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Bridging the Gap between Physical Internet Vision and Urban Logistics Operations through DISCO Living Labs

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Abstract: *Urban logistics ecosystems face severe fragmentation and inefficiencies. While municipal digitalization efforts are widespread, they frequently produce siloed platforms rather than genuinely interconnected networks. To address existing gaps, the operationalization of the Physical Internet (PI) in city logistics is investigated through the DISCO-X portfolio (a suite of specialized tools engineered specifically on PI principles). Extending the scope beyond ex-post mapping of existing solutions, a "PI-by-design" methodology is presented where core concepts like modularity, open asset sharing and decentralized data governance directly dictated architectural requirements. To evaluate methodological rigor and practical viability, the framework was methodically deployed across four diverse European Living Labs (Ghent, Copenhagen, Thessaloniki and Helsinki). Cross-case validation utilizing predefined performance indicators reveals how a federated data backbone mediates trust and interoperability among competing stakeholders, while spatial hyperconnectivity tools dynamically repurpose existing urban infrastructure for shared consolidation. The analysis advances PI theory by providing validated, scalable blueprints for urban data governance and digital interoperability.*

Keywords: *Physical Internet Roadmap, urban logistics, digital tools, collaborative systems.*

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 Problem Statement and Research Gap

Urban freight systems are under increasing pressure from e-commerce growth, stricter climate targets, scarcity of public space and the need to improve service reliability in dense urban areas. These pressures have intensified longstanding city-logistics problems related to fragmented operations, underused assets and weak coordination between public and private actors (Hesse and Rodrigue, 2004; McKinnon, 2018; Demir et al., 2022; Mohammad et al., 2023; Russo and Comi, 2024). In response, cities and logistics operators are adopting data-driven planning instruments, platform-based coordination, dynamic curb-management tools, shared delivery schemes and neighborhood logistics solutions. However, much of this innovation still targets isolated functions rather than system-wide integration.

From a Physical Internet (PI) perspective, this is a critical limitation. PI is not simply a vision of smarter freight technology; it is a systemic model of open, modular, interconnected and interoperable logistics networks in which assets, services and information flows can be combined across organizational boundaries (Montreuil, 2011; Ballot et al., 2014; Crainic and Montreuil, 2016; ALICE-ETP, 2020). The relevance of PI to urban logistics lies precisely in its capacity to recast city logistics as a hyperconnected network of networks rather than a set of isolated last-mile optimization. Yet much of the literature on digital urban logistics remains focused on individual applications—such as white-label delivery platforms, Crowdshipping schemes, routing tools or localized coordination services—without systematically examining whether these interventions create the interoperability conditions required for PI transition (Prandtstetter et al., 2019; Pufahl et al., 2020; Pourrahmani and Jaller, 2021).

Accordingly, the key research gap is not whether digital tools can improve urban freight operations, but how PI principles can shape the design, coupling and implementation of urban logistics innovations so that digitalization supports systemic transformation rather than isolated optimization. This requires analytical attention to the relations between tools, shared assets, data infrastructures and governance mechanisms. A city does not become PI-oriented because it deploys a digital twin, a locker system or a curbside application in isolation; it becomes PI-oriented when these components are organised so that shared resources, coordination rules and interoperable data flows reinforce one another.

1.2 Objectives and Scientific Contributions

This paper addresses that gap through the DISCO project, which developed and tested a portfolio of PI-led enabling tools across four Living Labs: Ghent, Copenhagen, Helsinki and Thessaloniki. Rather than treating these tools as stand-alone demonstrations, the paper analyses them as an urban interoperability architecture. The scientific contribution is threefold. First, it reconstructs how PI principles informed design choices and later enhancements, avoiding a purely ex-post mapping exercise. Second, it applies a structured interoperability assessment to compare tool interactions across living labs. Third, it triangulates these analytical results with pilot evidence, governance lessons and observed implementation outcomes. This allows the paper to distinguish validated PI contributions from links that remained planned or only loosely connected.

2 Conceptual framework and methodology

2.1 PI design tracing and the five-step analytical framework

The paper builds on the retrospective five-step framework developed in DISCO to identify PI-led enabling tool components. The framework begins with foundational analysis and PI requirement definition, proceeds through baseline alignment of existing tools with the ALICE PI Roadmap, examines tool enhancements made during living-lab implementation, validates them through operational evidence, and finally synthesises the features that materially enabled PI functions. This logic is analytically important because PI relevance is traced through design intentions, implementation decisions and observed effects rather than simply asserted after the pilots.

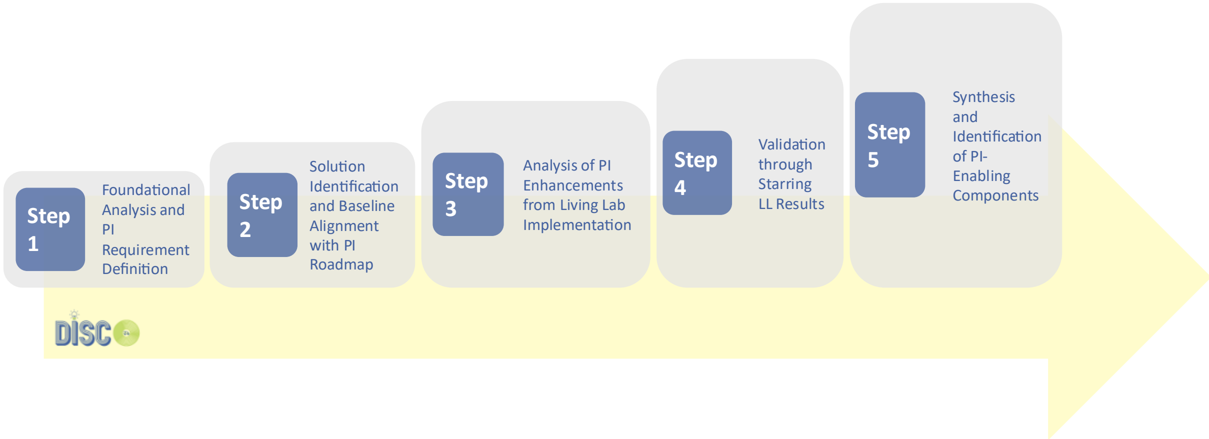

Figure 1: Framework for the analysis and identification of PI-led enabling tool components

2.2 Research design, analytical material and evaluation logic

The research design is a comparative embedded case study. The four Starring Living Labs are treated as the cases, while the embedded units of analysis are the interactions between enabling tools within each city. This choice responds to the need for methodological transparency: PI relevance is not inferred from isolated tools, but from the relationships they create between data infrastructures, shared assets and governance mechanisms.

The empirical material combines three evidence layers, as shown in Table 1.

Table 1: Research design, analytical material, and evaluation logic

Analytical block	Primary evidence	Operationalisation in the paper	Scientific value added
PI design tracing	Requirements analyses, architecture descriptions, and tool documentation	Reconstruct how PI principles shaped design choices and later enhancements	Shows whether PI influenced innovation ex ante and not only through ex-post mapping
Interoperability assessment	Pairwise interaction matrices for each living lab	Score interactions on six dimensions and classify maturity from 0 to 18	Makes cross-living-lab comparison systematic and transparent
Implementation validation	Pilot results, usage evidence, and governance lessons	Triangulate scores against observed outcomes, adoption evidence, and institutional frictions	Distinguishes validated contributions from planned-only links

First, PI design-tracing material was used to reconstruct how requirements analyses, architecture descriptions and tool documentation shaped the selection and enhancement of the enabling tools. Second, an interoperability assessment was applied to pairwise interactions in each living lab. Each interaction was scored on six dimensions—shared data types, direct data flow, shared platform, standardized connectivity, operational synergy and shared governance—using a 0 to 3 scale per dimension, resulting in a final maturity range from 0 to 18. Third, implementation evidence from the pilots was used to validate whether higher-scoring interactions were associated with operational uptake, measurable outcomes or institutional learning. Low interoperability corresponds to scores from 0 to 6, medium interoperability from 7 to 12, and high interoperability from 13 to 18.

3 The DISCO-X portfolio as PI-led enabling tools

The development of the DISCO-X solutions was guided by the Physical Internet roadmap developed by ALICE, which defines a long-term vision for the transition toward interconnected and sustainable logistics systems. This roadmap identifies several foundational building blocks required to enable the transition toward Physical Internet logistics systems, including standardized logistics units, open networks, interoperable systems, and collaborative governance frameworks. Within this context, the DISCO project adopts a PI-by-design approach, meaning that Physical Internet principles are embedded from the early stages of solution design rather than being considered as an ex-post evaluation criterion. This approach ensures that the developed tools inherently support interoperability, openness, and modularity.

Key principles include open logistics networks allowing multiple actors to access shared infrastructure and services; modularity and standardization enabling seamless integration of assets and services; hyperconnectivity allowing real-time coordination between logistics nodes, vehicles, and information systems; and collaborative governance structures ensuring fair access and trust between participating stakeholders. Building on these principles, the DISCO project developed a portfolio of five complementary innovations which group 23 different measures:

- DISCOCURB treats the curb as a shared and digitally managed urban resource. In practice, this includes dynamic booking and curbside monitoring tools, sensor-supported occupancy data and access-oriented routing functions. Its strongest PI contribution is not simply better parking information, but the creation of a transparent operational layer through which scarce curb space can be governed and shared more efficiently.
- DISCOPROXI addresses proximity-based logistics through micro-hub and locker planning, shared neighborhood logistics and route-support functions. In Thessaloniki, the tool family supported the design of a regulated shared smart-locker network instead of uncontrolled provider-by-provider proliferation. In Ghent, the related Urban Access Control logic supported compliant and greener last-mile routing through machine-readable regulatory data.
- DISCOESTATE focuses on collaborative logistics spaces. Its core instrument is the WareM&O platform, which transforms underutilized urban logistics real estate into a discoverable and bookable resource. The PI significance of this tool became stronger when blockchain-supported contracting, real-time availability exchange and building-management integration converted static real estate into a dynamic shared logistics node.
- DISCOBAY supports multimodal consolidation at peri-urban and urban interface nodes. Depending on the living-lab context, this involved digital-twin simulation for test-before-invest decisions, route-management functions that could recommend barge-to-bike alternatives, and databases for identifying underused infrastructure suitable for multimodal consolidation. The PI logic here lies in linking urban last-mile operations to shared middle-mile and hub structures outside the city centre.
- DISCOLLECTION provides the common data backbone of the portfolio. It includes the Smart Data Platform, data-space connectors, standardized regulatory and parking data, the Copenhagen Digital Twin, the Thessaloniki urban logistics dataspace and the Helsinki data pipeline to the Mobility Data Catalog. While the other DISCO-Xs often begin from an operational problem, DISCOLLECTION creates the interoperable digital layer that allows multiple services to discover, exchange and reuse logistics data under controlled governance conditions.

4 Results

4.1 DISCO-X to PI building-block alignment

The first analytical layer examines how the DISCO enabling tools align with the PI building blocks. Figure 2 synthesises this mapping. The purpose of the figure is not to claim that each tool fully embodies one PI block in isolation, but to show which elements of the portfolio materially supported nodes, logistics networks, systems of logistics networks, access and adoption, and governance.

Several observations are important. First, the portfolio is not concentrated in a single PI domain. Node-oriented tools were associated with lockers, logistics real-estate visibility, and platform capabilities for accessing logistics assets. Network-oriented functions emerged more strongly where route management, urban access control, simulation, or digital-twin applications connected logistics operations across actors. Second, system-of-systems effects were most visible in the data infrastructures that enabled different services to connect through shared data environments. Third, governance was not peripheral. Across the living labs, governance innovations were often the mechanism that made technological integration operationally meaningful, whether through data-sharing agreements, municipal rules, asset-sharing frameworks, or public access to curated datasets.

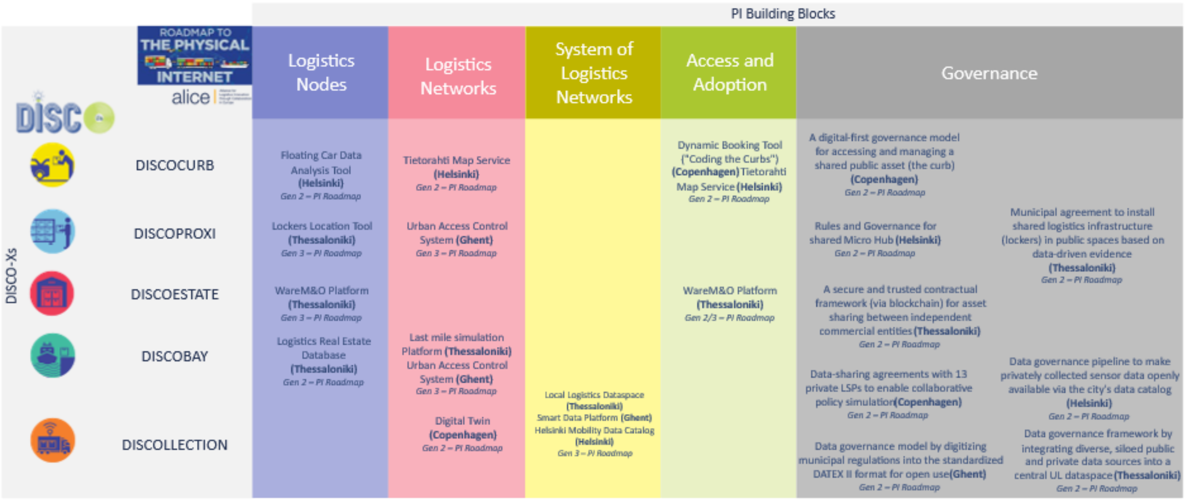

Figure 2: DISCO-Xs x PI Building Blocks alignment

This distribution matters for PI theory. It shows that urban PI transition is not only a matter of adding more advanced digital applications. It depends on combining digital components with institutional arrangements that enable shared use of physical resources and trustworthy exchange of data.

4.2 Cross-Living-Lab comparison

The second analytical layer examines how the enabling tools interacted in practice within the four Starring Living Labs. The comparison reveals distinct interoperability pathways rather than a single maturity ladder.

Ghent represents deep operational integration. Standardised regulatory data, urban access control, and operational workflows were tightly coupled, demonstrating how governance and operational execution can reinforce each other. Thessaloniki represents shared data-ecosystem integration, where separate applications remained operationally distinct but were linked through a common urban freight dataspace. Copenhagen represents strategic data integration, with the digital twin acting as an analytical hub for collaborative policy simulation and low-emission zone planning. Helsinki functions as a bridge case in which data publication, curb visibility, and shared logistics services began to connect, but with looser operational coupling than in Ghent or Thessaloniki.

Table 2 synthesises the dominant pathway, the main interoperability signal, and the validation evidence for each living lab. Presenting the cases in this compact form makes the comparison explicit and directly addresses the reviewers' concern that the previous version over-relied on narrative description.

Table 2: Comparative evidence from the four Starring Living Labs

Living Lab	Dominant pathway	Interoperability signal	Implementation evidence
Ghent	Deep operational integration	Urban access control workflow linked to standardized regulatory and curb data; high operational coupling	Implementation evidence included reduced route risk, shorter effective routes, and a barge-to-bike pilot demonstrating coordinated multimodal execution
Thessaloniki	Shared data-ecosystem integration	Distinct tools connected through a local urban freight dataspace and shared evidence layer	The urban consolidation depot was relocatec and equipped for controlled access; retailer and infrastructure evidence supported shared space and locker decisions
Helsinki	Data-to-service bridg	Microhub, curb-monitoring, and open-data publication pipelines connected with moderate coupling	The microhub involved multiple operators and thousands of deliveries, while urban logistics datasets were published through the city catalogue
Copenhagen	Strategic data integration	Digital twin combined partner data for scenario testing and policy design	Collaborative data agreements enabled simulation of zero-emission and hub scenarios, including strong emission reductions on affected routes

5 Discussion

The results show that the relationship between PI and urban logistics should be understood through interoperability architectures rather than through standalone digital tools. This is the paper's central analytical message. Across the four cities, the most convincing PI contributions were those in which physical assets, digital functions and institutional arrangements were mutually reinforcing. A digital twin created value when it was fed by shared operational data and used to shape policy. A locker or micro-hub solution mattered when it was embedded in regulatory decisions, municipal approvals and shared-access business models. A warehouse platform became PI-relevant when it supported transactional trust, real-time availability and integration with the wider data ecosystem.

This perspective also clarifies the originality of the DISCO contribution. The paper does not argue that PI transition follows a single maturity path. Instead, the living labs reveal at least three recurring pathways: operationally integrated workflows, shared data ecosystems, and strategically integrated policy platforms. These pathways are transferable because they describe organizational logics through which cities can structure interoperability according to their institutional capacity, data maturity and local priorities.

The comparison further highlights the importance of governance. Municipal actors were not passive observers of technology deployment. In all four cities, public authorities curated regulatory data, enabled or constrained access to public space, brokered agreements, published data, or supported the legitimacy of shared assets. PI transition in cities is therefore at least as much an institutional challenge as a technical one.

Finally, the paper aligns closely with the practical challenge of bridging high-tech and low-tech solutions. The DISCO evidence suggests that high-tech urban logistics applications create robust public value only when they are anchored in the management of low-tech urban assets such as curbs, school streets, waterways, pavilions, depots, loading zones and public-space permissions. This is especially relevant for cities seeking incremental but credible pathways towards PI-oriented logistics systems.

6 Conclusion

This paper repositioned DISCO as a research contribution on how Physical Internet principles can be operationalized in urban logistics through enabling tools and living-lab experimentation. By combining a five-step design-tracing logic, a structured interoperability assessment, and implementation evidence from four Starring Living Labs, the paper moved beyond descriptive project reporting.

Two conclusions stand out. First, PI relevance becomes credible when it can be demonstrated through concrete interoperability mechanisms linking digital tools, shared assets, and governance arrangements. Second, there is no single route to urban PI transition. Ghent, Copenhagen, Helsinki, and Thessaloniki each reached different but analytically comparable forms of interoperability. The most transferable contribution of the paper is therefore a framework for understanding and evaluating those pathways.

Future work should apply comparable scoring and validation approaches to additional cities and should examine whether the identified interoperability pathways remain robust as solutions mature and scale.

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