Exploring the Future of Urban Logistics Through Physical Internet Implementation Using Delphi

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Abstract. E-commerce growth has intensified urban delivery demands while cities pursue environmental neutrality. This creates tension between consumer expectations for rapid deliveries and CO_2 reduction goals, as faster services typically decrease load factors and increase emissions. While the Physical Internet paradigm holds significant academic promise for improving efficiency and reducing environmental impact, its practical implementation faces considerable barriers that contribute to a currently vague outlook on the widespread adoption of the PI. To navigate this uncertainty and better delineate future pathways, this study employed a structured three-phase methodology: (1) PI dimensions were identified through literature review, with each dimension presenting two options (optimistic and pessimistic scenarios); (2) DISCO experts voted on the most plausible options for each dimension by 2050, and these votes were analysed and used to generate nine archetypes; (3) these archetypes were then shared with 23 experts from industry and academia through a Delphi approach to identify the most plausible urban logistics PI scenarios. Results reveal optimism about technological advancements and futuristic logistics solutions, but significant hesitation regarding collaborative business models persists. This research provides expert and stakeholder insights to guide companies and city authorities in making informed investments and developing strategic initiatives for sustainable urban logistics transformation.

Keywords: Physical Internet, Urban logistics, E-commerce delivery, Sustainable logistics.

1 Introduction

The rapid expansion of e-commerce has reshaped urban logistics, intensifying the tension between demand for rapid delivery and municipal sustainability goals. The shift from consolidated business-to-business (B2B) flows to fragmented business-to-consumer (B2C) deliveries increases congestion, vehicle-kilometers traveled and per-parcel emissions in urban areas [1-3]; fast shipping and e-commerce further exacerbate this problem, as high speed tends to reduce load factors and increase carbon intensity per package [2, 4]. Although some studies suggest that e-commerce can lower emissions compared with individual shopping trips through consolidated van deliveries [5], these gains are often offset by return flows, atomized demand and expectations of immediacy [1, 4].

In response, the academic community has advanced the Physical Internet (PI) as a hyperconnected logistics paradigm inspired by the interoperability of the digital internet [6, 7], and its core principles include standardized modular π-containers and open, interconnected networks enabling the shared use of logistics assets across stakeholders [6, 8]. Simulation studies suggest substantial benefits, including transport cost reductions of up to 25% and CO_2 reductions of up to 32% through greater consolidation and asset utilization [9-11]; however, the literature also highlights major barriers to implementation, including missing standards for containers and data protocols [12], high upfront costs and uncertain returns on investment [13]. The repeated financial difficulties of Urban Consolidation Centers (UCCs) further illustrate the fragility of collaborative logistics models when critical mass is not achieved [14]. Beyond these technological and economic barriers, the most persistent challenge is organisational and behavioural, specifically the "collaboration conundrum" [15], which represents the reluctance of competing firms to engage in open data sharing and asset collaboration. This creates a "maturity mismatch" in which enabling digital technologies such as IoT and AI are relatively advanced, while the physical, economic and collaborative arrangements required for PI remain underdeveloped.

This study addresses the gap between theoretical promise and practical uncertainty by exploring plausible PI futures for urban logistics; here, archetypes are defined as internally coherent scenario configurations across the examined PI dimensions, while the 2050 horizon reflects the long-term nature of logistics and urban transition despite the uncertainty inherent in such a distant timeframe. The research question asks what the most plausible PI configurations for urban logistics systems by 2050 are, as assessed by industry experts and academic stakeholders. The study contributes by identifying a taxonomy of PI dimensions and options for urban logistics, introducing a methodology that combines algorithmic scenario generation with Delphi-based expert validation and providing empirically grounded insight into expert perceptions of PI implementation, including both areas of convergence and persistent uncertainty relevant to strategic decision-making.

2 Methods

A structured three-phase methodology was employed to systematically identify, generate and validate PI scenarios for urban logistics systems; this approach was specifically developed to navigate the uncertainty surrounding PI implementation while leveraging expert knowledge to identify the most plausible future configurations (**Error! Reference source not found.**). The dimensions and option pairs identified in Phase 1 were subsequently transformed into the questionnaire used in Phase 2, where each expert response generated a categorical preference profile that served as input for the exploratory scenario-generation.

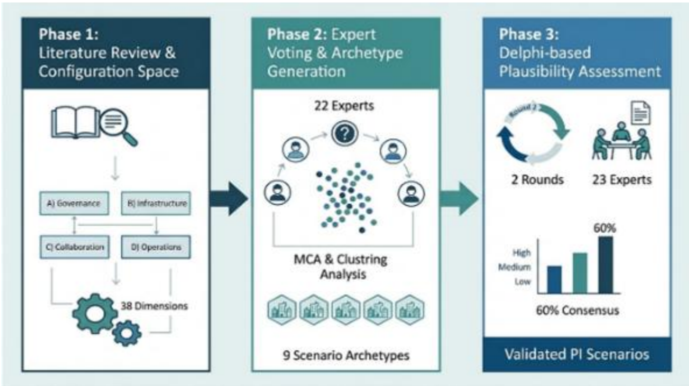

Fig. 1. Methodological Framework.

2.1 Phase 1: Literature-driven configuration space

The first phase involved a targeted literature review to identify the fundamental dimensions of PI implementation in urban logistics contexts. The review was intended to construct a configuration space for foresight analysis rather than to provide a full systematic review of the PI literature. Academic publications, project documents, policy reports and industry sources related to Physical Internet implementation, urban logistics, collaboration, microhubs, data governance and last-mile operations were screened and thematically synthesized to identify recurring implementation dimensions. Dimensions were retained when they were repeatedly discussed in the literature, were relevant to urban PI implementation, and could meaningfully differentiate future configurations. The literature review resulted in the identification of four primary sectors encompassing twelve decision components, which were further decomposed into thirty-eight specific dimensions. Each dimension was characterized by two distinct options representing contrasting implementation approaches: an optimistic scenario reflecting progressive adoption and integration, and a pessimistic scenario representing conservative or fragmented implementation approaches.

The four sectors identified were: (A) Governance and Planning, encompassing development approach, data-driven policy, engagement strategy and funding mechanisms; (B) Urban Space and Physical Infrastructure Allocation, including dynamic curbside management, utilization of public space, urban microhubs and microhub networks; (C) Collaborative Urban Logistics, covering multi-modal logistics and collaborative logistics networks and (D) Sustainable Urban Logistics Operations, incorporating future mobility and data-driven delivery operations. Each dimension was operationalized with specific Option 1 and Option 2 scenarios representing different implementation pathways. For example, the Long-Term Orientation dimension contrasted reactive governance approaches focusing on incremental fixes with proactive strategies involving consistent investment in advanced technologies and policy adaptation based on ongoing feedback.

2.2 Phase 2: Expert voting and archetype generation

The second phase involved collecting expert opinions on the most plausible options for each dimension through a structured survey administered to twenty-two experts primarily associated with the DISCO project (http://discoprojecteu.com), representing academic research, public authorities and logistics practice. This phase was used to generate differentiated scenario configurations, while broader plausibility validation was carried out separately in the Delphi phase through the inclusion of additional external stakeholders. The survey presented each of the thirty-eight dimensions with their corresponding Option 1 and Option 2 scenarios, asking experts to select the option they considered most plausible for implementation by 2050. To keep the subsequent expert elicitation manageable, each dimension was expressed as a binary contrast between a more integrated/progressive option and a more conservative/fragmented option. This dichotomization was used as an analytical simplification for scenario construction and does not imply that real-world transitions are inherently binary. The voting results were analyzed using Python-based algorithms to identify patterns in expert preferences and generate coherent scenario archetypes.

The analysis process began with vote statistics calculation to determine the distribution of preferences across dimensions and identify areas of consensus and uncertainty. Dimensions with the greatest voting uncertainty (smallest absolute gaps between Option 1 and Option 2 votes) were selected for scenario generation, as these represented the most contested aspects of PI implementation. Multiple Correspondence Analysis (MCA) was applied to the binary categorical response matrix (complete disjunctive coding of expert choices), which is an established use of the method for identifying patterns in categorical data. The expert coordinates in MCA space were subjected to K-means clustering analysis to identify distinct groups of experts with similar voting patterns. A nine-cluster solution was retained after inspection of the elbow plot and to preserve sufficient differentiation among scenario configurations for the subsequent Delphi. These clusters should be interpreted heuristically, as a device for generating a diverse set of internally coherent archetypes, rather than as statistically robust population segments. For each archetype, the most common choices across all dimensions were determined based on the voting patterns of experts within that cluster. This process generated nine comprehensive scenario descriptions representing different configurations of PI implementation in urban logistics systems.

2.3 Phase 3: Delphi-based plausibility assessment

The third phase employed a two-round Delphi approach to assessing the plausibility of the nine generated archetypes, with twenty-three experts from both the DISCO internal network and external logistics stakeholders participating in the validation process. These experts included academic researchers specializing in logistics and supply chain management, urban planning officials, logistics service providers and technology consultants.

In the first Delphi round, experts were presented with detailed descriptions of each archetype and asked to rate their plausibility on a scale from 1 to 10, where 1 represented extremely implausible and 10 represented extremely plausible. In the second round, experts were provided with aggregated results from the first round, including mean plausibility scores and anonymized qualitative feedback from other participants, and were invited to reconsider their initial assessments. Given the exploratory nature of the study, the long-term horizon and the heterogeneity of the panel, consensus was operationalized pragmatically as 60% of respondents assigning an archetype to the same plausibility category. For this purpose, ratings were grouped into three categories: low plausibility (1–3), medium plausibility (4–6) and high plausibility (7–10).

3 Results & Discussion

3.1 The configuration space for PI-led urban logistics

To improve readability, the configuration space is summarised in Table 1, which condenses the main sectors, components and representative contrasting dimensions used to structure the subsequent expert elicitation and archetype generation.

Table 1. Summary of the configuration space for PI-led urban logistics.

Sector	Main components	Illustrative dimensions
Governance & Planning	long-term orientation, cross-departmental integration, data/policy intelligence, stakeholder engagement, funding, regulatory adaptability	reactive vs proactive planning; siloed vs integrated governance; basic vs advanced data governance; project-based vs structural funding
Urban Space & Physical Infrastructure Allocation	curbside management, public-space allocation, microhub siting and structure, network density/access	static vs dynamic curb use; shared vs dedicated space; sparse vs dense microhub networks; peri-urban vs central siting
Collaborative Urban Logistics	multimodality, platform integration, PPP intensity, trust/data sharing, collaboration breadth, governance	isolated vs shared platforms; limited vs extensive data sharing; sector-specific vs cross-sector collaboration; decentralized vs coordinated governance
Sustainable Urban Logistics Operations	future mobility, implementation pace, infrastructure intensity, transparency, analytics, automation, resilience integration	descriptive vs predictive analytics; low vs high automation; separated vs integrated routine/emergency logistics

3.2 Archetypes derived from expert voting

Nine archetypes were generated by analysing the most contested dimensions and clustering expert voting patterns in MCA space; together, they span a continuum from closed, incumbent-centred innovation to open, shared and system-optimised futures, and from reactive governance to more agile and collaborative regimes.

The first archetype, "Technologically progressive yet operationally conservative", combines city-level monitoring and management investments with slow-moving governance and limited inter-organisational data sharing, while the second, "Fully integrated next-generation logistics network", represents the most ambitious configuration with proactive governance, dense shared infrastructure, unified digital platforms and AI-enabled synchromodal coordination; the third, "Technologically advanced private logistics ecosystem", combines high automation and optimisation with closed, incumbent-controlled assets and platforms.

The fourth archetype, "Cautious commons", prioritises open access to shared assets but with conservative technology adoption and static rules, and the fifth, "Centrally focused, exclusively managed network", concentrates advanced facilities in the urban core under exclusive concessions, combining efficiency gains with possible market asymmetries; meanwhile, the sixth, "Basic infrastructure focus, minimal innovation", relies on low-cost retrofits, sparse private nodes and rudimentary data governance, producing only marginal system-wide improvements.

The seventh archetype, "District-led innovation with fragmented governance", reflects localised experimentation without strong metropolitan interoperability, whereas the eighth, "Transition phase with a shared network and foundational tech", combines open access, common data platforms and moderate automation as an inclusive stepping-stone configuration; the ninth, "Advanced technology in exclusive, sparse nodes", concentrates predictive AI and resilience capabilities in a few high-capacity private sites, limiting broader system effects.

3.3 Delphi plausibility assessment, implications and limitations

The Delphi panel assessed the relative plausibility of the nine archetypes over two rounds using a 1–10 scale; using the adopted 60% convergence threshold, consensus was achieved for six archetypes. High plausibility was assigned to Archetypes 1, 3 and 8, medium plausibility to Archetypes 4 and 7 and low plausibility to Archetype 6, whereas no consensus was reached for Archetypes 2, 5 and 9.

These results suggest that relative to the other configurations examined, experts considered futures characterised by strong internal optimisation within bounded ecosystems more plausible than fully open, city-wide PI integration by 2050, while transitional models combining shared physical networks, common data layers and moderate automation were also judged comparatively plausible as intermediate pathways. By contrast, minimal-innovation approaches were viewed as less capable of meeting future sustainability and service requirements. Two broader patterns emerge; first, experts were generally optimistic about technology readiness, particularly regarding automation, predictive analytics and dynamic optimisation, and second, much greater hesitation persists around collaborative business models and the institutional arrangements needed for open, multi-party resource and data sharing at scale. In this sense, the main barriers to PI implementation appear not only technological but also organisational and institutional, involving trust, incentive alignment, liability, competition concerns and the distribution of costs, risks and value across actors.

The policy implications follow directly from these findings; for technology-forward but collaboration-light futures, early interoperability requirements could help avoid lock-in and reduce barriers for SMEs, whereas for shared-network trajectories, transparent data-governance frameworks, procurement models that reward shared access and regulatory sandboxes could support more efficient system-wide outcomes. Where district-led innovation is more plausible, mechanisms for horizontal learning and scaling may reduce fragmentation, although more broadly, the low plausibility of minimal-innovation pathways reinforces the need for coordinated investment in infrastructure if climate targets and service expectations are to be met.

This study should nevertheless be interpreted with caution because the 2050 horizon is intentionally long-term and therefore uncertain, meaning the findings reflect exploratory foresight rather than prediction. In addition, the binary structure of the dimensions was an analytical simplification, the expert pool was partly rooted in the DISCO network and the clustering step was used heuristically rather than as a statistically robust segmentation exercise.

4 Conclusion

This study provides a structured pathway from literature to plausible PI futures in urban logistics; a four-sector, twelve-component, thirty-eight-dimension space with seventy-six options was developed, while expert voting was translated into nine archetypes through MCA-supported clustering and Delphi assessment identified the configurations judged most plausible by 2050. High plausibility was assigned to technologically progressive yet collaboration-light systems, advanced private ecosystems and transitional shared networks; medium plausibility was given to cautious commons and district-led innovation, whereas low plausibility was attributed to minimal-innovation futures. Although fully integrated, open, synchromodal city-wide networks were not ruled out technically, they did not achieve consensus on institutional feasibility; thus, these findings can support cities and firms in prioritising investments, designing governance and data-sharing frameworks and sequencing transition steps toward more sustainable, resilient and efficient urban logistics.

Acknowledgements

This work was supported by the European Commission under the “DISCO” project (Grant Agreement No. 101103954). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

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