Orchestrating Physical Internet-Led Urban Logistics through Comprehensive Planning and Implementation Guidance from Meta Model Suite

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Abstract. The abstract should summarize the contents of the paper in short terms, i.e. 150-250 words. Rising CO_2 emissions from urban logistics, intensified by e-commerce growth, demand urgent sustainable solutions. Physical Internet (PI)-driven approaches, based on shared and collaborative concepts, show significant promise for creating efficient, interconnected logistics networks. However, cities often lack the expertise to orchestrate such transformative actions and effectively integrate the necessary digital and physical infrastructure. The Meta Model Suite (MMS) of the EU-funded DISCO project addresses this gap, with a primary goal of providing comprehensive guidance to city authorities through a structured, digital framework. The MMS assists cities in assessing their current logistics systems (including PI-led innovation readiness and digital maturity), facilitates the creation of future logistics scenarios and supports the selection of tailored "DISCO-X" innovations. Furthermore, the MMS offers a blueprint for developing necessary data frameworks, including local urban logistics dataspaces, and provides access to a library of tools and identifies essential infrastructure and potentially supportive regulations for the successful implementation of these PI-led solutions. Demonstrations in Living Labs such as Ghent, Copenhagen, Thessaloniki and Helsinki aim to validate these PI-led solutions, showcasing their potential to reduce congestion and emissions while improving service delivery, thereby fostering more sustainable and digitally competitive urban environments.

Keywords: Physical Internet, Urban Logistics, Sustainability, Meta Model Suite, Decision Support System, Digital Maturity, Orchestration Tool.

1 Introduction

The transportation sector is a cornerstone of the European economy, with 1.3 million enterprises employing 10.2 million people [1]. Between 1995 and 2019, freight transport volume grew by 41% before the COVID-19 pandemic [2]. The sector rebounded to a value-added output of €527.5 billion in 2021, surpassing pre-pandemic levels and contributing roughly 5% to EU GDP [3]. This recovery coincides with rapid e-commerce expansion, which pressures urban logistics and increases environmental impacts like CO2 emissions, particularly from last-mile deliveries, which account for up to 50% of total delivery emissions and 40–50% of total delivery expenses [4].

The Physical Internet (PI) paradigm addresses logistics challenges with an open, interconnected network modeled on the digital internet. PI centers on sharing modular assets, standardized containers and optimized routing to maximize efficiency, scalability and sustainability. Adopting PI concepts can enhance resource utilization to 85% from a 43% average [5], while simulations suggest system-wide savings of 26% through modular payload exchanges [6]. For scalability, ALICE [7] shows consolidating flows could handle a 300% demand increase with only 50% more assets. PI frameworks significantly decrease CO2 emissions; sharing warehouses and trucks can reduce emissions by 54% [8].

The transition of urban logistics networks to embrace Physical Internet (PI) principles is a complex task. Effective adoption requires tools to assess the readiness of a city, guide strategic planning and integrate diverse PI-driven solutions, while comprehensive orchestration is essential to manage this complexity and ensure a coordinated implementation of sustainable logistics strategies. This paper introduces the Meta Model Suite (MMS), an advanced orchestration tool developed within the HE DISCO project to facilitate this transition.

While existing Decision Support Systems (DSS) and urban freight assessment tools effectively diagnose logistical bottlenecks, they often stop at the analytical phase, leaving city planners without actionable transition pathways. The unique scientific contribution of the MMS lies in bridging this gap through a dual-action architecture: it combines a deterministic, rule-based diagnostic engine with the automated generation of adaptive, gap-remediation blueprints. Furthermore, unlike traditional standalone DSS frameworks, the MMS introduces a novel integration with federated data environments (Urban Freight Dataspaces), allowing cities to securely leverage operational data without centralizing sensitive commercial datasets. Specifically, the objectives of this paper are to:

1. present the conceptual framework and technical architecture of the MMS,
2. demonstrate its functionality as an orchestration tool, and
3. showcase its application and preliminary impacts in diverse urban environments.

The remainder of this paper is structured to first provide a detailed overview of the MMS's components. It will then illustrate its practical application and preliminary outcomes in selected European cities, discuss the implications of these results, and conclude by summarizing the contributions and outlining future research directions.

2 The Meta Model Suite

2.1 The DISCO Concept

The DISCO project aims to accelerate and expand a new generation of urban logistics and smart planning by enabling a transition towards decarbonized and digital cities. This objective is pursued through the delivery of innovative frameworks and tools and by shifting the paradigm of urban logistics planning towards an approach led by the PI. To this end, DISCO facilitates the adoption and scaling of innovative, best practice and replicable data-driven logistics solutions within Living Labs that adhere to the PI paradigm [7, 9–11].

In this context, DISCO-Xs represent a set of innovative solutions developed to address the challenges of urban logistics and planning. These solutions are designed to be economically viable, sustainable and driven by relevant technologies, demonstrating the benefits of consolidation and the capacity to reconfigure logistics operations [12]. The DISCO-Xs are, in short, defined as:

DISCOBAY – At peripheral TEN-T gateways, repurposes underused multimodal terminals into on-demand consolidation centers that dynamically route long-haul flows into green last-mile services (rail, inland waterways, EVs) via shared transport facilities, avoiding new infrastructure investments.

DISCOESTATE – In midtown logistics districts, creates a digital marketplace to match short-term demand with underused warehouse and distribution-center capacity, enabling flexible reuse of multistorey spaces as micro-distribution hubs [13].

DISCOPROXI – Within neighborhoods, deploys and manages adaptive micro-hubs (parcel lockers, local consolidation points) through optimized routing and smart networks to deliver zero-emission B2B/B2C services [14].

DISCOCURB – At street level, optimizes curb-side logistics by dynamically reallocating loading zones, parking bays, and micro-mobility docks based on real-time freight demand, using analytics and digital twins to boost delivery efficiency and reduce congestion.

DISCOLLECTION – Serves as the data backbone, equipping Living Labs with tools to onboard and federate logistics metadata into the Urban Freight Data Space for real-time routing optimization, dynamic access control, and continuous ecosystem improvement.

2.2 Overarching architecture

The Meta Model Suite, hosted at https://metamodelsuite.imet.gr, is a modular, service-oriented decision-support platform, the architecture of which unifies assessment, strategic planning and implementation guidance for urban logistics driven by the Physical Internet. The core of the system gathers user inputs (including city vision statements, baseline data on infrastructure and policies and digital maturity indicators) and processes them through embedded artificial intelligence (AI) and rule-based algorithms. This procedure guides municipalities through a structured process toward tailored PI solutions (DISCO-Xs).

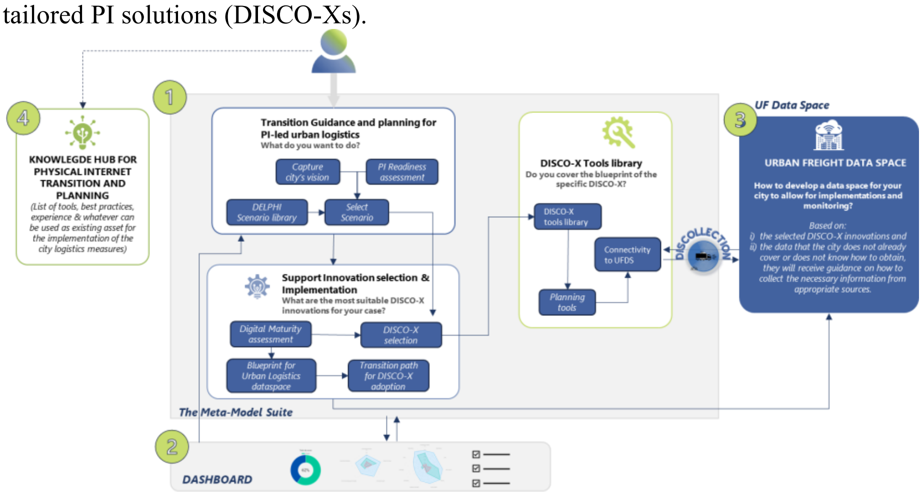

Fig. 1. The overarching Architecture of Meta Model Suite and the connection with other outcomes.

Functionally, the architecture of the MMS leads cities through a structured workflow that begins by capturing the strategic vision of a city and assessing its digital maturity. Based on this profile, the system recommends a tailored package of DISCO-X innovations and generates a blueprint for the necessary data infrastructure, such as a local Urban Freight Dataspace (UFDS). A configurable dashboard then allows the city to track implementation progress and KPIs. Externally, the MMS leverages the federated data catalogue of the UFDS and the Smart Data Platform from DISCOLLECTION to access both public and confidential logistics metadata without central data storage, preserving data sovereignty while enabling rich analytics. Likewise, integration with the ALICE Knowledge Hub ensures that methodological updates (such as new PI container standards, alliance network case studies or policy toolkits) are immediately available within the Transition Guidance and Tools Library.

2.3 Use Cases

The Meta Model Suite supports four core use cases that guide cities through the successive phases of Physical Internet (PI) adoption. Use Case 1 (Education) functions as an interactive resource to establish a foundational PI vocabulary and conceptual framework among local stakeholders. Use Case 2 (Strategic Visioning) benchmarks municipal objectives against PI best practices to formulate a customized, actionable transition roadmap. Building on this vision, Use Case 3 (Innovation Selection) leverages the city's Digital Transition Assessment to score infrastructural readiness and recommend an optimal, phased package of DISCO-X innovations. Finally, Use Case 4 (Practical Implementation) bridges strategy and execution by connecting cities to the DISCO-X Tools Library, automatically generating a tailored integration blueprint that specifies the precise datasets and infrastructure upgrades required for deployment.

2.4 DISCO-X selection

The DISCO-X selection methodology categorizes cities into distinct typologies to recommend optimal PI-driven innovations. To achieve this, the MMS utilizes a logistic regression model whose independent variables are derived from two comprehensive baseline assessments (Table 1). First, PI-led Innovation Readiness is evaluated via 18 qualitative questions, with criteria weights determined through the Analytic Hierarchy Process (AHP). Second, Digital Maturity is assessed across 11 indicators using a 5-point Likert scale. The model's regression coefficients were trained using baseline survey data from stakeholders across the four DISCO Living Labs, ensuring evidence-based, context-specific recommendations.

Table 1. Predictor variables and data sources for the Logistic Regression model

Variable Category (predictors)	Description & Scoring Logic	Primary Data Sources
PI-led Innovation Readiness	18 indicators weighted via AHP: Smart Actors (23%), Smart Governance (19%), Resources & Infra (19%), Networks (19%), Safety & Security (19%).	City stakeholder surveys, logistics baseline analyses.
Digital Maturity	11 indicators assessed via 5-point Likert scale across: Security, Interoperability, Commercial/Societal Support, and Environmental Impact.	Municipal IT, policy, and operations questionnaires.
Target Variable (Label)	City Typology classification leading to a specific DISCO-X recommendation.	Living Lab baseline classifications.

2.5 DISCO-X requirements guidance

Following the DISCO-X selection, the MMS transitions to the requirements guidance phase to translate the recommended innovation into an actionable implementation plan. It presents an interactive checklist of specific data, tools, infrastructure, and regulatory frameworks derived from the real-world DISCO Living Labs. To structure this, the MMS utilizes the MoSCoW prioritization method, classifying each requirement as either a "Must Have" (essential for core functionality) or a "Nice to Have" (an enhancement that is not strictly necessary). City planners perform a self-assessment against this checklist to indicate their current capabilities.

For example, a DISCOCURB deployment requires planners to evaluate categorized prerequisites. "Must Have" operational tools—such as dynamic scheduling software and live curb-monitoring apps—dictate corresponding "Must Have" data capacities, including real-time parking occupancy, municipal geospatial records, and urban logistics demand data. Similarly, mandatory infrastructure (e.g., occupancy sensors), regulations (time-based curb restrictions), and active collaboration between city authorities and freight carriers are strictly required. Conversely, virtual simulation platforms for planning, integration with Low-Emission Zones (LEZ), and joint sensor investments are classified as "Nice to Have." Based on this self-assessment, the MMS generates a clear readiness verdict, highlights critical capability gaps, and directs users to the DISCO-X Tools Library and the Urban Freight Dataspace (UFDS) blueprint for targeted remediation.

3 Use case implementation at Thessaloniki

Thessaloniki applied the MMS selection methodology (Section 2.4), achieving moderate baseline scores (e.g., 50% in PI-led Innovation Readiness) (Fig. 2).

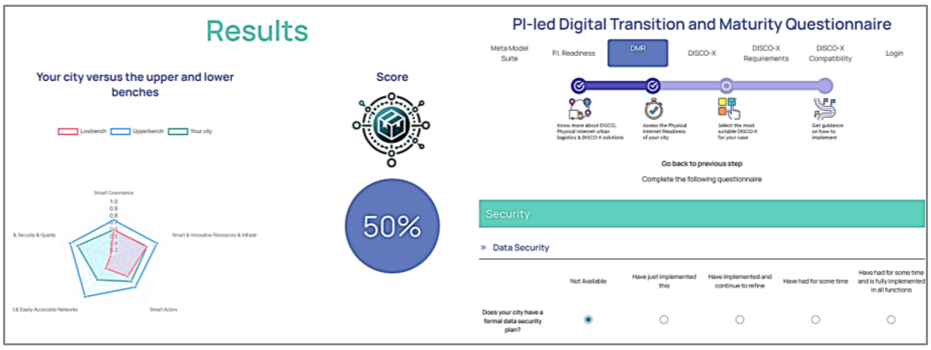

Fig. 2. The Physical Internet-led urban logistics readiness and the digital maturity readiness results.

Consequently, the MMS recommended a four-pillar package: DISCOBAY (multimodal consolidation), DISCOESTATE (warehouse marketplace), DISCOLLECTION (federated data backbone), and DISCOPROXI (shared parcel lockers to reduce first-/last-hundred-metre inefficiencies).

To transition from recommendation to deployment, Thessaloniki completed the Interoperability and Technical Compatibility Checkpoint for DISCOPROXI. The city successfully validated all MMS capability requirements. For Tools and Data, Thessaloniki met "Must Have" criteria by capturing operational data from over 1,000 stakeholders, leveraging municipal GIS open data portals, and deploying secure access systems. It also fulfilled "Nice to Have" criteria by developing an optimal facility location tool and a Logistics Real Estate Database. For Infrastructure and Stakeholders, the city met "Must Have" requirements by successfully installing five physical smart lockers in public spaces, driven by a strong, active collaboration between the Municipality, CERTH, and local couriers. Since Thessaloniki satisfied all "Must Have" requirements, the MMS issued a "can be deployed" verdict for DISCOPROXI. Similar compatibility checks were sequentially performed for the remaining recommended solutions.

To evaluate the operational impact of the DISCOPROXI deployment, preliminary quantitative key performance indicators (KPIs) were monitored. The city established a baseline of 62 minutes per delivery route, 9.7 freight kilometers per vehicle daily, and a weighted average emissions factor of 0.13 $kgCO_2/km$. During the pilot, the shared locker network achieved a 26% fulfillment utilization rate and an 82% first-time delivery success rate, averaging 1.20 € per parcel. Beyond quantitative metrics, a critical qualitative lesson learned was that while technical readiness was high, overcoming initial data-sharing hesitancy among competing Logistics Service Providers (LSPs) required active, neutral mediation by the municipality.

4 Conclusions and limitations

This paper introduced the Meta Model Suite (MMS) as an orchestration tool to accelerate Physical Internet (PI) adoption in urban logistics. By bridging analytical readiness assessments with automated gap-remediation blueprints, the MMS provides city authorities with actionable transition pathways. As demonstrated in Thessaloniki, these data-driven blueprints calibrate local Sustainable Urban Logistics Plans, ensuring interventions strategically align with the UN Agenda 2030 (SDGs 9, 11, 13). Furthermore, standardized PI-readiness and digital maturity indicators ensure methodological replicability across diverse European cities.

However, limitations exist. Practically, federated dataspace integration is often hindered by legacy municipal IT infrastructures and varying data governance standards. Methodologically, the logistic regression model relies on self-reported survey data, risking subjective bias. Finally, overcoming private stakeholders' hesitancy to share operational data remains a significant barrier. Future research will focus on automated data-ingestion APIs to reduce survey reliance and formalized trust frameworks to incentivize public-private data sharing.

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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