By putting industry stakeholders from large-scale companies to SMEs first in this novel approach, multiple levels of their strategic, tactical and operational organization can be mapped to specific KPIs. This allows them to make a more informed selection of transport modes, specifically tailored to their logistical needs. By

including high-speed transportation requirements and criteria, the framework is particularly relevant for emerging transportation technologies and their development such as hyperloop and digital tools such as AI which are becoming essential to meet the future demand for both passenger and freight transport.

Additionally, the framework bridges the gap between current political developments with new regulation, novel technologies and their adoption from the logistics industry in first use cases. The approach outlined in this framework could be envisioned to be implemented in logistics tools and software at later stages as well. In real world use cases and high-speed transport corridors in Europe, the framework can provide an improvement, especially considering novel solutions.

Not included in this framework are requirements and KPI such as safety, passenger comfort, and risk which are needed for passenger transport, but cannot be included to limit the scope of this research. They should be included in future enhancements to improve the comprehensiveness of the decision making approach for transport modes.

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Toward Modular Equivalence: Mapping Last-Mile Encapsulation to the Physical Internet Container Ecosystem

Nafe Moradkhani¹, Yann Bouchery¹, Florian Lebeau¹, Olivier Labarthe¹, and Walid Klibi¹

1. KEDGE Business School, CESIT, Bordeaux, France

Corresponding author: nafe.moradkhani@kedgebs.com

Abstract: *The Physical Internet (PI) envisions logistics as an open, modular, and seamlessly connected system. However, last-mile delivery—particularly via cargo bikes—remains fragmented, with current encapsulation practices relying on ad hoc methods such as non-standardized bags that are frequently reopened or redistributed at urban microhubs. This paper explores how these existing practices can be interpreted as early forms of PI encapsulation and how they might evolve toward modular equivalence with upstream container systems. Using real-world parcel-level data from urban delivery operations, we approximate a metric of encapsulation integrity to evaluate the consistency with which parcels remain grouped throughout their delivery path. Our findings reveal that several features already exhibit latent PI characteristics, such as modularity and partial traceability. We propose a conceptual framework to classify these practices as proto-PI encapsulation and explore their compatibility with higher-level logistics modes. This work offers a data-driven perspective on how last-mile systems can gradually align with PI principles without requiring immediate standardization or major infrastructure changes.*

Keywords: *Physical Internet, Encapsulation, Last-mile delivery, Modular logistics, Cargo bike, Urban logistics.*

Physical Internet (PI) Roadmap Fitness: ☒ PI Nodes, ☒ PI Networks, ☒ System of Logistics Networks, ☒ Access and Adoption.

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

1 Introduction

The Physical Internet (PI) proposes a paradigm shift in the design and operation of logistics systems by organizing the flow of goods through standardized, modular, and interoperable units—analogue to the way the digital Internet transmits data through packets (Montreuil, 2011; Montreuil et al., 2013). Central to this vision is the principle of encapsulation: goods are enclosed in containers that abstract their physical and commercial heterogeneity, allowing them to move autonomously and efficiently through open, shared logistics infrastructures (Montreuil et al., 2013; Pan et al., 2015). These containers— π -containers—are not passive boxes but intelligent and traceable carriers of both physical payload and logistical metadata, including routing, service level, and handling requirements (Sallez et al., 2016). As such, encapsulation serves as both a physical and informational layer that enables interoperability, decouples supply chain actors, and supports real-time orchestration of transport resources across networks (Buldeo Rai et al., 2017). While this logic has gained traction in long-haul and intermodal logistics—where π -container standards and industrial pilots have been explored—its application in urban delivery remains limited. The last mile is characterized by fragmented

operations, diverse stakeholders, and constrained infrastructures, all of which make the deployment of standardized containers challenging (Labarthe et al., 2024). In practice, urban delivery networks—particularly those relying on cargo bikes—adopt informal parcel grouping strategies to overcome operational constraints. Since cargo bikes have limited range and cannot directly access sorting centers typically located outside city centers, deliveries require a modal transfer at a central urban hub. To support this intermodal flow, parcels are pre-bundled into reusable fabric bags that facilitate transfer and reduce handling at modal breaks. These bags function as soft, modular units, preserving grouping consistency across transport modes. Parcel aggregation is generally done based on **basic geographical units**—hereafter referred to as *basic units*—in line with recent formulations by Bruni et al. (2024) in the context of stochastic last-mile delivery planning. These groupings are often altered at urban microhubs in response to operational mismatches such as load imbalances, sorting delays, or failed deliveries. As a result, the integrity of these groupings is frequently compromised, undermining the modularity and routing autonomy that PI encapsulation demands. Nevertheless, the emergence of repeatable grouping patterns around spatially defined basic units suggests that a latent modular structure may already exist. Basic-unit-based parcel bagging—while ad hoc—reflects a logic of localized encapsulation that could, in principle, be aligned with PI container hierarchies. If stabilized, such groupings may provide a scalable unit for routing, allocation, and flow consolidation in urban logistics. The question, then, is not whether current systems comply with PI standards, but whether they exhibit behaviors that approximate PI logic and can serve as stepping stones toward modular equivalence. This paper investigates to what extent current last-mile delivery practices exhibit characteristics of PI-compatible encapsulation. Using parcel-level operational data from a French logistics provider, we analyze how delivery groupings are formed during preparation, assigned to couriers, and potentially redistributed across delivery routes. We propose a metric of *encapsulation integrity*, quantifying the consistency with which parcels destined for a specific basic unit remain grouped throughout the delivery process. We then assess these patterns against PI criteria, identifying the extent to which informal bagging practices mirror the modularity, reusability, and flow independence central to the PI model. Our contribution is both empirical and conceptual. We introduce a method to detect and measure real-world encapsulation behaviors, characterize operational irregularities that challenge modularity, and propose a framework for interpreting these groupings as proto-encapsulation. By mapping these units to the broader PI container ecosystem, we outline a realistic pathway for integrating last-mile operations into the Physical Internet without imposing radical technological or structural transformation. The remainder of the paper is structured as follows. Section 2 reviews foundational literature on PI encapsulation, modular logistics, and last-mile delivery constraints. Section 3 introduces the methodology used to construct and interpret the encapsulation integrity metric. Section 4 presents the results of our analysis on spatial consistency, reallocation patterns, temporal dynamics, and volume sensitivity. It also synthesizes key insights into a modular alignment framework, outlining practical pathways for advancing encapsulation logic within last-mile logistics under the Physical Internet vision.

2 Foundations and Operational Gaps in PI Encapsulation

The concept of encapsulation in the Physical Internet is inspired by the abstraction model of the digital Internet, where data is transmitted through packets that contain both content and routing metadata. This analogy—first formalized by Montreuil (2011) and later operationalized by Ballot et al. (2014)—recasts logistics objects as “physical packets” embedded with modular structure and standardized metadata. Rather than being tied to specific carriers or infrastructures, encapsulated goods can flow independently across interconnected logistics networks by leveraging shared dimensions and service descriptors. The objective is to enable

flexible handling, automation, and the decoupling of transport decisions from individual stakeholders (Montreuil et al., 2012). The π -containers, a core construct in PI design, were introduced as modular units that encapsulate goods within a physical shell enriched with informational “headers” for routing and access control (Sallez et al., 2016). These containers are designed to be interoperable—stackable, traceable, and compatible with automated sorting and routing systems—supporting synchromodal and decentralized freight orchestration. Pan et al. (2015) emphasize their integration into dynamic logistics networks via service platforms capable of coordinating flows without centralized scheduling. Critically, π -containers are not passive units; they are “active,” equipped to support real-time updates and interaction across logistics operations (Sallez et al., 2016; Shaikh, S. et al., 2019; Tran-Dang, H. et al. 2020). In the layered PI architecture, encapsulation operates across multiple levels of granularity—from small-item capsules (sub-containers) to macro containers suitable for maritime or rail freight (Ballot et al., 2015). Each layer follows strict modularity rules to ensure that higher-level containers can be decomposed into smaller standardized units. The Open Logistics Interconnection (OLI) model (Montreuil et al., 2012) further specifies interoperability mechanisms among these layers, including service routing, quality tracking, and encapsulation renewal when crossing nodes or switching modes. Encapsulation is both physical and logical: the goal is to treat each encapsulated unit as a black box during transport, where the contents are not accessed or altered. This black-box paradigm ensures that decisions on handling and routing can be made purely at the container level, enhancing network efficiency and resource pooling (Biggi & Tretola, 2015). By separating payload from routing control, encapsulation becomes the enabler of plug-and-play logistics systems—where goods move with minimal human intervention across complex, multi-actor ecosystems. However, while these foundations are well established, most studies focus on high-level models or controlled environments. Their applicability to real-world, volatile logistics contexts—especially in the urban last mile—remains largely unexplored.

Encapsulation has seen its most advanced applications in structured multimodal systems, where standardized containers—such as π -containers—have been developed to support modularity across road, rail, and maritime networks. Within these controlled environments, encapsulation evolves from a conceptual model to a functional tool that enables seamless interoperability between physical infrastructures and digital platforms (Ballot et al., 2014; Pan et al., 2015). These containers are modular in structure and also enriched with smart capabilities—designed as reusable, data-rich units capable of autonomous transitions across transport modes. Their design allows them to maintain informational continuity, support automation, and enable real-time coordination within synchromodal logistics frameworks (Montreuil et al., 2020).

The Modulushca project marked one of the first large-scale demonstrations of Physical Internet encapsulation, introducing the M-Box as a modular unit for the distribution of fast-moving consumer goods across Europe (Tretola, G., 2013). These units conformed to PI principles through standardized dimensions, handling compatibility, and embedded metadata for real-time tracking and coordination (Ballot et al., 2015; Sarraj et al., 2014). Tretola and Verdino (2015) extended this logic by proposing a Canonical Data Model to enable seamless interoperability and message translation between logistics information systems. More recently, the Ponera Group has advanced this paradigm by developing smart, reusable industrial packaging modules that can be configured in multiple layouts. Designed for circular logistics, their solution emphasizes reduced environmental impact, enhanced traceability, and increased operational flexibility—all aligned with PI modularity and sustainability goals.

In applied settings, encapsulation has been examined for co-modal routing scenarios, where a container may sequentially transition across different carriers and geographies. Sarraj et al. (2014) demonstrate that π -containers can act as atomic routing units in distributed logistics optimization, with the container itself managing its own routing metadata. Their simulation results suggest improvements in container fill rate, synchronization, and decarbonization of long-haul logistics chains. Similarly, the concept of "routing goods, not vehicles", emphasized by Ballot et al. (2015), hinges on the idea that containers can be decoupled from fixed transport schedules and dynamically integrated into available transport slots across modes. From a technical standpoint, Sallez et al. (2016) introduced the concept of *active containers*—modular units embedded with sensing and communication capabilities that report their status, location, and service parameters. These smart containers enable dynamic routing, transforming them from passive freight units into autonomous logistics agents capable of interacting with digital platforms. This active functionality is essential for orchestrating freight flows across synchromodal, multimodal networks.

Despite these advances, much of the research on encapsulation remains confined to controlled environments where loading, unloading, and routing are pre-planned, and where cargo typically shares the same destination. Such conditions are ill-suited to the fragmented and heterogeneous nature of last-mile distribution. Even sophisticated pilot projects—such as container switching between trucks and subway lines—depend on tightly integrated infrastructures and well-aligned actors. As Ghilas et al. (2016) point out, the use of public transport for freight logistics, while promising, remains limited in scale and adaptability. Similarly, Dupouy et al. (2024) highlight the potential for hyperconnected container flows in urban contexts, but note that such systems require high levels of coordination, standardized interfaces, and digital traceability. These cases reveal the current boundaries of encapsulation feasibility: successful implementation still hinges on clear interfaces, uniform protocols, and dedicated assets—conditions that are rarely met in the fragmented, variable settings of last-mile delivery. This tension between conceptual elegance and operational complexity underscores the need to explore alternative forms of encapsulation in less formalized environments. In particular, we investigate how basic-unit-based parcel groupings and reusable soft containers in cargo-bike networks might approximate the modular behaviors of π -containers and extend encapsulation logic into urban logistics.

Cargo-bike logistics—valued for their sustainability and urban adaptability—pose specific constraints to standardized encapsulation envisioned by the Physical Internet. Unlike multimodal systems with dedicated infrastructure and rigid equipment, cargo-bike networks face spatial, ergonomic, and capacity limitations. Manual handling and restricted vehicle space preclude the use of rigid PI-compliant containers. Instead, parcels are grouped in lightweight, soft-shell bags—flexible but lacking structural interoperability. Urban logistics' inherent dynamism exacerbates this: daily volume fluctuations and frequent rerouting lead to manual bag reallocations, fragmenting parcel clusters and disrupting their continuity as routing units. Unlike π -containers, designed to preserve contents from origin to destination, soft groupings are regularly opened, reassigned, or consolidated at microhubs—typically without standardized interfaces or traceability. This lack of modular integrity is exacerbated by the absence of standardized containerization and digital traceability. As noted in recent studies, such as Faugère et al. (2020), resorting at microhubs increases workload and delivery times, while Liu et al. (2023) highlight the pressing need for modular container design and digital interconnectivity to improve last-mile efficiency and sustainability.

Despite these challenges, several characteristics of cargo-bike operations hint at a modular logic that could be formalized. Delivery preparation routines often follow consistent spatial boundaries—such as districts or postal sectors—that mirror PI’s recursive structuring of container hierarchies (Montreuil et al., 2020; Faugère et al., 2020). The repeated use of delivery zones to organize workflows suggests that operational encapsulation is already emerging, even if informally. Furthermore, many soft containers are reused and sometimes labeled, and logistics platforms increasingly track their assignment, indicating potential for basic informational headers and process traceability (Kaboudvand et al., 2021; Escribano-Macias et al., 2022). Urban microhubs also offer structural opportunities. As intermediate sorting and consolidation nodes, they can serve as local encapsulation renewal points—mirroring node-level transitions in PI architecture (Ghilas et al., 2016; Liu et al., 2023). When integrated with digital routing platforms and linked to bag identifiers, even lightweight containers can support more consistent encapsulation across routes and time. The rise of dynamic routing algorithms, app-based courier coordination, and low-cost IoT devices facilitates “soft encapsulation”—a hybrid approach where informational modularity compensates for physical limitations (Sallez et al., 2016; Ballot et al., 2015). Though structurally distinct from π -containers, these systems can achieve comparable flow autonomy and modular traceability when parcel groupings are treated as black boxes during handovers.

In summary, while cargo-bike systems fall outside the traditional domain of containerized logistics, they are not incompatible with encapsulation. On the contrary, their inherent flexibility and route regularity offer a fertile ground for the development of PI-aligned practices—provided that modular grouping, continuity, and informational embedding are strategically encouraged rather than retrofitted.

3 Capturing Encapsulation Integrity in Cargo-Bike Delivery

This section outlines the data and methodological framework used to assess the modular behavior of last-mile delivery operations in relation to Physical Internet (PI) principles. The analysis draws on parcel-level records at two core stages: (i) **Preparation**, where parcels are grouped into soft containers (reusable fabric bags) based on predefined delivery basic units; and (ii) **Execution**, where these grouped bags are assigned to couriers for final delivery via cargo bikes. While the intended operational logic aims to preserve these groupings from depot to doorstep—ensuring modular consistency throughout—the realities of urban logistics often intervene. Variations in daily demand, limited cargo-bike capacity, failed deliveries, or manual reallocation at microhubs can disrupt the original structure and force reassignment.

To evaluate how well these groupings persist through operational disruptions, we introduce the concept of **encapsulation integrity**: the extent to which parcel clusters prepared at sorting facilities remain unchanged throughout the delivery process—that is, until each parcel is individually delivered without premature extraction from its bundle. We also define **encapsulation drift** as the measurable divergence between the intended grouping structure—referring to how parcels are initially clustered into bags during preparation—and the actual routing configuration during delivery, where multiple bags are often consolidated onto a single cargo bike. These constructs allow us to examine modular consistency without requiring formal containerization. Encapsulation integrity is evaluated across four operational dimensions—**Spatial Cohesion**, **Temporal Synchronization**, **Structural Separation**, and **Volume Resilience**—each captured by a dedicated performance *Metric*, presented in *Table 1*.

Table 1: Metrics for Evaluating Encapsulation Integrity

<i>Dimension</i>	<i>Metric</i>	<i>Interpretation</i>
Spatial Cohesion	Zone Consistency Score (ZCS)	Measures how consistently parcels from a basic unit are handled within the same route
Temporal Synchronization	Temporal Cohesion (TC)	Evaluates how tightly grouped parcels are delivered within a shared time window
Structural Separation	Spillover Rate (SR)	Indicates the extent to which parcel flows breach assigned basic unit boundaries
Volume Resilience	Encapsulation Stability Index (ESI)	Assesses how encapsulation quality varies with changes in parcel volume

3.1 Zone Consistency Score (ZCS)

The **Zone Consistency Score (ZCS)** quantifies spatial cohesion by measuring how well parcel groupings—defined during preparation—remain unchanged during delivery. Each parcel is assigned a four-digit code, which serves as its basic geographical unit (basic unit) for bagging. The first two digits of this code form broader routing clusters that align with operational zones. These basic units serve as the reference for bagging parcels at the sorting facility. In contrast, the first two digits of the code form broader operational clusters that approximate how cargo-bike routes are typically organized. ZCS is computed by identifying, for each basic unit on a given day, the proportion of its parcels delivered by the same cargo bike. A high ZCS indicates that the grouping defined at preparation was preserved through delivery; a low score reflects spatial fragmentation across vehicles. We evaluate ZCS at two levels:

- **Basic-unit level (4-digit code):** Reflects the structural integrity of parcel bags as physical grouping units.
- **Cluster level (2-digit prefix):** Captures routing coherence by examining whether operational bike assignments align with spatially grouped areas.

This dual-level approach allows us to distinguish between physical grouping practices and their translation into routing decisions.

3.2 Temporal Cohesion (TC)

Temporal Cohesion (TC) captures the synchronization of deliveries within each basic unit by measuring the dispersion of parcel delivery times. It reflects the degree to which grouped parcels are delivered within a tightly bound time window, a proxy for temporal modularity. While spatial metrics assess whether parcels are handled within the same route, TC evaluates whether they are also delivered in a temporally compact sequence—an essential aspect of efficient, modular routing. High TC values indicate that parcels follow coherent operational trajectories, whereas wide time spreads suggest disruptions such as route imbalance, dynamic reassignments, failed deliveries, or reallocation at microhubs. This allows us to identify patterns of fragmentation not evident in spatial metrics alone. Basic units with stable TC values demonstrate temporal regularity and potentially better workload coordination, reinforcing their compatibility with encapsulated flow logic under the PI framework.

3.3 Spillover Rate (SR)

Spillover Rate (SR) quantifies the extent to which parcel flows deviate from their intended basic unit boundaries. Specifically, it measures the proportion of parcels from a given basic unit that are delivered by bikes predominantly assigned to other basic units. This metric reveals structural leakage—instances where operational actions override spatial modularity. While high ZCS indicates intra-basic-unit cohesion, SR captures inter-basic-unit contamination. A low SR implies clean compartmentalization of parcel flows; a high SR signals routing overlap, potential inefficiencies, or lack of modular discipline. SR is particularly useful for diagnosing systemic drift in networks that appear cohesive at a local level but exhibit hidden reassignments or imbalanced workload distribution. In PI-aligned systems, low spillover reflects the preservation of zone autonomy and supports scalable, plug-and-play logistics configurations.

3.4 Encapsulation Stability Index (ESI)

The Encapsulation Stability Index (ESI) evaluates how resilient modular behavior is under varying workload conditions. It tracks whether spatial and structural coherence—captured by metrics such as ZCS or SR—is maintained consistently as delivery volume fluctuates. High ESI implies that encapsulation logic holds across light and heavy operational days, indicating scalable modularity. In contrast, a low ESI suggests that grouping integrity degrades under pressure, pointing to load-sensitive fragility. This may manifest as parcel reassignment, route overlap, or the erosion of zone-based compartmentalization. ESI is computed by examining how encapsulation scores change across volume tiers (e.g., quartiles of daily parcel load per basic unit). Negative trends indicate bottlenecks in sorting, routing, or courier capacity. In the PI framework, ESI reflects a system’s ability to maintain plug-and-play modularity at scale—a key requirement for interoperable logistics networks.

4 Toward Modular Readiness: Encapsulation in Practice

This section examines how current parcel operations align with modular encapsulation logic, drawing on spatial (ZCS), temporal (TC), structural (SR), and load-dependent (ESI) behaviors. Results are presented from one microhub at last-mile as a representative instance to illustrate how modular integrity emerges—or breaks down—within real-world routing conditions. The goal is not to evaluate isolated performance, but to identify systemic signals of grouping stability and drift that inform the broader framework.

4.1 Spatial Cohesion (Zone Consistency Score)

The spatial results reveal an important distinction between grouping integrity and routing consistency. At the **bag level (4-digit)**, ZCS values are generally higher, suggesting that parcels grouped during preparation tend to remain together throughout the process. This indicates a degree of internal cohesion that aligns with modular handling principles, even in the absence of formal containerization. In contrast, **route-level consistency (2-digit)** is less stable. Bags appear to circulate across couriers or routes more frequently, especially during periods of high volume or operational adjustment. This pattern suggests that while encapsulated units are effectively formed, they are not always preserved at the route execution stage—pointing to a gap between structural grouping and functional modularity.

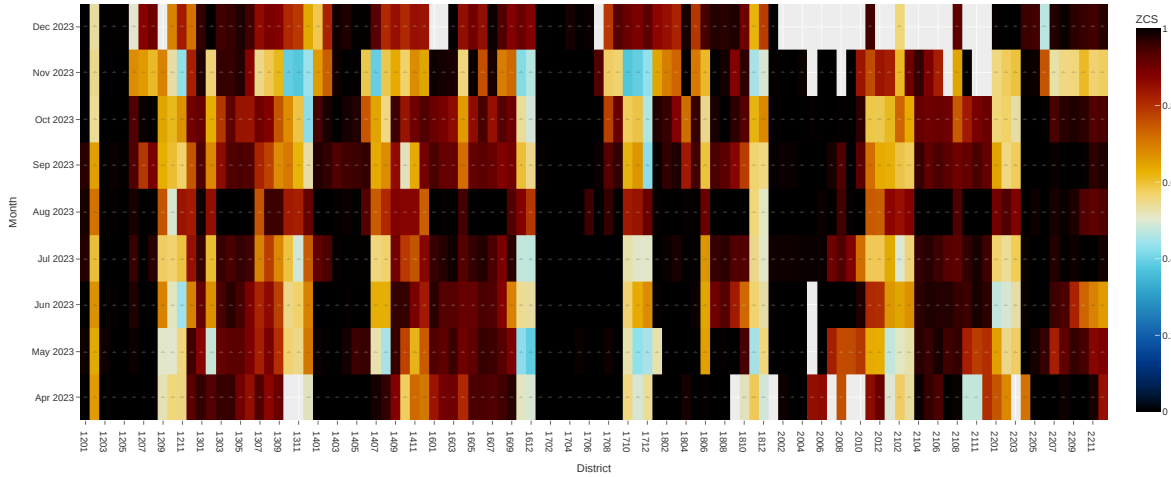


Figure 1: Zone Consistency Score (ZCS) at the 4-digit level (bag-level). High scores suggest stable parcel grouping within basic units over time.

Figure 1 shows that bag-level ZCS scores are consistently high across most months, suggesting that parcel groupings during preparation are generally cohesive and aligned with specific basic units. This supports the hypothesis that, despite informal practices, soft bagging routines tend to reflect latent modular logic.

In contrast, when we move to the **route level** (2-digit), a different picture emerges. Figure 2 reveals lower and more volatile ZCS scores at the route level, indicating that parcels initially grouped for a given basic unit may be redistributed across routes during execution. This

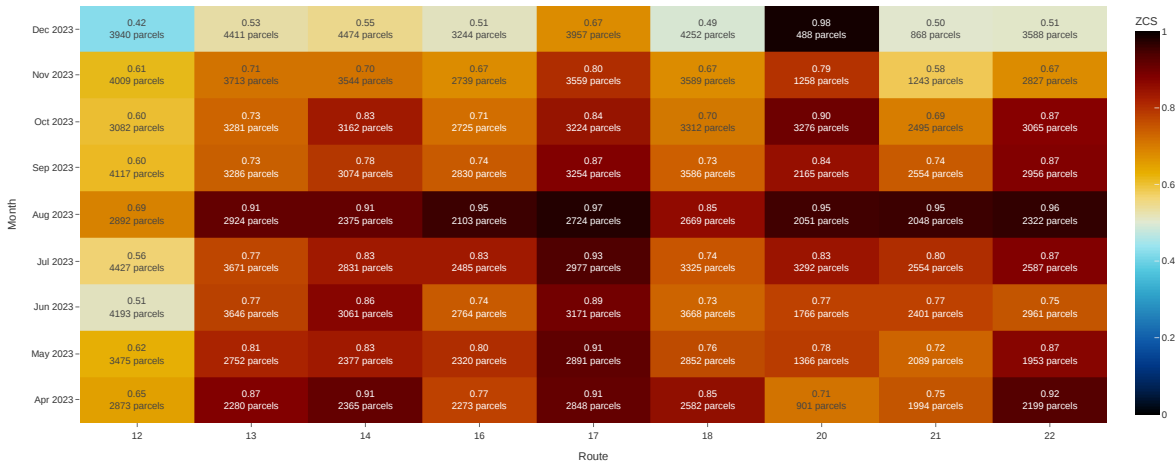


Figure 2: Zone Consistency Score (ZCS) at the 2-digit level (route-level). Lower scores reflect that bags, while well-formed, are often reassigned across delivery paths.

divergence points to operational friction—likely stemming from balancing, reassignment, or ad hoc rerouting at microhubs—that disrupts spatial modularity.

To better understand this duality over time, we combine the ZCS distributions across both levels and examine their monthly evolution. Figure 3 shows that while the distribution of ZCS scores at the grouping stage remains narrow and concentrated around high values, the routing stage displays greater dispersion and a declining trend from October onward. This trend suggests that as volumes increase or operational constraints accumulate, spatial cohesion is more difficult to maintain during delivery execution.

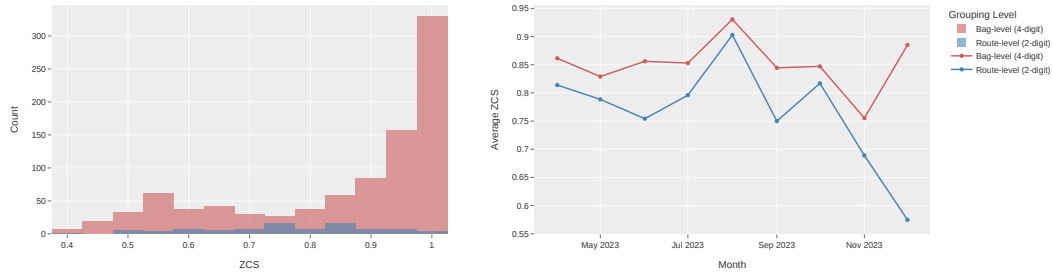


Figure 3: ZCS distribution and monthly trends (April–December). Histogram confirms concentration of high group-level cohesion, while monthly averages reveal divergence between grouping and routing consistency over time.

Together, these results highlight a critical distinction: **while initial parcel preparation follows modular logic, operational execution often breaks that logic.** This decoupling between structure and flow is a central challenge for aligning current practices with Physical Internet (PI) principles.

4.2 Temporal Stability (Temporal Cohesion)

Temporal Cohesion (TC) captures the synchronization of parcel deliveries within basic units by measuring the dispersion of delivery times. As a complement to spatial cohesion (ZCS), TC reflects how tightly grouped parcels are delivered in time—a key proxy for modular execution. High TC suggests consistent, compact delivery flows; low TC indicates temporal fragmentation due to reallocation, route imbalance, or flexible dispatching at microhubs. We examine TC from two complementary perspectives. Figure 4 presents delivery time distributions for selected basic units, combining histograms with smoothed overlays. Basic unit 1704, despite handling high volumes, shows a sharply peaked curve—indicating well-synchronized execution. In contrast, Basic unit 1202 displays a broader, flatter distribution, likely shaped by the operational demands of a commercial zone or extended delivery windows. These differences mirror their ZCS profiles and illustrate how spatial and temporal cohesion may reinforce (e.g., Figure 4)—or diverge from—each other.

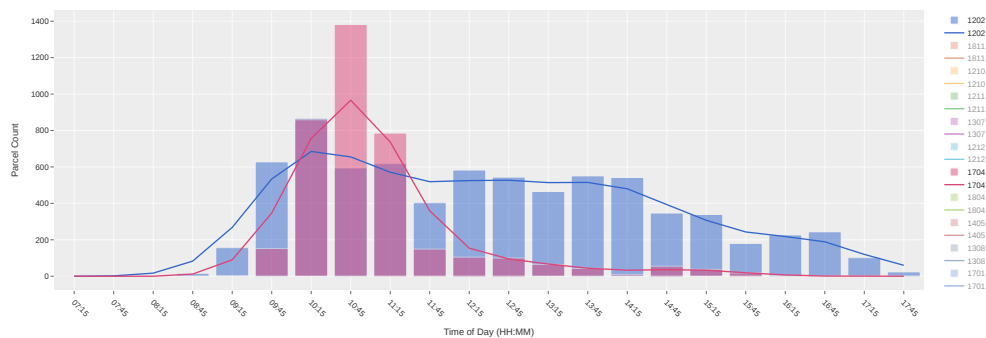


Figure 4: Delivery volume per 30-minute interval for selected basic units. Bars represent parcel counts, and overlaid curves indicate smoothed temporal distribution. Compact peaks suggest synchronized execution, while broader curves reflect more fragmented or extended delivery activity.

Figure 5 plots average daily parcel volume against temporal cohesion (TC) at the basic-unit-month level, where TC is measured using the coefficient of variation (CV) of delivery times. CV captures the relative dispersion in delivery schedules, allowing for meaningful comparisons across basic units with differing average route durations. The positive relationship suggests that temporal cohesion tends to deteriorate as delivery volume increases, pointing to rising coordination challenges under higher load conditions.

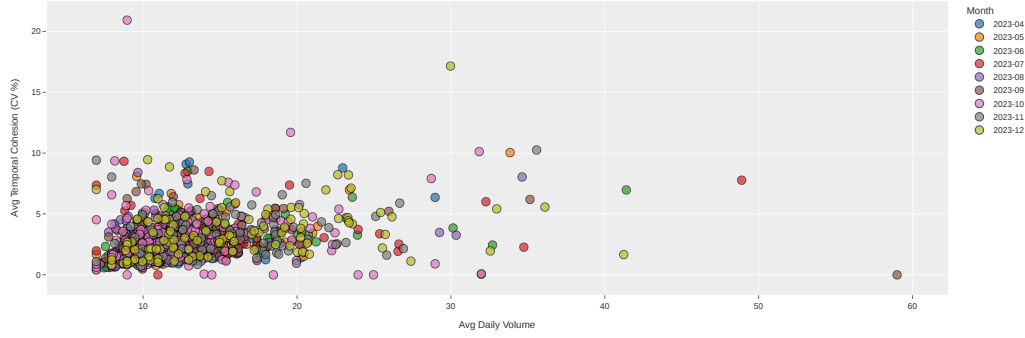


Figure 5. Scatterplot of average daily volume versus temporal cohesion (TC) at the basic-unit-month level. TC is measured as the coefficient of variation (CV) of delivery times. Higher volumes tend to be associated with increased temporal dispersion. Patterns reinforce the relationship between volume stress and cohesion drift across urban routing conditions.

Together, these results reveal how temporal modularity strengthens or deteriorates across basic units and workloads. When considered alongside spatial patterns, TC helps expose hidden drift and reinforces the need for integrated spatial-temporal alignment to support PI-compatible encapsulation.

4.3 Structural Separation (Spillover Rate)

While route-level ZCS in Section 4.1 (Figure 2) quantifies **internal dispersion**—how consistently parcels from a basic unit are handled by the same courier—Spillover Rate (SR) captures **external contamination**: how frequently deliveries of a basic unit are executed by couriers not primarily serving that zone. Though ZCS and SR are mathematically linked ($SR \approx 1 - ZCS_{RouteLevel}$), they diagnose distinct operational breakdowns. ZCS reflects the internal cohesion of modular flows; SR reveals violations of territorial boundaries. Figure 6 visualizes SR across basic units and days, with point color indicating the degree of spillover and size reflecting delivery volume.

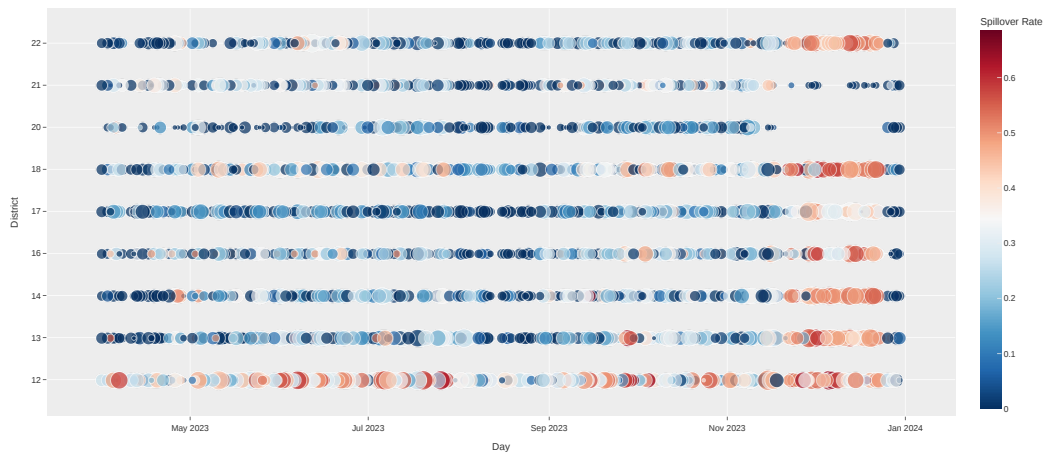


Figure 6: Daily spillover rates by basic unit. Circle size reflects delivery volume; color encodes the extent of cross-route allocation.

SR values increase noticeably from October onward (see route-level ZCS in Figure 3), likely due to seasonal pressure and reactive route adjustments. In addition to these transient spikes, some basic units (e.g., 12) exhibit persistently high SR, revealing systemic exposure to routing leakage. Trends underscore that even when parcel preparation achieves cohesion (as suggested by strong bag-level ZCS in Figure 1), modular integrity can still deteriorate during execution.

4.4 Volume Resilience (Encapsulation Stability Index)

This section presents the empirical application of ESI, introduced in section 3.4, focusing on how encapsulation behavior responds to operational volume. In contrast to static metrics such as ZCS, TC, or SR—which capture spatial or temporal coherence at a given moment—ESI quantifies dynamic resilience: the degree to which modular parcel structures maintain their integrity as delivery volume fluctuates. Formally, ESI is computed as the Pearson correlation between encapsulation quality (ZCS) and parcel load over time. By construction, this means that when ZCS remains stable or increases across volume tiers, ESI is positive—signaling robustness. When ZCS drops under load, ESI becomes negative—indicating fragility. A high ESI implies that modular behaviors—such as consistent bag-to-basic-unit mappings—are preserved even under elevated demand, indicating structural scalability. In contrast, a low or negative ESI reflects deterioration: as load increases, parcel groupings become more fragmented, exposing systemic frictions in preparation, routing, or allocation processes.

Volume Effect on Encapsulation Behavior. To interpret ESI trends, we examined how ZCS varies across parcel volume per bag (see Figure 7). A clear trend emerges: as parcel volume per bag increases, average ZCS generally declines, suggesting that grouping coherence weakens under load. This likely reflects operational shifts that prioritize capacity over modular integrity, such as opportunistic packing. However, the degree of degradation varies—some months show abrupt drops beyond certain thresholds (e.g., >200 parcels), while others exhibit a more gradual decline. Viewed longitudinally, ZCS volatility across volume bins closely aligns with ESI scores: basic units sustaining high ZCS under varying volumes tend to show stable or positive ESI, while those experiencing marked ZCS drops at high load often exhibit low or negative ESI. These findings confirm ESI’s value as a stress-test metric—capturing the presence of modularity and its resilience under operational pressure.

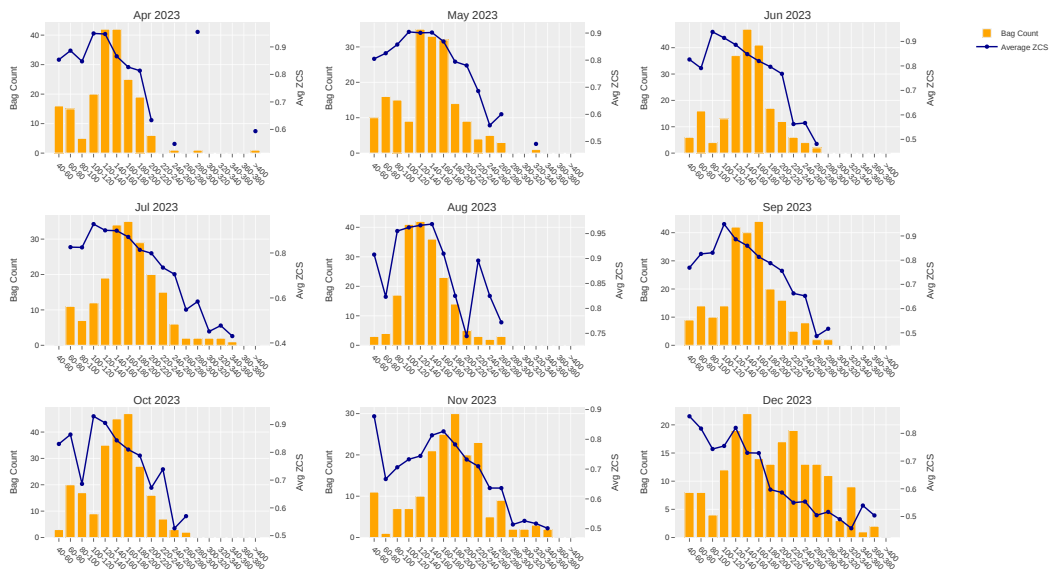


Figure 7: Monthly relationship between parcel volume per bag and Zone Consistency Score (ZCS)

Route-Level vs. Bag-Level Stability. This section compares ESI dynamics at two levels of granularity to assess how modular structures respond to operational stress.

- **Route-Level ESI (2-digit)** typically displays flat or repetitive trends over time. While modular integrity appears stable under average workloads, it often deteriorates sharply as volume increases (Figure 8). This pattern suggests structural rigidity—likely due to fixed bike-to-route assignments or limited buffering mechanisms—and reinforces earlier evidence of spillovers and temporal diffusion.

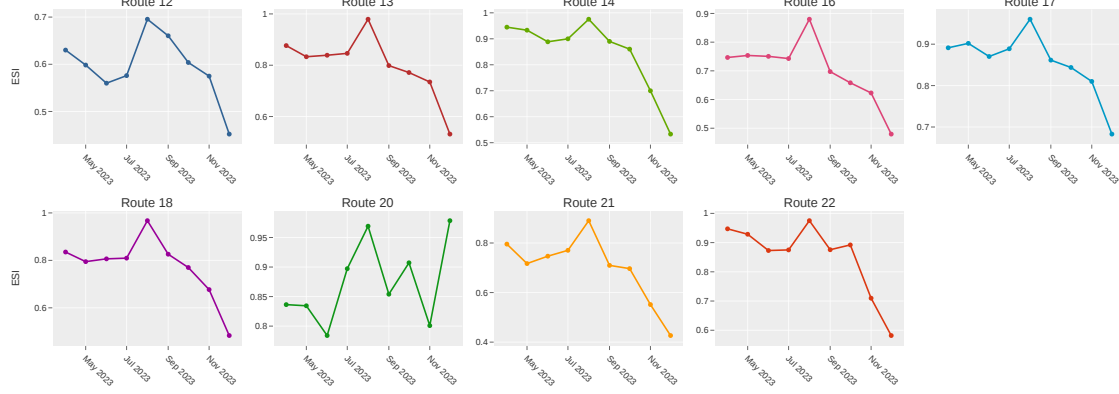


Figure 8: Route-Level ESI

- **Bag-Level ESI (4-digit)** reveals more differentiated behavior. While some zones maintain high ESI over time (≈ 1), others exhibit clear sensitivity to rising volumes—particularly in later months. These declines align with drops in the Zone Consistency Score (ZCS) at higher bag loads (Figure 9), where modular coherence weakens. Although the magnitude and onset of degradation vary, the broader trend remains consistent: systems that lack flexibility in handling volume exhibit reduced encapsulation stability under operational stress.

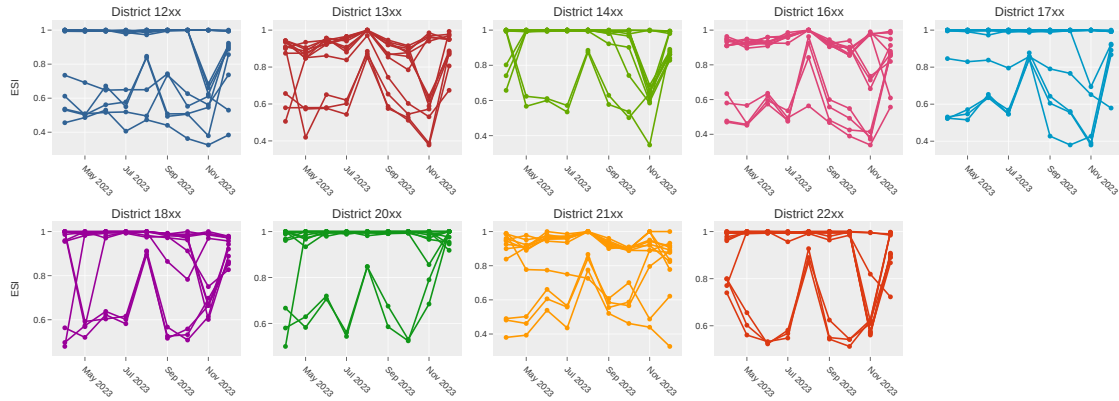


Figure 9: Bag-Level ESI

Diagnostic and Design Implications. Beyond being a performance metric, ESI serves as a diagnostic tool for assessing modular system resilience. While static indicators like ZCS may suggest effective encapsulation, ESI reveals its stability under fluctuating conditions—particularly volume stress. This distinction is critical for evaluating system readiness in line with Physical Internet (PI) principles. The interaction between volume and modularity translates into actionable guidance:

- Zones with declining ESI and ZCS under high load may benefit from targeted interventions—such as pre-sorting or adaptive buffering—while stable zones offer replication templates and baselines for modular policy design.

- Zones exhibiting stable ESI across conditions can serve as reference models for scalable modular practices or as pilots for plug-and-play deployment.

Ultimately, ESI reframes the question from “*how modular is the system?*” to “*how resilient is that modularity under stress?*”—a necessary shift for evaluating scalable, interoperable logistics. Importantly, this analysis reinforces a core principle of the Physical Internet: *scalability must not compromise modular integrity*.

Conclusion. This study advances a data-driven framework for interpreting proto-encapsulation in last-mile delivery through the lens of the Physical Internet (PI). By formalizing the concept of *encapsulation integrity* and examining it across spatial, temporal, structural, and volumetric dimensions, we show that cargo-bike operations—though informal—already reflect emerging modular patterns. Bag-level groupings act as de facto encapsulation units, while urban microhubs mirror PI node behavior by enabling local consolidation and reassignment. Through several metrics, we diagnose the stability, adaptability, and cohesion of these groupings under real-world constraints. Together, these tools outline a practical and modular alignment strategy: one that enhances existing workflows without requiring full standardization. Rather than forcing transformation from above, our approach supports incremental convergence with PI principles—paving a scalable path toward interoperable, resilient urban logistics.

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PIOS (π OS): Operating System for Logistics Nodes

Timothy Tian¹, Xiao Hu²

1, 2: WaterMirror Technology, Shanghai, China

Corresponding author: tianmin@watermirror.ai

Abstract: This paper proposes an innovative framework for a Logistics Nodes Operating System (PIOS, π OS), grounded in the principles of computer architecture and operating systems. By systematically mapping the von Neumann architecture, computer operating system concepts, computer network protocol stacks, and cloud computing paradigms onto the physical logistics domain, we define a logistics node equipped with PIOS (π OS) as a "Physical Computer". We further leverage a layered protocol stack based on the "Open Logistics Interface" (OLI) model to establish hyperconnectivity among these distributed Physical Computers. This framework establishes the foundational infrastructure for the Physical Internet, enabling unified abstraction, resource virtualization, and service standardization across heterogeneous logistics nodes. It provides both a theoretical model and a technical pathway towards achieving global logistics network interoperability and operational efficiency.

Keywords: Physical Internet, PIOS (π OS), Operating System, Physical Computer, OLI, Logistics Node, Hyperconnected Global Logistics Network, Global Logistics Cloud

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

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

1 Introduction

The global logistics system faces a fundamental challenge: the non-standardized management and operation of heterogeneous nodes such as ports, warehouses, sorting centers, among others. These facilities typically operate with isolated, customized systems, mirroring the fragmented hardware landscape of early computing prior to the advent of unified operating systems. This fragmentation results in persistent data silos, resource mismatches, and significant operational inefficiencies. Compounding these issues are critical systemic inefficiencies, evidenced by vehicle underutilization rates often exceeding 40% and facility utilization rates frequently falling below 60%, collectively underscoring the imperative for systemic transformation.

The Physical Internet (PI) emerges as a transformative paradigm, envisioned as a global, open logistics network founded on principles of interconnectivity, standardization, and shared resource utilization – analogous to the digital Internet. Within the PI framework, the diverse facilities of traditional logistics are abstracted based on their primary functions into four standardized node types: π -Gateway, π -Transit, π -Hub, and π -Store (Montreuil et al., 2010). Building directly upon this abstraction and inspired by foundational computer science principles, we propose the Logistics Node Operating System (PIOS, π OS). PIOS serves as a universal software layer that further abstracts these heterogeneous physical nodes into

standardized, programmable computational units – effectively acting as "Physical Computers." Central to realizing the PI vision is a protocol-based system facilitating "packet-switched logistics". This system aims to enable a hyperconnected global logistics network and underpin a "Global Logistics Cloud" capable of providing virtualized, on-demand logistics resources and services.

2 Conceptual Design of the Logistics Node Operating System (PIOS, π OS)

The conceptual design of the Logistics Node Operating System (PIOS, π OS) critically examines and adapts core principles from two foundational pillars of computer science: the von Neumann architecture (von Neumann, 1945; Hennessy & Patterson, 2017) and computer operating systems (Silberschatz et al., 2018).

Inspiration from the von Neumann Architecture

The enduring relevance of the von Neumann architecture lies in its stored-program concept and its unified framework for information processing. It defines a computer system through distinct functional components – Input, Output, Memory, Arithmetic Logic Unit (ALU), and Control Unit – and mandates that both instructions (programs) and data are encoded in a common digital format and stored within a unified memory subsystem. The Central Processing Unit (CPU), acting as the system's core, sequentially fetches, decodes, and executes these instructions, enabling computation through controlled data flow and manipulation (Hennessy & Patterson, 2017).

This architecture provides fundamental inspiration for the PIOS design:

Abstraction of Physical Operations: Complex physical processes within a logistics node (e.g., receiving, storing, sorting, shipping) can be abstracted into digitally definable, storable, and executable entities analogous to computer programs ("process programs") and their associated "state data".

Unified Information Representation & Centralized Control: The von Neumann model underscores that unified digital representation of operational logic and state, coupled with centralized storage and ordered processing control, forms the essential foundation for building an intelligent operational core within logistics nodes.

Core Decision-Making Engine: Analogous to the CPU acting as the computer's "brain," PIOS necessitates a centralized decision-making and coordination engine. This engine is responsible for interpreting logistics "process programs," executing them based on current "state data," and thereby orchestrating the synchronized operation of diverse physical equipment within the node.

Lessons from Computer Operating Systems

A computer operating system (OS) is the core software layer responsible for managing hardware resources, providing essential services to application software, and abstracting hardware complexity to offer a consistent execution environment (Tanenbaum & Bos, 2014). Its fundamental functions include:

Resource Management: Efficient allocation and scheduling of key hardware resources (CPU, Memory, I/O devices, storage) (Silberschatz et al., 2018).

Process/Thread Management: Creation, scheduling, synchronization, and communication between executing programs (processes/threads).

Task Scheduling: Determining the order and timing of process execution to optimize resource utilization and system responsiveness.

Abstraction & Virtualization: Presenting simplified, standardized interfaces to applications while hiding intricate hardware details (e.g., file systems, device drivers).

User/Program Interfaces: Providing mechanisms for user interaction (shells, GUIs) and application programming (APIs, system calls).

This established paradigm offers critical design principles for PIOS:

Resource Abstraction & Management: Similar to an OS managing CPU cycles and memory blocks (Silberschatz et al., 2018), PIOS must abstract heterogeneous physical resources within a logistics node (e.g., storage space, handling equipment, dock doors, labor) into standardized, manageable virtual units. It must provide mechanisms for discovery, allocation, scheduling, and monitoring of these virtualized resources.

Hardware Foundation: The "Physical Computer"

The hardware foundation of the Logistics Node Operating System (PIOS, π OS) is conceptualized as the "Physical Computer." This framework reconceptualizes heterogeneous logistics nodes (e.g., warehouses, ports, hubs) by rigorously mapping their physical infrastructure and functional capabilities onto a five-layer architecture inspired by the von Neumann model:

Input/Output (I/O) Subsystem: Physically embodied by docking stations and intelligent gate systems. Functionally analogous to computer I/O devices (e.g., keyboards, displays, network interfaces), this layer handles the physical ingress and egress of goods and the exchange of data and control signals with external systems and transport units.

Memory Subsystem: Comprising high-density storage systems (shelving, racks, automated storage/retrieval systems - AS/RS) acting as the primary dynamic storage, and designated buffer zones functioning as high-speed registers/caches. This layer is responsible for the temporary or semi-permanent holding of physical goods and associated digital state information.

Arithmetic Logic Unit (ALU) Subsystem: Realized through dedicated computational engines for real-time route planning, optimization algorithms, and decision logic. This layer performs the "computational" tasks essential for logistics operations, such as calculating optimal paths, scheduling resources, and resolving operational constraints.

Control Unit Subsystem: Represented by the core resource scheduling kernel of PIOS. Conceptually comparable to an operating system's process scheduler, this layer orchestrates the overall execution flow. It interprets logistics "instructions" (process programs), manages the state machine of operations, dispatches tasks to equipment, and ensures coordinated execution across the node.

Data Path & Communication Bus: Constituted by the integrated network infrastructure (e.g., industrial IoT networks, control system buses, data communication backbones) interconnecting all subsystems (I/O, Memory, ALU, Control) and physical actuators/sensors. This layer facilitates the exchange of control commands, sensor data, and state information, enabling synchronized operation.

This structured von Neumann-inspired architecture transforms logistics nodes from functionally isolated entities into standardized, programmable units. By providing a unified abstraction layer over diverse physical hardware shown in Table 1, it enables system-wide

resource virtualization and coherent management under the PIOS software layer, fulfilling the vision of the node as a general-purpose "Physical Computer" within the Physical Internet.

Table 1: Correspondence between the von Neumann Architecture and the Physical Computer

von Neumann Architecture	Physical Computer	Description
Input/Output Devices	Docks and Smart Gates	Function as physical input/output interfaces, similar to keyboards/displays
Memory	High-Density Shelving	Serve as dynamically allocated storage, analogous to main memory
Registers	Buffer Zones	Act as fast-access temporary storage for intermediate operations
Arithmetic Logic Unit (ALU)	Route Planning and Optimization Engines	Perform computational tasks like routing, task allocation, and pathfinding
Control Unit	Resource Scheduling Kernel	Orchestrates task execution, similar to an OS process scheduler
Data Path & Bus	Communication Infrastructure Connecting Subsystems	Transfers data between modules, akin to system buses

3 OS Kernel: Virtualization Engine for Logistics Resources

The PIOS kernel implements a resource-centric virtualization paradigm, extending the Unix/Linux philosophy of "everything is a file" to abstract heterogeneous physical assets into Logistics Objects (LOBs). These LOBs represent standardized digital proxies for goods (packages, pallets), equipment (forklifts, AMRs, conveyors), and spatial resources (storage locations, dock doors). Resource management is orchestrated through four core modules:

Logistics Process Management (LPM)

Operational tasks (e.g., "retrieve item A to dock D") are encapsulated as L-Processes – stateful execution entities defined by:

Process Control Block (PCB): Unique PID, priority level, resource allocation map

State Machine: Ready (awaiting resources), Running (executing), Blocked (waiting for I/O/event)

Scheduler: Preemptive priority-based scheduling dynamically interrupts low-priority tasks to execute high-urgency requests (e.g., expedited shipments), overcoming throughput limitations of naive FCFS policies.

Logistics File System (LFS)

Physical storage is virtualized via:

Dynamic Space Partitioning: Shelf zones segmented into fixed-size logical storage pages (e.g., 1 m³ blocks) allocated on-demand based on item dimensions.

Virtual Address Mapping: Creates a unified "Global Virtual Shelf" abstraction, enabling transparent access to distributed storage resources across π -Hubs/ π -Stores.

Page Replacement Policies: Implements LRU (Least Recently Used) algorithms for optimizing buffer zone utilization.

Logistics Metadata Layer (LML)

Lifecycle traceability is ensured through L-Metadata – immutable structured records attached to each LOB shown in Table 2, containing:

Table 2: L-Metadata Structure

Field	Description
Traceability	GS1-compliant identifier chain
Environment	Time-series temp/humidity sensor logs
Operational	Access history, handler IDs, events
Integrity	Cryptographic hash of metadata stack

Updates use a log-structured append-only model, ensuring tamper-evident audit trails and crash consistency.

Unified Device Driver Layer (UDDL)

Hardware heterogeneity is abstracted via:

Standardized Control Interface: Vendor-agnostic APIs for motion control (ROS2-based), sensor polling, and status reporting.

Dynamic Driver Loading: Plug-and-play integration of equipment (e.g., AGVs, robotic arms) via loadable kernel modules (LKMs).

Real-Time Telemetry: Continuous monitoring of device health metrics (e.g., battery levels, error codes) through embedded IoT agents.

4 The Open Logistics Interface (OLI) Model: Enabling Interoperability for the Physical Internet

Inspired by the foundational role of the TCP/IP suite and OSI model in enabling universal digital connectivity (Armbrust et al., 2010; Mell & Grance, 2011), the Physical Internet (PI) conceptualizes a standardized architecture for global logistics (Montreuil et al., 2012). Building upon this vision shown in Table 3, we adopt the Open Logistics Interface (OLI) model as the core protocol stack enabling interoperability between PIOS-governed "Physical Computers."

The OLI model adopts a layered abstraction mirroring network principles, defining distinct functional scopes:

Physical Layer: Governs the movement and manipulation of physical entities (π -containers, goods) within nodes and across transport links. Includes sensing/actuation interfaces.

Link Layer: Ensures operational integrity through real-time consistency checks between physical operations and their digital twins. Detects/corrects deviations (e.g., misloads, damage).

Network Layer: Manages internode connectivity and path integrity. Provides routing within/across π -networks while preserving service-level agreements (SLAs) defined by upper layers.

Routing Layer: Determines optimal inter-node paths for π -containers based on efficiency, reliability, cost, and priority constraints. Abstracts transport/handling services.

Shipping Layer: Orchestrates end-to-end fulfillment of orders (sets of π -containers) from origin to final recipient, ensuring coordination across legs and modes.

Encapsulation Layer: Standardizes the packaging of goods into uniquely identified, PI-compliant π -containers prior to network entry.

Logistics Web Layer: Provides the user/service interface for logistics applications (e.g., booking, tracking, billing) via standardized APIs.

Integration with PIOS & Value Proposition:

The protocol stack based on OLI model is natively implemented within each PIOS instance. PIOS acts as a protocol processor, executing layer-specific logic for both internal operations and cross-node communication. This integration delivers:

Universal Interoperability: The protocol stack based on OLI model serves as a lingua franca, enabling seamless interaction between heterogeneous PIOS nodes, eliminating traditional silos.

Modular Evolution: Decoupled layers allow independent upgrades (e.g., new handling tech at L1 without impacting L3 routing).

Network-Wide Optimization: Standardized data exposes global state, enabling coordinated optimization of routing, resource allocation, and capacity.

Simplified Ecosystem Integration: Well-defined layer interfaces drastically lower barriers for onboarding new nodes/services.

Deeply integrated with PIOS, the protocol stack based on OLI model forms the essential nervous system of the Physical Internet. It transforms isolated logistics nodes into cooperative, intelligent components of a globally efficient, resilient, and sustainable hyperconnected network.

Table 3: Open Logistics Interface Model

Layer	OSI Model	TCP/IP: Digital Internet	OLI Model: Physical Internet
1	Physical	Physical	Physical
2	Data Link	Data Link	Link
3	Network	Network	Network
4	Transport	Transport	Routing
5	Session	Application	Shipping
6	Presentation		Encapsulation
7	Application		Logistics Web

5 Towards a Logistics Cloud: Virtualization and Service Orchestration

Inspired by virtualization's transformative impact in distributed computing (Barham et al., 2003; Buyya et al., 2009), this work extends the paradigms of resource abstraction, dynamic provisioning, and cloud service models to global logistics networks. Modern computing leverages internet connectivity to form virtualized resource pools, enabling scalable, on-demand cloud services (IaaS, PaaS, SaaS) decoupled from physical infrastructure. Analogously, we propose a cloud-inspired architecture for the Physical Internet:

Hyperconnected Network Fabric

Logistics nodes, operating as autonomous "Physical Computers" under the Physical Node Operating System (PIOS, π OS), interconnect via the Open Logistics Interface (OLI) model protocol stack. This standardized framework enables secure smart physical packets exchange, semantic interoperability, and coordinated control, forming an Open Hyperconnected Logistics Network – a federated ecosystem analogous to internet-connected compute clusters.

Unified Resource Virtualization

Mirroring computational virtualization, heterogeneous physical assets within nodes (e.g., storage space, material handling equipment, transport capacity, human operators) are abstracted by PIOS into standardized virtual resource units. These units form globally addressable resource pools, enabling:

- Dynamic Partitioning/Aggregation (e.g., combining storage across nodes)
- On-Demand Allocation based on real-time service requests
- Multi-Tenancy with isolated QoS guarantees

Logistics-as-a-Service (LaaS) Orchestration

Leveraging virtualized resources and the Open Hyperconnected Logistics Network, PIOS orchestrates elastic service delivery through layered abstractions shown in Table 4:

Table 4: Logistics-as-a-Service (LaaS) Layered Abstractions

Service Layer	Function	Examples
Infrastructure (IaaS)	Virtualized logistics resources	Virtual Warehouse (vWaaS), Transport Capacity (TCaaS)
Platform (PaaS)	Execution environment for logistics workflows	Route Optimization Engines, Digital Twin APIs
Application (SaaS)	End-user logistics applications	Integrated Fulfillment (IFaaS), Predictive Analytics (PAaaS)

Architectural Impact:

This framework shifts logistics from asset-centric silos to a service-oriented paradigm:

- Virtualization maximizes asset utilization and enhances resilience through resource pooling.
- OLI model based Open Hyperconnected Logistics Network ensures vendor-agnostic interoperability and global scalability.
- LaaS Model enables on-demand access to a global logistics resource cloud, driving unprecedented supply chain agility, efficiency, and cost optimization.

6 Challenges and Outlook

Critical Challenges

The realization of the PIOS framework and its integration into the Physical Internet faces significant hurdles requiring focused attention:

6.1.1 Security and Trust Assurance

The hyperconnected nature of the Open Hyperconnected Logistics Network introduces pervasive attack surfaces (e.g., data integrity breaches, unauthorized node access, supply chain attacks). Mitigating these necessitates hardware-rooted security integrated into PIOS, leveraging primitives such as Physical Unclonable Functions (PUFs) for device authentication

and Trusted Platform Modules (TPMs) for secure key storage and attestation. End-to-end encryption and zero-trust architectures are essential for securing data in transit and at rest across the network.

6.1.2 Standards Interoperability

Achieving seamless global operation mandates strict compliance and interoperability with established international logistics standards. This includes, but is not limited to:

- ISO 18185 (Electronic container seals)
- GS1 standards (Identification, barcoding/RFID, data sharing)
- ISO/IEC 15459 (Unique identifiers for transport units)
- Domain-specific protocols for IoT (MQTT, CoAP) and robotics (ROS).

Bridging semantic gaps between legacy systems and PIOS/OLI model is paramount for adoption.

6.1.3 Cross-Border Regulatory Harmonization

The global scope of PI necessitates overcoming heterogeneous customs regulations, trade compliance frameworks (e.g., AEO, C-TPAT), and data sovereignty laws across jurisdictions. Developing adaptive PIOS modules capable of dynamically configuring workflows to satisfy diverse international legal requirements is a complex but critical enabler for frictionless transnational logistics.

Key Future Research Directions

Building upon the PIOS foundation, promising avenues for advancement include:

6.2.1 Distributed Edge Intelligence:

Embedding real-time analytics and decision-making capabilities directly within PIOS nodes ("Edge Logistics Computing") will minimize latency for time-critical operations (e.g., dynamic rerouting, fault response). This requires lightweight ML models and distributed consensus protocols optimized for resource-constrained node hardware.

6.2.2 Logistics Metaverses via Digital Twins:

Developing high-fidelity, network-scale Logistics Digital Twins synchronized with the physical Open Hyperconnected Logistics Network enables:

- Proactive simulation and mitigation of global supply chain disruptions
- "What-if" scenario planning for resilience optimization
- Virtual commissioning and testing of new node configurations or protocols.

This demands advanced multi-scale modeling and real-time data integration capabilities.

6.2.3 AI-Driven Sustainable Logistics

Leveraging the PIOS's global visibility and control to minimize environmental impact through:

Dynamic Carbon-Aware Routing: AI algorithms optimizing routes in real-time for minimal fuel consumption/emissions, incorporating traffic, weather, and vehicle type.

Resource Pooling Efficiency: Maximizing asset utilization (vehicles, storage) across the network to reduce idle capacity and associated waste.

Circular Economy Integration: Enabling transparent tracking and optimized reverse logistics for reuse/recycling.

Addressing these challenges and pursuing these directions is essential for transforming the PIOS/OLI model framework from a theoretical model into a robust, globally operational infrastructure for the Physical Internet, ultimately enabling sustainable, resilient, and hyper-efficient logistics.

Conclusion

This paper has presented the Logistics Node Operating System (PIOS, π OS) as a foundational framework for realizing the Physical Internet (PI) vision. By systematically reinterpreting and mapping core principles of computer architecture (von Neumann model), operating system kernels (resource virtualization, process management), and networking stacks (layered protocols) onto the logistics domain, PIOS resolves the fundamental challenge of interoperability across heterogeneous logistics nodes – the "Tower of Babel" problem plaguing global supply chains.

The dual pillars of this architecture are:

The "Physical Computer": A standardized architectural abstraction transforming diverse logistics nodes (π -Gateway, π -Hub, etc.) into programmable, resource-virtualized units.

The Open Logistics Interface (OLI) model: A layered protocol stack enabling secure, semantic interoperability and coordinated control between PIOS-managed nodes, forming the Open Hyperconnected Logistics Network.

Together, PIOS and Open Logistics Interface (OLI) model endow the global logistics network with the essential properties of the digital Internet:

- **Openness:** Vendor-agnostic integration via standardized interfaces.
- **Programmability:** Dynamic control and orchestration of physical workflows.
- **Scalability:** Modular expansion enabled by layered abstraction.
- **Virtualization:** Efficient on-demand resource provisioning.

This convergence of computational paradigms and physical logistics enables the paradigm shift towards Logistics-as-a-Service (LaaS). When standardized π -containers flow as securely encapsulated, intelligently routed units across the Open Hyperconnected Logistics Network – analogous to IP packets traversing the Internet – logistics transitions from fragmented, asset-bound operations to a globally integrated, service-oriented utility.

The true transformation lies not merely in data exchange, but in encoding operational intelligence into the system itself: "Code governs matter, not just bits." PIOS represents a fundamental architectural renaissance for global supply chains, paving the way for unprecedented levels of efficiency, resilience, and sustainability.

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Accelerating Automotive Lithium-ion Battery Flows via Physical Internet Principles in COSCO SHIPPING's Network

Yumang Ye¹, Timothy Tian², Tao Xia³, Libin Zhang⁴, Qiuyuan Sheng⁵, Wanqing Yang⁶

1, 3, 4, 5, 6: COSCO SHIPPING Logistics Supply Chain, Shanghai, China

2: WaterMirror Technology, Shanghai, China

Corresponding author: yeym@coscologistics.sh.cn

Abstract: The global logistics of automotive lithium-ion batteries present critical challenges regarding efficiency, transparency, and sustainability. This paper introduces a Physical Internet (PI)-oriented optimization framework to address these issues in end-to-end cross-border transport, validated via COSCO SHIPPING's "China–Europe" service. The framework's core contributions include the integration of standardized modular packaging to enhance asset utilization and reduce waste, and dynamic multi-objective optimization for resilient intermodal routing. Key findings from empirical validation demonstrate significant improvements: the system achieved a 23% compression in empty-container volume and reduced packaging costs to 16.7% of baseline levels. Additionally, traceability efficiency was enhanced by 83%, transit times were shortened by up to 42 hours, and the overall carbon footprint was lowered by 26%. These results underscore the PI framework's capacity to markedly improve operational efficiency, transparency, and sustainability in automotive lithium-ion battery supply chains, offering a reproducible paradigm for global high-value goods logistics.

Keywords: Physical Internet; Automotive lithium-ion batteries supply chain; Standardized modular packaging; Collapsible returnable container; Multimodal transport optimization

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

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

1 Introduction

The rapid expansion of the global electric-vehicle industry has driven an equally sharp rise in international demand for automotive lithium-ion battery logistics. Transporting these batteries, however, faces four persistent challenges: (i) capacity bottlenecks and high costs—particularly for packaging and regulatory compliance; (ii) significant environmental burdens from carbon emissions and solid waste (Farasis Energy, 2022); (iii) complex safety and traceability requirements; and (iv) limited end-to-end visibility. To address these issues and strengthen supply-chain resilience and sustainability, COSCO SHIPPING Logistics has embedded core Physical Internet (PI) principles (L'Internet Physique, 2014) into its "China battery plant → European OEM" end-to-end service. PI can be viewed as the "next-

generation Internet of logistics,” enabling open and efficient asset sharing across networks (Montreuil, 2011).

2 Related Work

The logistics of automotive lithium-ion batteries, critical components in the burgeoning electric vehicle and renewable energy sectors, have garnered increasing research attention. Existing studies predominantly focus on specific facets of this complex supply chain. For instance, considerable work has addressed packing and handling solutions to enhance safety and comply with stringent dangerous-goods regulations (PHMSA, 2021; China Battery Industry Association, 2023). Advanced container designs with improved thermal management and impact resistance have been proposed to prevent fires and damage in transit (PHMSA, 2021). In parallel, efforts to reduce environmental impact through reusable packaging have been explored. Other research streams concentrate on optimizing transportation modes and routes, often employing simulation or mathematical modeling to minimize costs or transit times for specific corridors (Regattieri, 2015; Farasis Energy, 2023). Industry case studies, such as Farasis Energy (2023), document how tailored intermodal route planning for EV battery shipments can yield substantial cost and time savings on China–Europe lanes. Furthermore, traceability and regulatory compliance have been explored through technologies like RFID and IoT for real-time tracking, with preliminary blockchain applications piloted to improve data transparency and security (GS1, 2023; China Automotive Battery Research Institute, 2023). Global standards bodies (GS1, 2023) have developed universal identifiers to enable end-to-end tracking, and recent industry white papers describe blockchain-based systems to share battery lifecycle data among stakeholders (China Automotive Battery Research Institute, 2023).

However, these approaches often exhibit significant limitations. Firstly, many existing methods tackle challenges in isolation, lacking a holistic, end-to-end systemic perspective. Improvements in one segment (e.g. safer packaging) may not be integrated with upstream or downstream processes, thus diminishing potential efficiency gains (Montreuil, 2011). For example, an innovative battery package design might not align with optimized container loading or intermodal transfer operations, leading to suboptimal overall performance. Secondly, a predominant focus on incremental improvements within traditional logistics paradigms often fails to address fundamental inefficiencies related to asset sharing, interoperability, and network-wide visibility. Current automotive lithium-ion batteries logistics systems frequently suffer from fragmented data silos, proprietary handling systems, and inefficient empty-container repositioning (CIMC Group, 2022), resulting in underutilized capacity and avoidable environmental impacts (Farasis Energy, 2022). Thirdly, while digitalization efforts are underway, they often lack the comprehensive integration and security necessary for seamless and trustworthy cross-border operations. In practice, data exchange among multiple parties remains limited, and sensitive battery information cannot freely circulate due to privacy and regulatory concerns. These gaps make it difficult to achieve true end-to-end visibility and coordination under conventional approaches.

3 Physical Internet: Conceptual Foundations

The Physical Internet is a revolutionary paradigm for logistics and supply-chain operations. Mirroring the Digital Internet’s ethos of openness, standardization, interoperability, and sharing, PI seeks to create a worldwide, intelligent, open logistics network. By combining (i) standardized, modular cargo units, (ii) networked infrastructure, and (iii) smart operational governance, PI enables physical assets to flow with the efficiency, transparency, traceability,

cost-effectiveness, and sustainability characteristic of data packets—thereby cutting total logistics cost (economic and environmental) and fortifying supply-chain resilience.

4 COSCO SHIPPING’s PI-Enabled Practice: Core Measures and Outcomes

Standardization and Modular Foundations

Container innovation and PI compatibility. Departing from the “wooden pallet + carton” paradigm shown in Figure 1, we designed a PI-compliant unit shown in Figure 2: a *plastic pallet base* plus a *collapsible pallet box* with a modular nesting frame. The design conforms to ISO 668 and related standards.

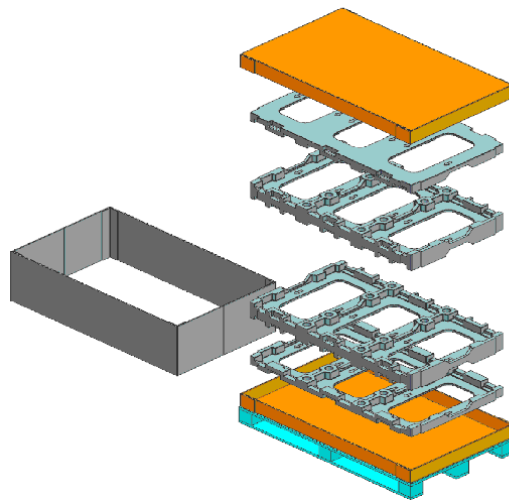


Figure 1 Original Packaging Container: Wooden pallet + Carton + Nestable Design

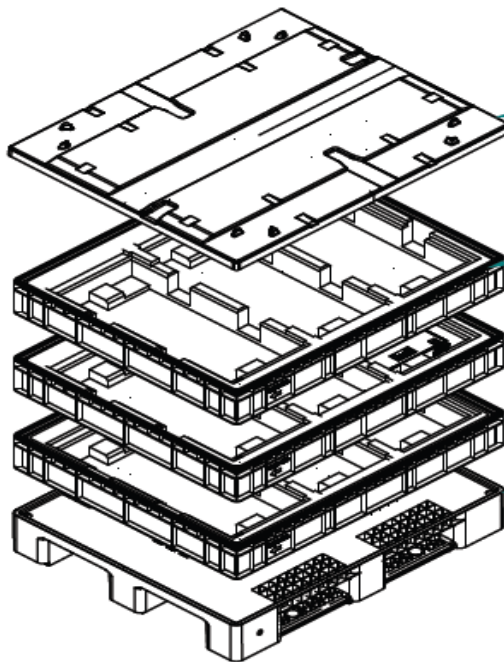


Figure 2 *Modified Packaging Container: Plastic Pallet + Collapsible Crate/Returnable Container + Nestable Design*

Outcomes. Multimodal compatibility improved significantly; collapsibility yields a 23 % reduction in empty-container volume; loading density for battery modules rose from 78 % to 92 %, providing a robust foundation for cross-docking operations.

Life-Cycle Benefit Optimization

Materials and reuse. High-density recycled HDPE is used for the container, combined with an efficient pooling mechanism (average cycle count = 6) and a dedicated reverse-logistics network.

Outcomes. Packaging solid waste fell by 83.3 %, per-cycle packaging cost dropped to 16.7 % of the baseline, packaging-related carbon emissions declined by 41 %, and Extended Producer Responsibility (EPR) compliance cost was cut by 28 %, achieving concurrent economic and environmental gains.

Digital Traceability and Network Collaboration

Digital-twin–based four-dimensional tracking. A PI digital-twin model captures spatial location, temporal node, quality status, and accountable party throughout the chain.

Technologies. “Dual-code” (physical + digital) labels shown in Figure 3, GIS + BeiDou positioning, BMS data streaming, and blockchain smart contracts.



Figure 3 *Current Traceability Code for Automotive Lithium-Ion Battery Logistics*

Outcomes. Real-time, transparent traceability from production line to vehicle installation; 83 % faster traceability and 65 % lower recall cost.

Cross-Border Data Security and Compliance Sharing

Technical architecture. A PI data gateway combines edge computing, homomorphic encryption, zero-knowledge proofs, and IPFS decentralized storage to meet EU GDPR and related regulations.

Outcomes. Sensitive data remain “usable yet invisible” during cross-border flow, preserving data sovereignty and earning TÜV SÜD certification.

Industry sharing. COSCO SHIPPING promotes an “outer-box standardization + inner-liner customization” model, leading a China–EU battery-packaging pool and co-drafting technical standards to accelerate regional PI networks.

Intelligent Warehousing and Networked Path Optimization

Dynamic PI network planning. The linear point-to-point model is replaced by a dynamic “dual hubs (China central DC, EU gateway hub) + multiple en-route relay DCs” structure.

Smart decision support. An NSGA-II Pareto multi-objective algorithm minimizes total economic cost, warehouse occupancy, and out-of-stock risk, providing real-time inventory positioning and route optimization across the PI cloud.

Definition

- R_i The full-rent of warehouse i during the project period;
- Z_i The handling cost per unit of goods in warehouse i ;
- F_j The total delivery volume from factory F to warehouse A in week j ;
- C_i The transportation cost per unit of goods between warehouse i and warehouse $i + 1$;
- O The customs declaration cost per unit of goods;
- S The dangerous goods declaration cost per unit of goods;
- $T_{j,i}$ The dwell time of goods at location i in week j ;
- Q_i The storage cost per unit of goods per unit of time in the dock or dangerous goods warehouse;
- K_2 The European T1 transit cost per unit of goods from port E to warehouse B ;
- K_3 The European T1 transit cost per unit of goods from warehouse B to warehouse C ;
- $x_{i,j}$ The inventory quantity of warehouse i in week j ;
- x_{i0} The initial inventory quantity of warehouse i in the project;
- U The customs clearance cost per unit of goods;
- W The freight forwarder agency fee per unit of goods at the port of destination;
- V_i The maximum storage capacity of warehouse i ;
- M_i The maximum unit transportation capacity of goods between warehouse i and warehouse $i + 1$ or within the customer factory;
- D_j The demand of consumer in week j ;

m The total number of warehouses in the logistics network;

n The number of discrete planning periods in the planning horizon;

The main objective is to minimize the economic cost in the project,

$$\begin{aligned} \min_x f_1(x) = & \sum_{i=1}^m R_i + \sum_{j=1}^{n-1} Z_1 F_j \\ & + \sum_{j=1}^{n-1} (C_1 + Z_2 + W + O + S + Q_4 T_{j,4} + Q_5 T_{j,5} + K_2)(x_{2,j+1} + x_{3,j+1} - x_{2,j} - x_{3,j} + D_j) \\ & + \sum_{j=1}^{n-1} (C_2 + K_3 + Z_3)(x_{3,j+1} - x_{3,j} + D_j) + \sum_{j=1}^{n-1} (C_3 + U) D_j \end{aligned}$$

The first secondary objective is to minimize the quantity of a single type of goods stored in warehouse C under the premise of meeting the needs of customer G each week, so as to flexibly allocate the types of goods in warehouse C:

$$\min_x f_2(x) = \sum_{j=1}^n (x_{3,j} - D_j)$$

The second secondary objective is that the storage capacity of warehouse A should be greater than the sum of the goods delivered by factory F each time.

$$\min_x f_3(x) = \sum_{j=1}^n (x_{1,0} - x_{2,j+1} - x_{3,j+1} + x_{2,j} + x_{3,j} - D_j)$$

Constraint Conditions:

- (1) The quantity of goods shipped from warehouse A to warehouse B each week cannot exceed the storage capacity of warehouse A;

$$x_{2,j+1} + x_{3,j+1} - x_{2,j} - x_{3,j} + D_j \leq V_A, \quad \forall j \in J$$

- (2) The quantity of goods shipped from warehouse B to warehouse C each week cannot exceed the storage capacity of warehouse B;

$$x_{3,j+1} - x_{3,j} + D_j \leq V_B, \quad \forall j \in J$$

- (3) The maximum storage capacity of warehouse C must be sufficient to fulfill the demand of customer G each week;

$$V_C \geq D_j, \quad \forall j \in J$$

- (4) The quantity of goods shipped from warehouse A to warehouse B each week cannot exceed the maximum unit transportation capacity of goods between warehouses A and B;

$$x_{2,j+1} + x_{3,j+1} - x_{2,j} - x_{3,j} + D_j \leq M_A, \quad \forall j \in J$$

- (5) The quantity of goods shipped from warehouse B to warehouse C each week cannot

exceed the maximum unit transportation capacity of goods between warehouses B and C;

$$x_{1,j} + F_j \leq M_B, \quad \forall j \in J$$

- (6) The outbound transportation capacity of warehouse C must be sufficient to fulfill the weekly demand of each customer;

$$M_C \geq D_j, \quad \forall j \in J$$

- (7) The transportation time of a single automotive lithium-ion battery shipment should be longer than the sum of the transportation time of each segment;

$$T_j^{sum} \geq T_{j,12} + T_{j,23} + T_{j,36}, \quad \forall j \in J$$

Pareto Optimality Criterion:

Pareto optimality is defined as a situation where it is impossible to make one solution better without making another solution worse.

Since the above problem can be expressed as:

$$f(x) = \min_x (f_1(x), f_2(x), f_3(x))$$

Pareto Dominance Relationship:

For any two decision-making box quantities, a', b' , $a' < b'$ (a' dominates b'), if the following two conditions are met:

$$1) f_c(a') \leq f_c(b'), \forall c \in \{1, 2, \dots, N\}$$

$$2) f_d(a') \leq f_d(b'), \exists d \in \{1, 2, \dots, N\}$$

If either of the above conditions is violated, then the decision - making vector a' is inferior to the decision-making vector b' . If a' dominates b' , a' is called a non- dominated solution.

The solution set is: $P = \{x^* \in R^D | \nexists \bar{x} \in R^D\}$

Then, all obtained solutions will lie on the surface shown in the Figure 4 below, collectively forming the Pareto optimal solution set.

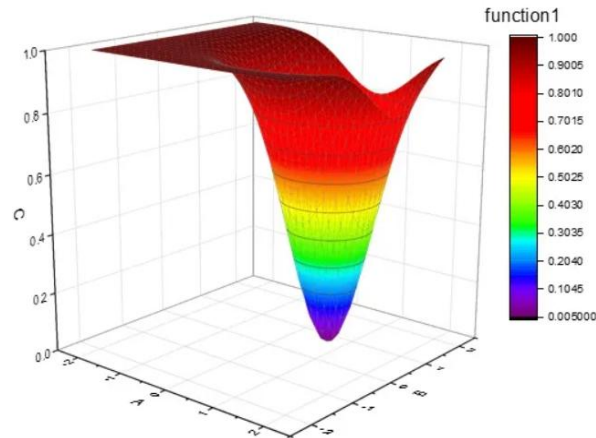


Figure 4 Representation Form of the Three-Objective Pareto-Optimal Solution Set

Integrated Carbon-Reduction and Efficiency Gains

Sea–rail dual-route design. Northern and southern intermodal corridors are continuously simulated and adjusted via PI digital twins.

Outcomes. Northern-route transit time down by 42 h and unit carbon emission by 19 %; southern-route cost per container down by 28 %; total chain carbon footprint reduced by 26 %, achieving joint improvements in efficiency and sustainability.

Conclusion

COSCO SHIPPING’s PI pilot for cross-border automotive lithium-ion battery logistics has successfully embedded standardization, sharing, network integration, and intelligent governance into a complex international supply chain. The system innovation overcomes longstanding bottlenecks in efficiency, cost, and environmental impact while elevating transparency, resilience, and sustainability—materializing PI’s vision of “moving physical assets with the speed and transparency of information.” This case offers valuable guidance for deploying PI in high-end manufacturing and in automotive lithium-ion battery chains worldwide.

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A Decomposition-Based Deep Reinforcement Learning Framework for Omnichannel Replenishment and Fulfillment

Maryam Kolyaei

Supervised by A/P Lele (Joyce) Zhang & Dr Michelle Blom

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OPTiMA

Managing replenishment and fulfillment across multiple sales channels requires carefully balancing inventory flow to minimize stockouts and overstocks. Replenishment involves determining order quantity in cycles, while fulfillment focuses on meeting uncertain demand across channels with limited capacity, both posing significant challenges. We address this problem in large-scale networks and propose a decomposition-based Deep Reinforcement Learning (DRL) algorithm. Our framework enhances demand management, scalability, and efficiency, ensuring robust performance under varying demand conditions.

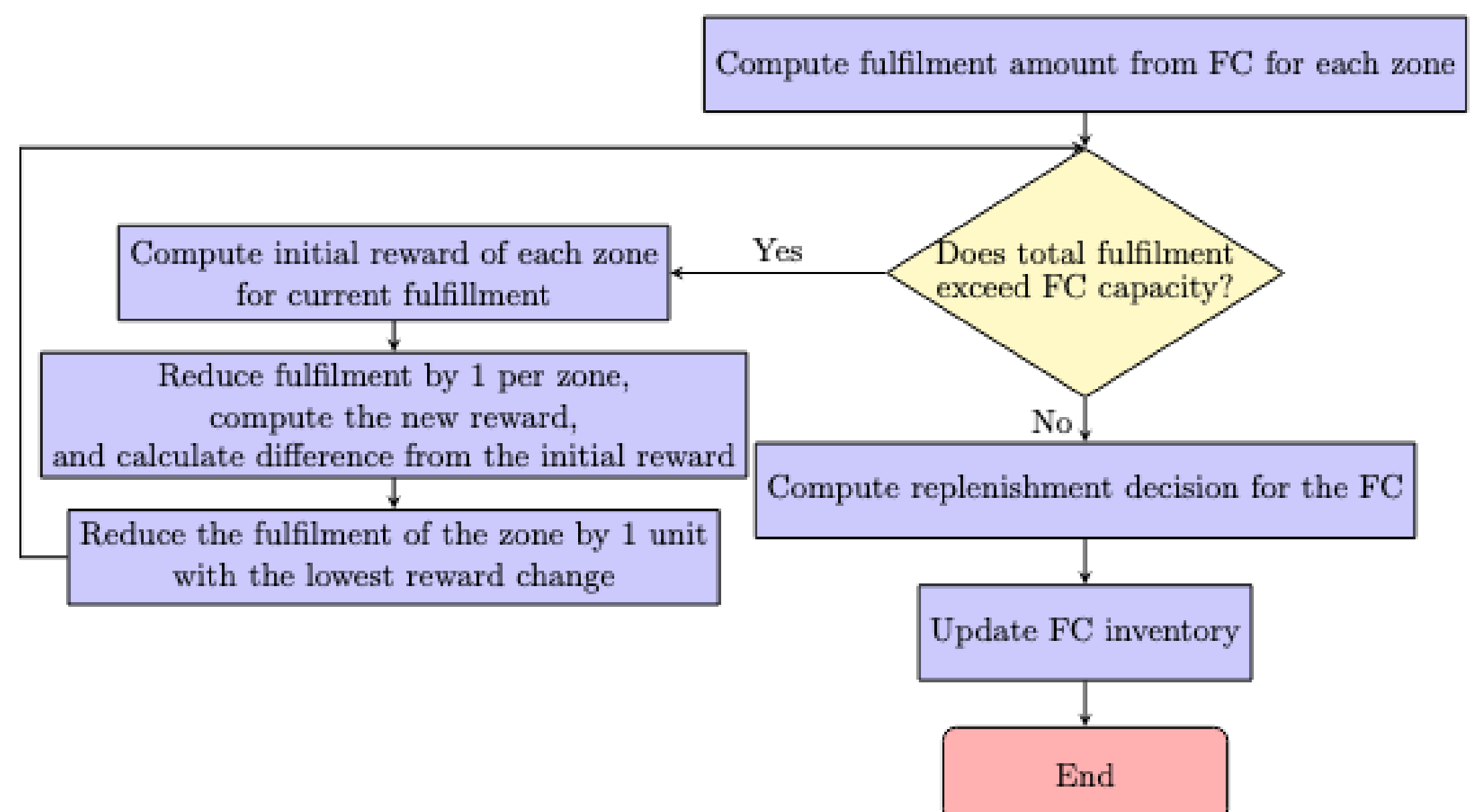
Introduction

In the omnichannel retail network studied, a retailer serves customers through walk-in, home delivery, and Click-and-Collect (C&C) channels. The fulfillment strategy prioritises store customers, due to the higher cost of lost sales in these channels, as observed in real-world operations. Order fulfillment, full, partial, or unfulfilled, depends on stock availability, profitability, and anticipated demand across zones. Online orders can be sourced from either stores or a fulfilment centre (FC). Data are available in (Kolyaei et al. , 2025)

Methodology

We build on the Markov Decision Process (MDP) model for omnichannel replenishment and fulfilment proposed by Kolyaei et al. (2025), who developed a DRL-based method using modified state-action Proximal Policy Optimisation (SA-PPO).

Method: We introduce a new DRL-based method, the product-zone-based decomposition (PZD), for large-scale omnichannel networks. PZD divides the problem into subproblems based on products and zones, each managing replenishment and fulfillment independently. To ensure global feasibility while effectively coupling these subproblems, we propose an iterative fulfillment refinement process. The Figure illustrates this process for each products, at every time steps. Our method is benchmarked against SA-PPO and the perfect information (PI) baseline, which solves a deterministic version of the problem with stochastic demands revealed *a priori*.



The flowchart of the PZD with an Iterative Fulfillment Refinement Process for each product, at every time step.

Results

We compare SA-PPO and PZD based on their objective gaps relative to the PI baseline and policy training time in a network with 2 products and 4, 10, 50, and 100 zones. As shown in the table, PZD outperforms SA-PPO across both metrics. For instance, with 2 products and 10 zones, PZD reduces the objective gap relative to PI by 5% over SA-PPO, while achieving a solution 97% faster. In larger instances exceeding 50 stores, SA-PPO fails to converge to a solution, while PZD remains scalable.

The performance of SA-PPO and PZD. The objective gap is the average percentage relative to the perfect information (PI) for a network with 2 products. Standard deviations are included.

-: means the algorithm was unable to produce a valid output.

Number of stores	Objective gap		Policy training time (hr)	
	SA-PPO	PZD	SA-PPO	PZD
4	9±1	7±1	2.7	0.13
10	13±1	8±1	4.7	0.13
50	-	12±1	-	0.13
100	-	15±1	-	0.13

Further research

The study opens several avenues for future research, including incorporating shipment uncertainties, assessing the impact of different delivery services, and enhancing the explainability of the DRL algorithm.

Analytics of Joint logistics for collecting used battery

YAKATA, Tomoyoshi ^{1,2)}, Gjergj A. Dodbiba ²⁾, YOSHIDA Kotaro^{1,2)}, FUJITA, Toyohisa
1)Shinko Holdings Corp.
2)The University of Tokyo Graduate School of Engineering.

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Introduction

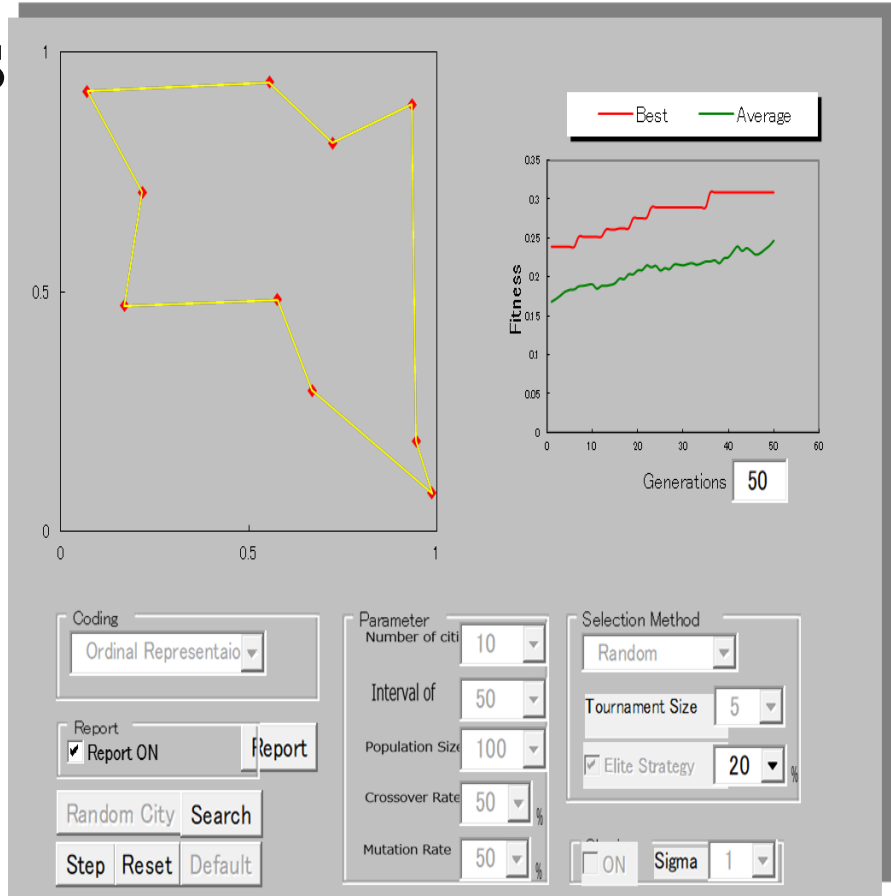
Our group planed used battery recycling. We succeeded in our recycling a dry cell, and making ferrite powder. We also suppose the collecting method for used batteries. We simulated TSP method of Genetic Algorithm. But the calculation has the limit to solve. We suggest the new method to solve the theme. The new method has the peculiar point like not only shorter route but also maximum collection. We discus those points bellow.

Objectives

We would like to decide the model for the joint logistics and collecting used batteries. In the Genetic algorithm, The first priority is shortest route decision. But in our model, in addition to that, the maximization of colleting used battery quantity is the dominant factor. So we must prioritize the amount of dry battery collection in addition to seeking the shortest transportation route when determining the delivery route. The purpose is to optimize joint logistics for the shortest delivery route prioritized for dry battery collection.

Methodology

We calculate the shortest route by TSP model for this case. We encountered the problem followings
①A high crossover rate does not necessarily mean it is good. ②The population size will be capped. For example, a chromosome size of 32 bits suggests that a population size of 32 is preferable. Following graph shows the results of 50 generations and crossover rate of 50% in a random format, and it has better values than any other calculation results.



Results

For the Joint logistics, The determining factor for optimization is not the shortest path. In the collection of used batteries, the amount collected is the primary determining factor. The most suitable delivery course goes around the base with much quantity of collection with precedence, and a course having low quantity of collection is a course to add to the route at the stage when collection quantity reached the optimal amount. This maximizes the collection volume. The model optimized by the TSP is provided by the following formula. Parameter(gathering of distribution centers): $V = \{0,1,2,\dots\}$, d_{ij} : distance of center to center. Variables : $x_{ij} \in \{0,1\}$ If i to j , then substitute 1, not substitute 0. Objective function is $\sum_{i \in V} \sum_{j \in V, i \neq j} d_{ij} x_{ij}$ For Joint logistics, the order charge amount of the delivery base is necessary for quantity of collection of the used battery.

Conclusions

Conclusions: We tried to get optimization of joint logistics model by corrected TSP. But as we mentioned on the results above, For joint logistics, especially collecting used battery in the case of using delivery services, We need to prioritize maximizing the recovery quanti. If so, Since the optimization model is based on recovery quantity rather than the shortest path, it is optimal to find large facilities with a high recovery quantity along the shortest path, create a network, and then traverse the shortest path solved by TSP. This also resolves the bit problem in TSP, enabling the optimization of collaborative logistics.

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Physical Internet-enabled Pitting Defect Detection in Gears Using Dual-Module Kolmogorov-Arnold Network

Dejun Xi, Baotong Zhang, Yi-jia Wang

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Introduction

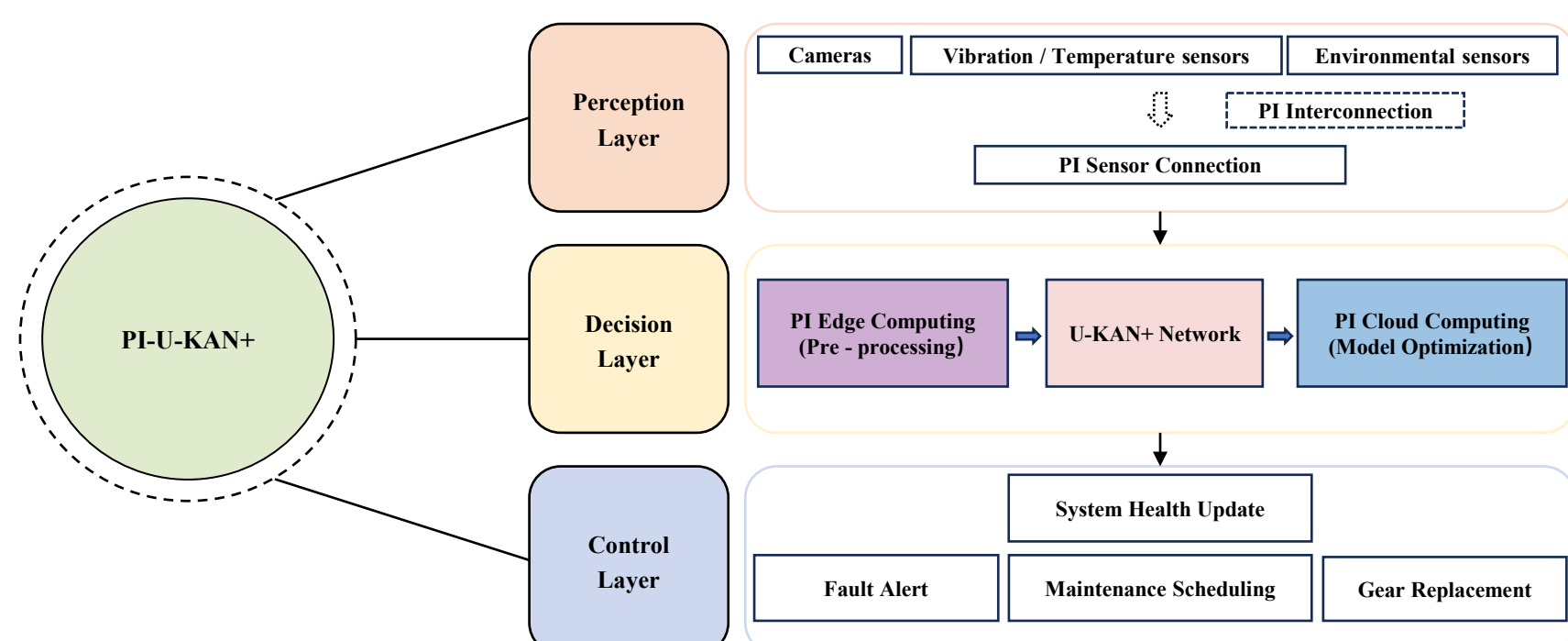
In the landscape of industrial intelligent operation and maintenance under the Physical Internet (PI) framework, early detection of key component defects in mechanical equipment has emerged as a critical cornerstone for realizing smart manufacturing ecosystems. Specifically, pitting defects in gears pose unique challenges: their small size, complex background interference, multi-scale distribution, and susceptibility to oil stain noise lead to high false negative rates in traditional detection methods. The Physical Internet, as a next-generation paradigm emphasizing end-to-end connectivity and real-time data fusion, provides a novel framework to address these issues by integrating sensor networks, edge computing, and intelligent decision-making systems.

Related work

While KANs (Kolmogorov-Arnold Networks) have shown promise in interpretable defect recognition, their integration with PI principles remains underexplored. The PI's architecture—featuring PI Networks for seamless data transmission and Logistics/Commercial Data Platforms for unified information management—offers potential to enhance KAN-based detection systems. For instance, PI's emphasis on interoperable data interfaces and edge-cloud collaboration aligns with the need for real-time, scalable gear inspection in smart factories.

Method

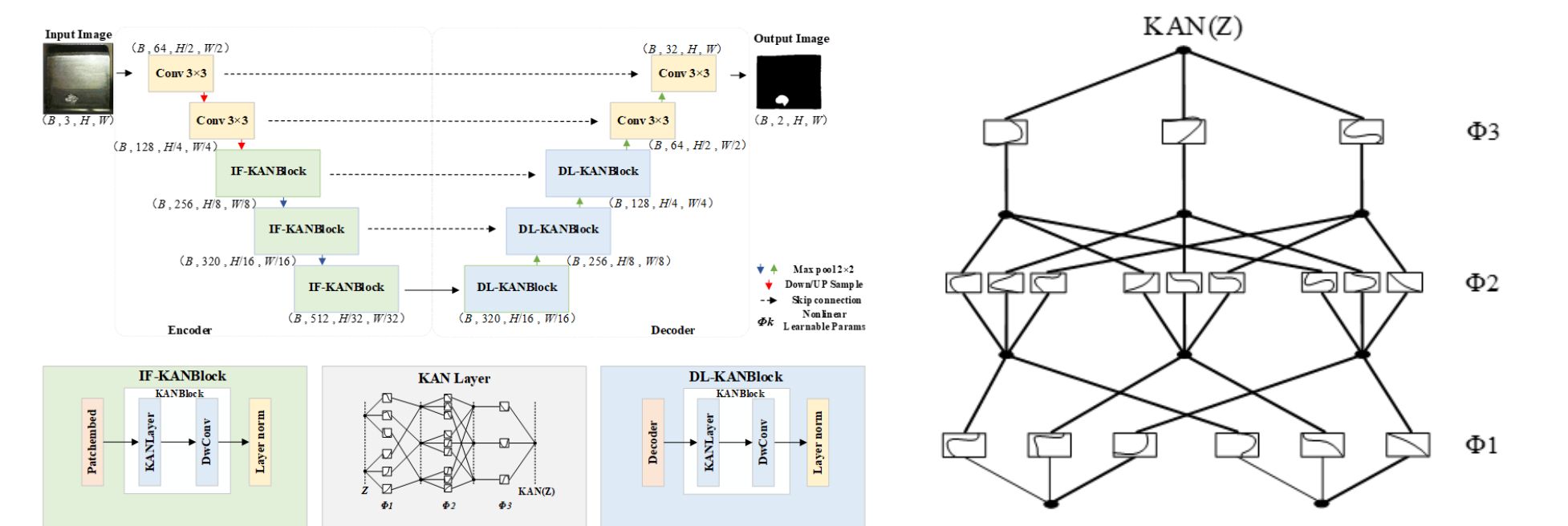
We have presented a physical Internet-enabled method for detecting pitting defects in gears. Dual-module Kolmogorov-Arnold network (U-KAN+) is used for gear pitting detection. By designing the Industrial Feature Enhancement Module (IF-KAN) and the Defect Localization Module (DL-KAN), we enhance the extraction of surface texture features and the identification of defect boundaries respectively.



Sensor Fusion via PI Principles: The Industrial Feature Enhancement Module (IF-KAN) implicitly leverages PI's sensor interconnection concepts, enabling integration of multi-source data (e.g., visual imagery, vibration signals) for comprehensive feature extraction.

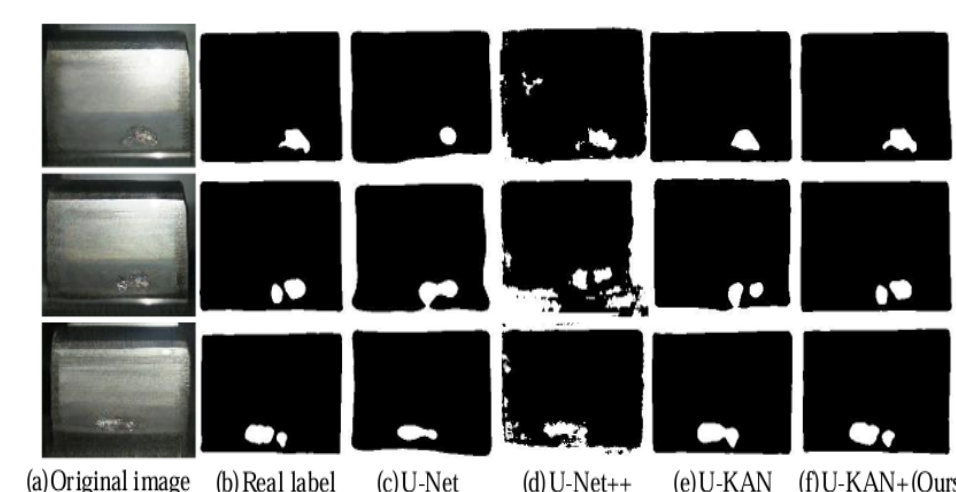
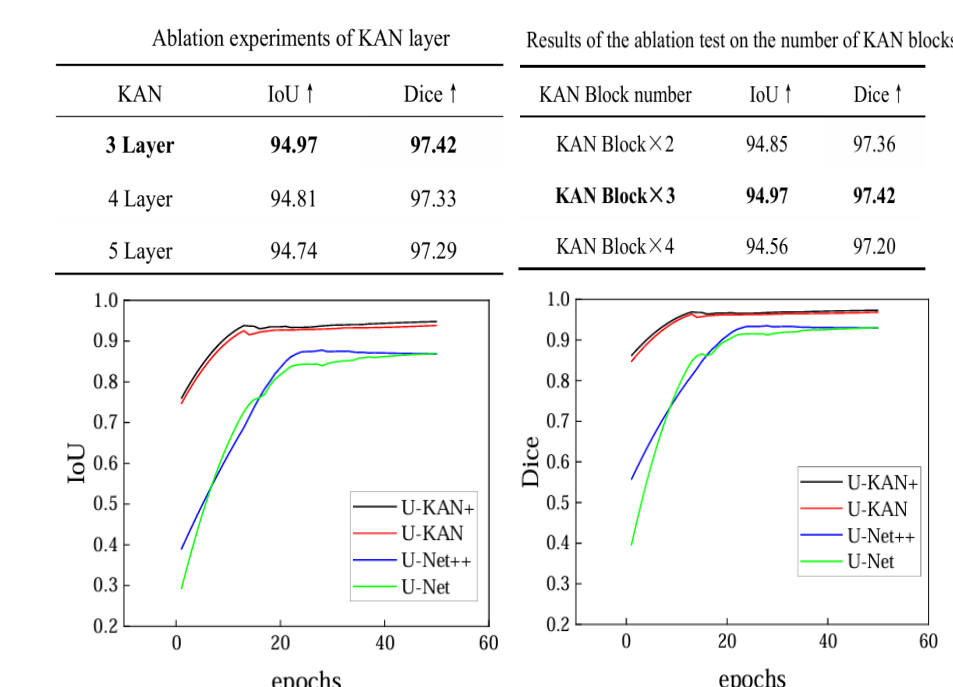
Edge-Cloud Collaborative Framework: The network's cross-level skip connections and modular architecture echo PI's edge computing philosophy, facilitating low-latency processing of

gear surface data while maintaining cloud-based model optimization capabilities.



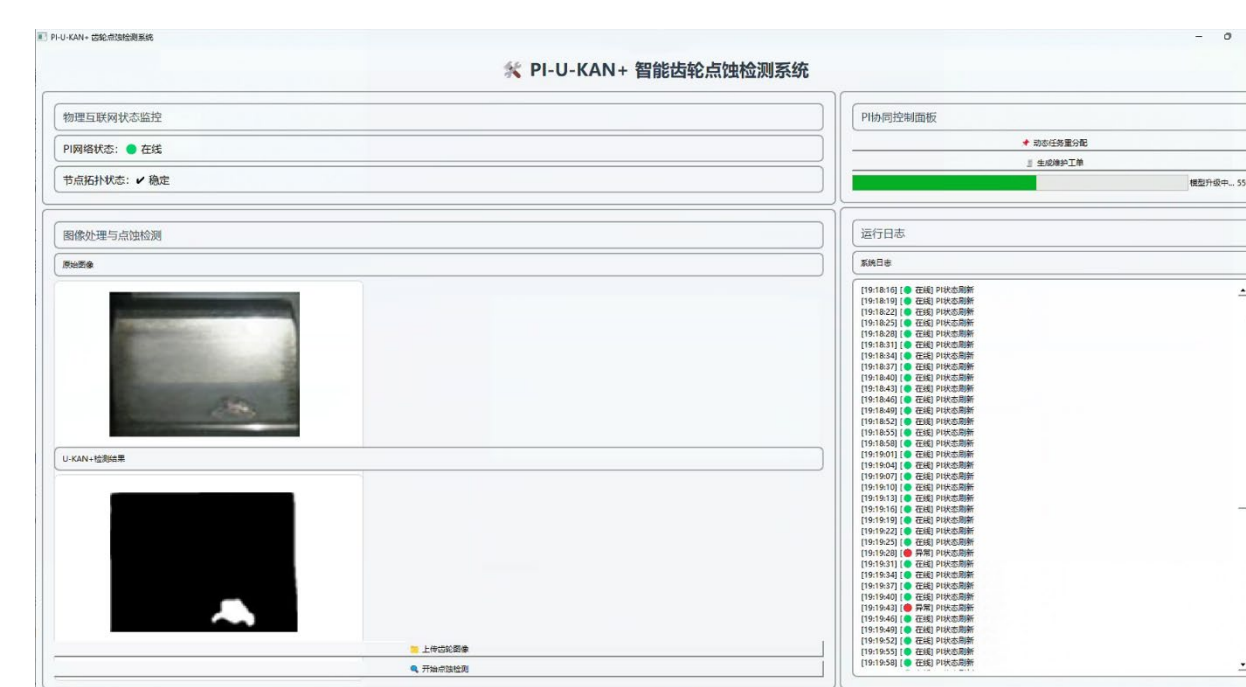
Experiments

The experiments conducted on the dataset GearPitting for gear pitting data and in the public library of industrial components have shown that, compared with models such as U-Net and U-KAN, this model maintains a high IoU index while improving the Dice coefficient, and also has an enhanced convergence speed. The ablation experiments have verified the effectiveness of the KAN layer in detecting minor defects, and the visualization analysis has confirmed that the network can effectively focus on the micrometer-level pitting areas, providing a reliable solution for industrial non-destructive testing.



Results

Compared with the traditional method, the segmentation result of U-KAN + with PI is closest to the true label, which can better reflect the best performance of this method. In addition to comparing the segmentation accuracy of different models, the detection efficiency of the proposed detection method with other models for each pitting image is further compared through the application interface.



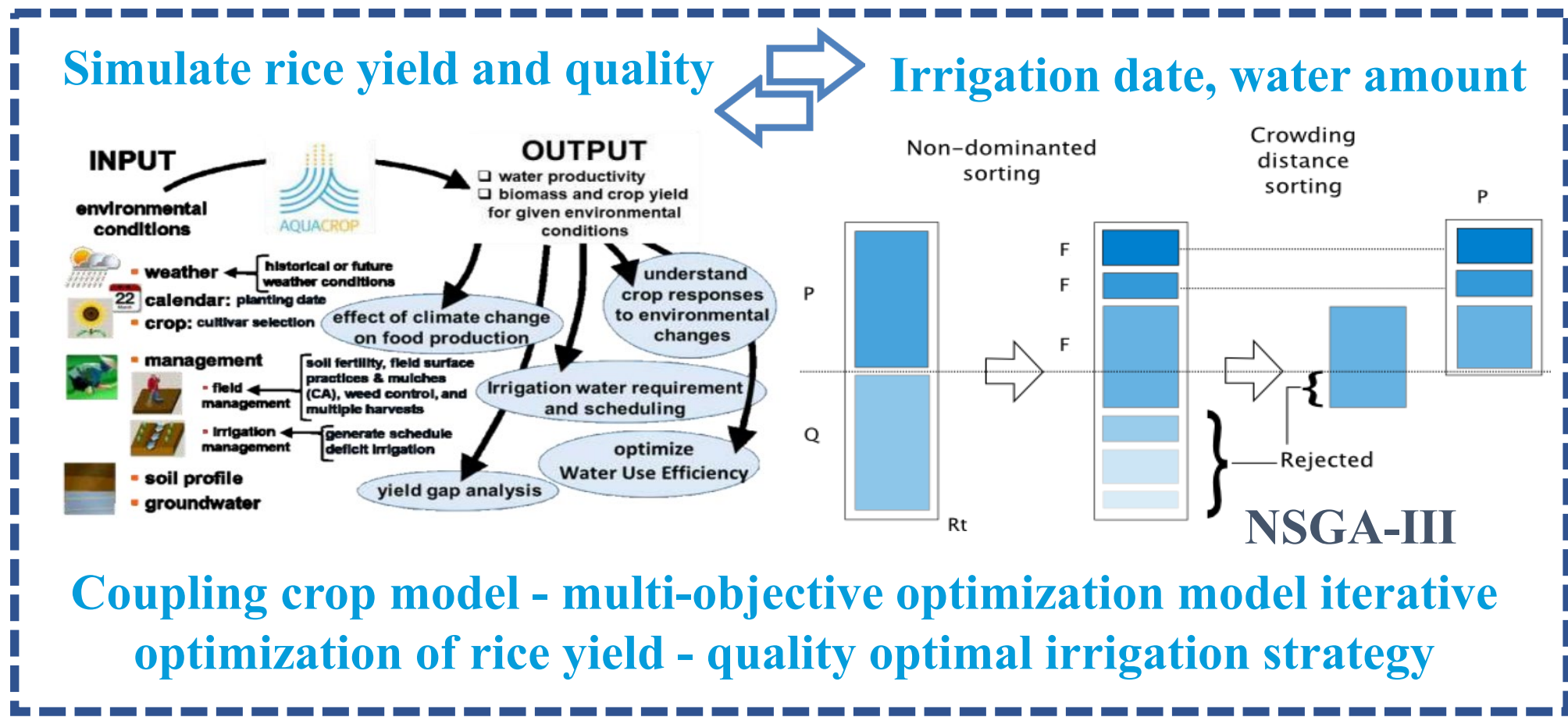
Conclusion

By integrating the principles of physical Internet, the PI-U-KAN + model solves the core challenges of gear pitting detection in intelligent manufacturing: connectivity, intelligence, and scalability.

Introduction

Materials and Methods

Real-time meteorological and soil data obtained via the physical internet are used to predict crop water requirements and calibrate crop model parameters. By integrating the crop model with an intelligent optimization algorithm (NSGA-III), optimal decisions regarding irrigation timing and volume are made, resulting in an optimized rice irrigation strategy that balances multiple objectives, including increased yield, improved quality, and water conservation.



Results



Figure 10 consists of two main parts. The left part is a 3D scatter plot showing the relationship between PC (x-axis, 0.0 to 1.0), AC (y-axis, 0.0 to 1.0), and C (z-axis, 0.0 to 1.0). Data points are colored by year: S1 (yellow), S2 (orange), S3 (green), and S4 (purple). Red lines connect points for the same year across the different axes. The right part is a circular sunburst chart for the year 2023, showing the mean values of Y, C, AC, and PC for four irrigation treatments: 45mm, 470mm, 400mm, and 280mm. The chart is divided into four segments representing the years S1 (green), S2 (orange), S3 (green), and S4 (pink). The mean values are labeled on the segments.

3D Scatter Plot Data (Approximate Mean Values):

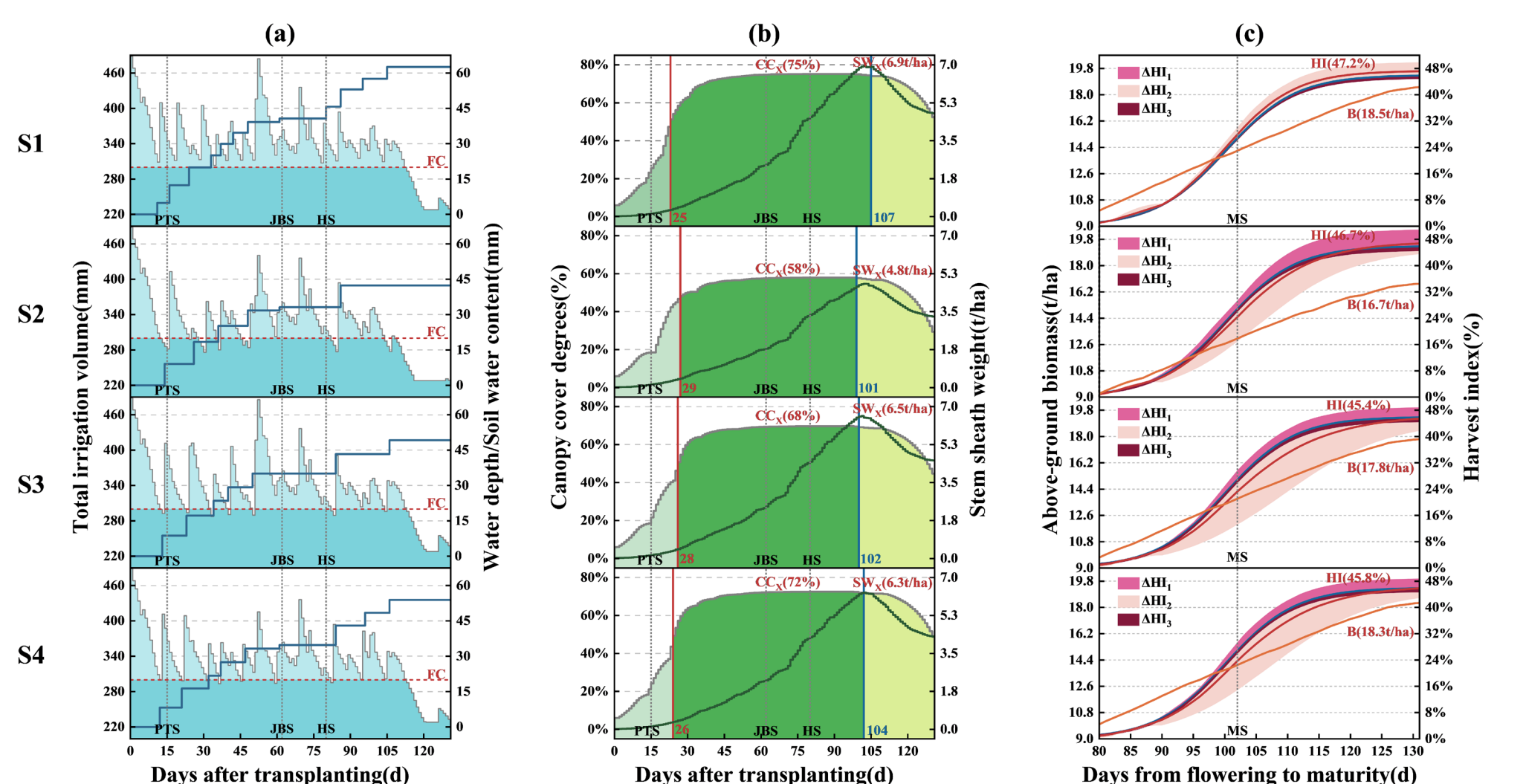
Year	PC (Mean)	AC (Mean)	C (Mean)
S1 (Yellow)	0.75	0.85	0.75
S2 (Orange)	0.25	0.15	0.25
S3 (Green)	0.50	0.40	0.50
S4 (Purple)	0.60	0.60	0.60

2023 Circular Sunburst Chart Data (Mean Values):

Irrigation Treatment	Y (Mean)	C (Mean)	AC (Mean)	PC (Mean)
45mm	0.81	0.58	0.71	0.63
470mm	0.39	0.39	0.60	0.60
400mm	0.71	0.46	0.97	0.81
280mm	0.33	0.05	0.14	0.51

(b).optimal results

To develop various irrigation schemes in response to climate change, the crop growth conditions under different climate scenarios are analyzed, and the response relationships between crop growth indicators and rice yield and quality are investigated.



Conclusion

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