Meta Model Suite: Facilitating Sustainable Urban Logistics Planning Through the Adoption of the Physical Internet Paradigm

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Abstract
Urban logistics demand has soared due to post-pandemic e-commerce growth and rising fast-delivery expectations, pressuring cities to cut CO_2 and adopt greener practices. The Physical Internet (PI) envisions an open, interconnected network—warehouses, distribution centers, and retailers sharing resources via internet-style data handling and standardized modular containers—to streamline supply chains, lower costs, and reduce environmental impact. The HE DISCO project's Meta Model Suite orchestrates PI adoption by assessing urban digital maturity, using AI to recommend tailored innovations (locker alliances, optimal Urban Consolidation Centers), and offering strategic planning tools from HE URBANE. It also provides implementation of guide data frameworks, tools, and infrastructure—for seamless integration. Case studies in Ghent, Copenhagen, Thessaloniki, and Helsinki show marked congestion and emission reductions alongside better service delivery, illustrating PI's potential to transform urban logistics and boost sustainable, digitally competitive cities.
Keywords: *Physical Internet, Urban Logistics, Sustainability, Meta Model Suite, Decision Support System, Digital Maturity, Orchestration Tool*

1. Introduction

The transportation sector stands as a cornerstone of the European economy, comprising 1.3 million public and private enterprises that employ 10.2 million individuals and provide crucial services across the EU (Eurostat, 2024). Between 1995 and 2019, the industry exhibited substantial growth, with freight transport volume increasing by 41% and passenger transport by 33%, before experiencing a temporary setback during the COVID-19 pandemic (Directorate-General for Mobility and Transport, 2024). Despite these disruptions, the transportation and storage sector quickly rebounded, achieving a value-added output of €527.5 billion in 2021, surpassing pre-pandemic performance and contributing roughly 5% of the EU's GDP (Eurostat, 2025). This robust recovery coincides with exponential growth in e-commerce, with global sales projected to rise from $6.09 trillion in 2024 to $6.56 trillion in 2025, an annual growth rate of 7.8% (Lin, 2024). European e-commerce specifically is forecasted to expand by 51% between 2024 and 2029 (Statista, 2024). This rapid expansion amplifies existing pressures on urban logistics networks, intensifying environmental impacts such as elevated CO_2 emissions, particularly from last-mile deliveries, which can account for up to 50% of total delivery emissions and 40-50% of total delivery expenses (Sarkar, 2023).
The Physical Internet (PI) paradigm proposes a revolutionary approach to these logistics challenges by promoting an open, collaborative, and interconnected logistics network inspired by the digital internet's model. Central to PI is the strategic sharing of modular assets and infrastructure, standardized modular containers, and optimized routing mechanisms designed to maximize efficiency, scalability, and sustainability. Adopting PI concepts within collaborative networks can substantially enhance resource utilization, achieving utilization rates as high as 85% compared to the traditional average of 43% (Barbarino, 2018). Simulation studies further suggest potential system-wide savings of up to 26%

through open exchanges of modular payloads (Ballot et al., 2012). ALICE-ETP (2020) highlights the scalability of PI solutions by demonstrating that fully consolidating flows across an open network could accommodate a 300% rise in transport demand with only a 50% increase in required assets. Implementing PI-based logistics frameworks can significantly decrease CO_2 emissions; for instance, sharing warehouses and trucks under PI principles can reduce emissions by up to 54% while simultaneously optimizing routing and location selection (Naganawa et al., 2024). The SENSE H2020 report indicates that shifting 50% of road freight to rail via PI-inspired modal integration could reduce greenhouse gas emissions by up to 60%, given that 24% of goods-vehicle kilometres in the EU run empty and loaded vehicles average only 57% of weight capacity (European Commission CORDIS, 2019). At the urban level, the KoMoDo project in Berlin—where five operators share a micro-hub—achieved annual CO_2 savings exceeding 11 tons by consolidating last-mile deliveries using e-cargo bikes (Zhen, 2021). Beyond environmental gains, PI frameworks can unlock major cost savings. Inefficient vehicle usage currently imposes a €160 billion annual burden on the EU, and a 50% modal shift to rail under PI could cut logistics costs by 32% (European Commission CORDIS, 2019). Additionally, McKinsey & Company (2022) reports that multi-client fulfillment sites achieve 7–9% cost reductions compared to dedicated facilities, with 90% of logistics experts noting profit-margin improvements of 5–10% through collaborative operations. Standardizing modular container sizes further enhances cargo efficiency, with EU research indicating that just six box sizes can cover 85% of typical cargo dimensions, increasing load factors by 15% for manufacturers and up to 50% for retailers when combined with PI-style pooling (European Commission Research and Innovation, 2021).

Transitioning urban logistics networks to embrace PI principles entails considerable complexity due to the multifaceted nature of urban logistics ecosystems. Effective adoption requires tools capable of systematically assessing city-specific readiness, guiding strategic planning, and facilitating the integration of diverse PI-driven solutions. Comprehensive orchestration mechanisms are essential to manage this complexity and ensure coordinated implementation of sustainable logistics strategies.

This paper introduces the Meta Model Suite (MMS), an advanced orchestration tool developed within the HE DISCO project, designed to facilitate the integration and deployment of PI-driven urban logistics solutions. Specifically, the objectives of this paper are:

- To present the conceptual framework and technical architecture of the MMS.
- To demonstrate the functionality of MMS as an orchestration tool, integrating assessment, strategic planning, and implementation guidance for effective PI adoption.
- To showcase its application and preliminary impacts across diverse urban environments, specifically Thessaloniki utilizing the URBANE strategic tool.

The remainder of this paper is structured as follows: Section 2 provides a detailed overview of the conceptual underpinnings and technological components of the Meta Model Suite. Section 3 illustrates its practical application and preliminary outcomes in selected European cities. Section 4 discusses the implications of these results, and Section 5 concludes by summarizing the contributions and outlining future research directions.

2. Meta Model Suite

2.1 Overarching architecture

DISCO aims at fast-tracking and upscaling to a new generation of urban logistics and smart planning; enabling the transition to decarbonized and digital cities, delivering innovative frameworks and tools, and changing the Urban Logistics and Planning paradigm with a Physical Internet (PI) – led approach. To achieve its objectives, DISCO take-up and upscaling of innovative, best practice, and replicable data-driven logistics solutions and planning in the Living Labs following the Physical Internet paradigm (ALICE, 2020; Dong & Franklin, 2021; Sharma et al., 2022; Ambra et al., 2019).

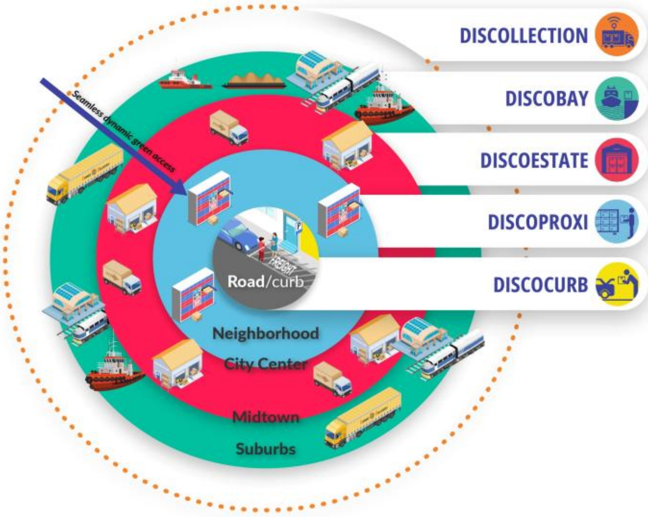

Figure 1: *A Spatial Perspective of DISCO-X Innovations within the PI paradigm of Urban nodes.*

In this context, DISCO-Xs are understood as a set of innovative solutions to address the challenges of urban logistics and planning. These solutions are designed to be economically viable and sustainable, driven by relevant technologies, and demonstrate the convenience of consolidation and the ability for driving reconfiguration of logistics operations (McKinnon et al., 2015).

- **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 with green-mode operations and relieving land-use pressures.
- **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 in line with access and emission regulations.
- **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/, has been conceived as a modular, service-oriented decision-support platform whose architecture unifies assessment, strategic planning, and implementation guidance for Physical Internet–driven urban logistics. At its core sits a web-based orchestration engine that gathers user inputs—city vision statements, baseline data on infrastructure and policies, and digital maturity indicators—and, through embedded AI and rule-based algorithms, steers municipalities step by step toward tailored PI solutions (DISCO-Xs).

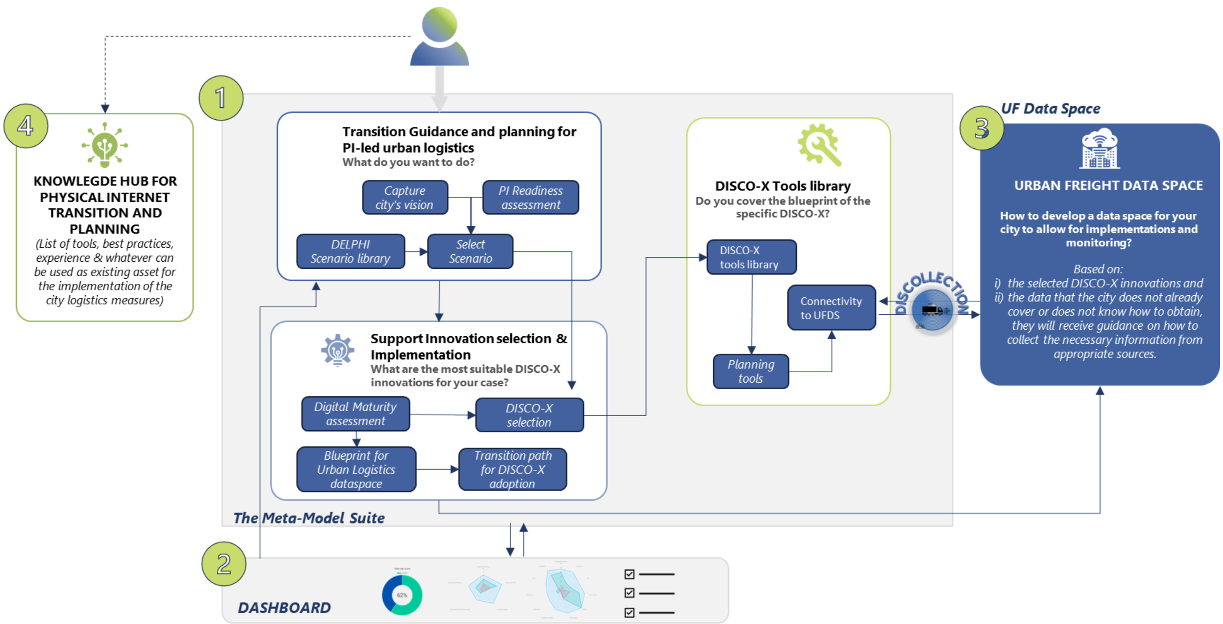

Figure 2: *The overarching Architecture of Meta Model Suite and the connection with other outcomes*

Functionally, the architecture proceeds through a five-stage workflow. Stage 1 captures a city's strategic vision and baseline context via the Transition Guidance interface, which uses expert-derived factors to recommend one or more PI scenarios. Stage 2 invokes the Digital Transition Assessment, benchmarking the city's current use of digital services, security protocols, and environmental data practices. By combining these outputs, Stage 3 classifies the city into one of four PI typologies—Inspired, Acceleration, Ready, or Partnership—each mapped to a pre-configured DISCO-X innovation package. In Stage 4, the DISCO-X Tools Library generates a blueprint for an Urban Logistics Dataspace: it identifies required datasets (traffic flows, locker occupancy, curb usage), suggests middleware services (real-time analytics, geofencing APIs), and outlines essential infrastructure upgrades (sensor networks, consolidation centers). Finally, Stage 5 activates a configurable Dashboard that tracks implementation milestones, visualizes KPI progress (emissions reductions, cost savings, service levels), and feeds lessons learned back into the platform for continuous refinement.

Externally, MMS leverages the UFDS's federated data catalogue and the Smart Data Platform from DISCOLLECTION to access both public and confidential logistics metadata without central data storage, preserving sovereignty while enabling rich analytics. Likewise, integration with the ALICE Knowledge Hub ensures that methodological updates—new PI container standards, alliance network case studies, or policy toolkits—are immediately available within the Transition Guidance and Tools Library. This dual linkage to live data and live knowledge positions MMS not merely as a static repository but as an evolving hub that grows in parallel with advances in PI research and urban logistics practice.

In sum, the Meta Model Suite architecture delivers a cohesive, scalable, and future-proof framework for cities to transition toward Physical Internet–driven logistics. By blending modular components, rigorous data integration, and user-centred workflows, MMS empowers urban authorities to leapfrog traditional planning silos, forge collaborative logistics alliances, and realize measurable gains in efficiency, sustainability, and resilience.

2.3 Use Cases

The Meta Model Suite supports four core use cases that illustrate how its modular services, embedded AI, and federated data frameworks can be applied to real-world urban logistics challenges. Each use case aligns with a distinct phase of Physical Internet adoption—from foundational learning to hands-on tool deployment—and demonstrates how MMS guides stakeholders through education, strategic visioning, innovation selection, and practical implementation. Together, these scenarios offer a clear roadmap for cities and logistics operators to harness PI principles, leveraging data-driven insights and collaborative networks to achieve more sustainable, efficient, and resilient urban freight systems.

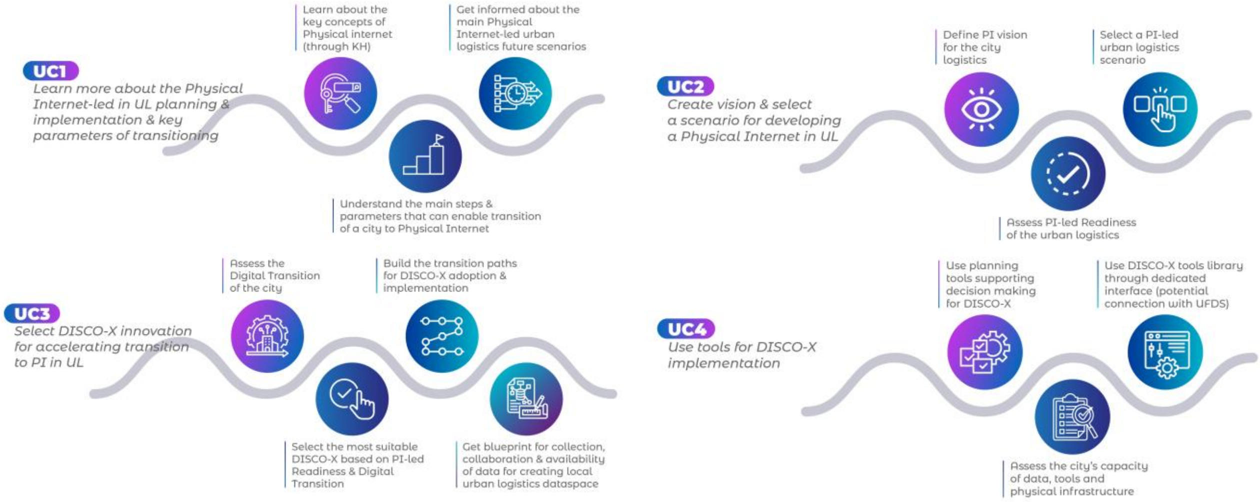

***Figure 3:** Description and main functionalities of MMS Use cases*

Use Case 1 positions MMS as an interactive educational resource, introducing users to the core tenets of the Physical Internet and its transformative potential for urban logistics. Through an intuitive, web-based interface, stakeholders access concise overviews of PI concepts—such as standardized modular containers, open-network principles, and optimized routing algorithms. This module not only defines key parameters like connectivity, interoperability, and process optimization but also provides self-paced tutorials and case summaries to illustrate successful PI pilots. By grounding planners, policymakers, and service providers in a common PI vocabulary and conceptual framework, MMS ensures that subsequent strategic and operational modules build on a solid, shared understanding of what a PI-driven logistics transition entails.

Once users are versed in PI fundamentals, **Use Case 2** guides them through crafting a bespoke PI vision and selecting implementation scenarios tailored to their city's context. The Transition Guidance module solicits inputs on strategic objectives—such as emission reduction targets, e-commerce growth ambitions, or smart-city integration goals—as well as baseline indicators of digital maturity, infrastructure capacity, and stakeholder readiness. Embedded assessment algorithms then benchmark these inputs against best-practice PI scenarios (e.g., micro-hub consolidation, locker network roll-outs, or intermodal modal shifts), allowing users to compare predicted impacts on cost, emissions, and service levels. The outcome is a clear, actionable scenario roadmap that aligns municipal ambitions with PI capabilities, thereby demystifying the path from high-level urban logistics goals to concrete PI deployment strategies.

Building on the defined vision, **Use Case 3** focuses on pinpointing the optimal set of DISCO-X innovations that will accelerate a city's journey toward a fully-fledged Physical Internet (see Figure 6). Leveraging the Digital Transition Assessment results, MMS evaluates each city's existing ICT infrastructure, data governance frameworks, and partner ecosystems to score readiness for specific DISCO-X modules—such as standardized container pooling, dynamic routing engines, or shared micro-depot networks. Through interactive decision trees and "what-if" simulations, users explore trade-offs between incremental pilots (e.g., e-cargo bike corridors) and more ambitious roll-outs (e.g., federated warehouse alliances). Clear guidelines on resource needs, stakeholder collaboration protocols, and data-sharing mechanisms equip planners with the information required to assemble a phased implementation plan that maximizes early wins while laying groundwork for broader PI integration.

Use Case 4 transforms strategy into action by connecting cities to the DISCO-X Tools Library—MMS's "app store" for PI solutions—hosted within the Urban Freight Data Space. Users browse a curated catalog of software components, data-ingestion services, and analytics dashboards, each annotated with functional descriptions and integration guidelines drawn. The suite details connectivity requirements (e.g., RESTful API endpoints, data schema expectations) and outlines best practices for federated data access, ensuring seamless interoperability with existing urban ICT platforms. As users select tools—such as real-time curb management modules or AI-driven demand forecasting engines—MMS automatically generates a tailored integration blueprint, specifying required datasets, middleware configurations, and infrastructure upgrades. This end-to-end guidance enables cities and Living Labs to deploy DISCO-X solutions confidently, monitor KPI progress via the MMS dashboard, and iterate on deployments through continuous feedback loops.

2.4 DISCO-X selection

The DISCO-X selection methodology constitutes a critical phase within the Meta Model Suite (MMS), systematically guiding cities toward the adoption of the most suitable DISCO-X innovations based on their unique urban logistics requirements, digital maturity, and readiness for Physical Internet (PI) solutions. This structured process ensures alignment between city-specific capabilities and optimal DISCO-X measures, enhancing the likelihood of successful implementation and impactful results.
The selection methodology integrates two essential assessment tools: the PI-led Innovation Readiness Assessment and the PI-led Digital Maturity Assessment. These assessments provide a comprehensive diagnostic framework, categorizing cities into distinct typologies reflective of their readiness to transition towards PI-driven logistics solutions. Upon categorization, cities engage in a targeted selection process utilizing a decision-support model developed specifically for this methodology.
Upon this, machine learning methodologies were applied to guide users select the most suitable urban logistics solution. Specifically, a logistic regression model was used to define relationships between city profiles—characterized by innovation readiness scores and digital maturity levels—and the successful adoption of specific DISCO-X solutions. By harnessing empirical data and expert-derived scenarios, the model ensures evidence-based recommendations tailored precisely to each city's contextual needs.
The outcomes of this process manifest as tailored DISCO measure packages, each comprising one or more DISCO-X solutions explicitly configured to meet the city’s strategic logistics goals.
Finally, cities are informed about the necessary data, tools, infrastructure and regulation and are guided on how to fulfil these requirements in order to enable the successful implementation of their selected DISCO-X solutions.

2.5 Physical Internet-led Strategic Tools

The rapid growth of e-commerce has significantly increased the pressures on urban last-mile logistics, necessitating smarter and more sustainable distribution strategies. Within the broader framework of Physical Internet-driven logistics, strategic planning tools play a pivotal role in optimizing the placement, scale, and operational efficiency of key infrastructure components such as micro-hubs, parcel lockers, and fleet sizing and mixture optimization.
These strategic planning tools utilize advanced continuous optimization methods and stochastic modeling approaches to assist city planners and logistics providers in determining the most effective configurations of logistics infrastructure. By systematically modeling and assessing operational efficiencies, environmental impacts, and economic viability, these tools support informed decision-making aimed at achieving ambitious CO_2 reduction targets and enhancing overall logistical performance.

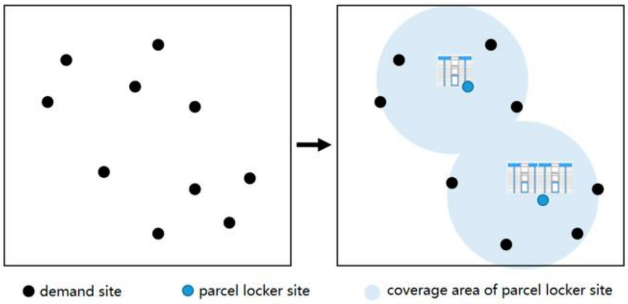

Figure 4: *The concept of parcel locker network in the context of DISCOPROXI (Wang et al. 2022)*

At the neighborhood level, these tools facilitate the design and deployment of micro-hub networks, including parcel lockers and local consolidation points, strategically positioned to reduce delivery vehicle kilometers and enhance accessibility for end-users. Optimization models evaluate trade-offs between operational costs, such as labor costs and handling efficiency, and external societal costs including congestion and emissions considering also capital costs for infrastructure investments.

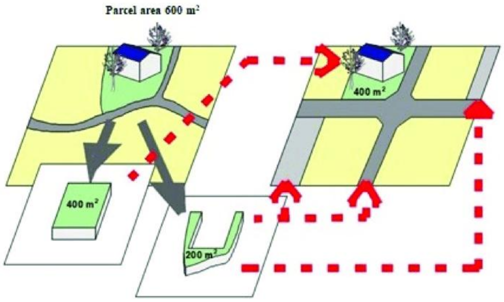

Figure 5: *The optimal number of consolidation centers (Pamuković et al. 2020)*

Additionally, at the urban scale, strategic tools guide the establishment of novel urban micro-consolidation centers, optimizing their number and location to effectively aggregate and distribute goods from various logistics providers. This approach minimizes redundant delivery trips and environmental footprints while accommodating the fast-paced demands of urban e-commerce deliveries.

Through comprehensive scenario analyses, these strategic tools also assess the benefits of shared infrastructure solutions versus individual company networks, providing policymakers with clear insights into potential environmental, economic, and operational advantages of collaborative logistics models.

Collectively, these strategic planning tools offer robust, transparent, and data-driven methodologies that empower urban planners and logistics operators to effectively navigate the complexities of transitioning towards sustainable and efficient urban logistics systems.

3. *Use case implementation at Thessaloniki*

3.1 Selection of the most suitable urban logistics measure

The initial application of the Meta Model Suite (MMS) in Thessaloniki involved a systematic selection of the most impactful DISCO-X innovations, directly following the DISCO-X selection methodology outlined in Section 2.4. This process began with the city undergoing the PI-led Innovation Readiness Assessment and the PI-led Digital Maturity Assessment. As depicted in Figure 6, Thessaloniki achieved moderate scores in both evaluations (56% for innovation readiness).

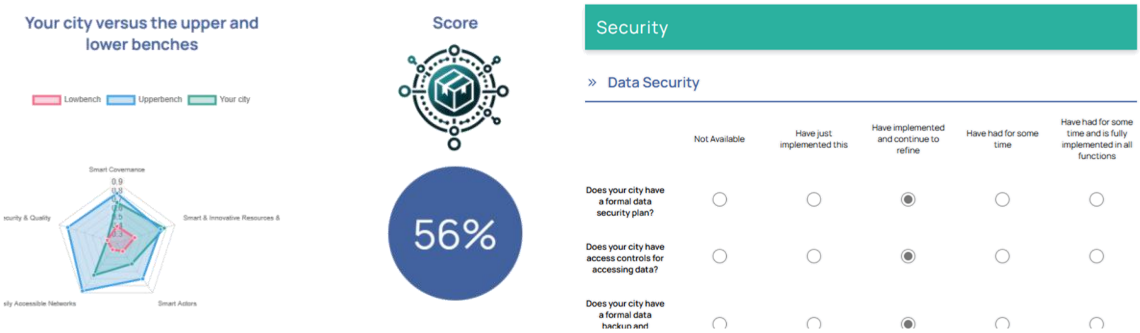

Figure 6: *The Physical Internet led urban logistics readiness and the digital maturity readiness results*

For Thessaloniki, the MMS recommends a four-pillar package comprising DISCOBAY, which repurposes underused peripheral multimodal terminals into dynamic consolidation nodes to shift freight onto green last-mile services; DISCOESTATE, a digital marketplace matching short-term demand to idle midtown warehouse capacity to create micro-distribution hubs; DISCOLLECTION, a federated data backbone that onboards and harmonizes logistics metadata for real-time routing and access control; and

DISCOPROXI, the deployment of shared parcel lockers and micro-hubs in neighbourhoods to consolidate flows and slash first-/last-hundred-metre inefficiencies.

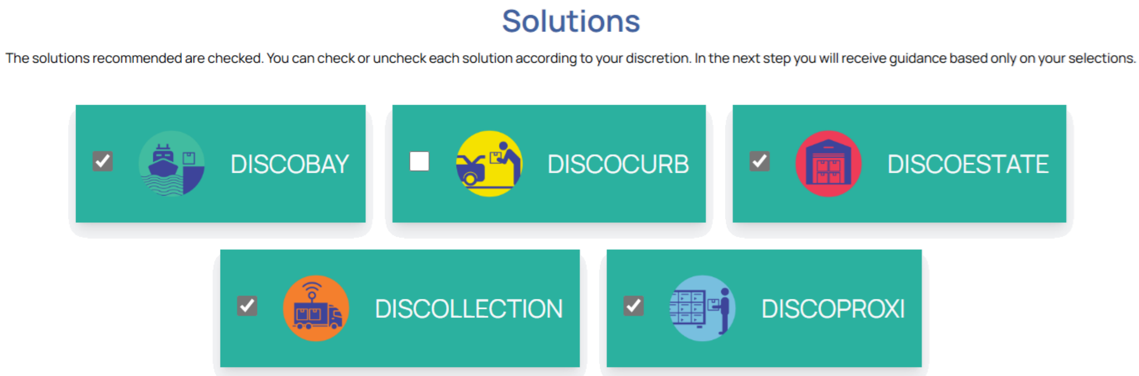

***Figure 7:** The suggested DISCO-X solutions*

This selection ensures that the chosen innovations are aligned with Thessaloniki's readiness and strategic goals, paving the way for effective implementation. The following section details the assessment of a specific component of the recommended DISCOPROXI solution.

3.2 Locker alliance network

Following the selection of DISCO-X solutions, where DISCOPROXI was identified as a key innovation for Thessaloniki, a detailed assessment of one of its core components—a locker alliance network—was undertaken. This evaluation aligns with the objectives of DISCOPROXI, which includes deploying and managing adaptive micro-hubs like parcel lockers. Furthermore, this analysis utilized Physical Internet-led Strategic Tools, which are designed to optimize infrastructure components such as parcel lockers and micro-hubs.

For this specific use case in Thessaloniki, the HE URBANE Impact Assessment Radar (IA-Radar) planning tool (https://ia-radar.imet.gr/planning), an example of such a strategic tool, was employed. The scenario involved seven companies participating in city logistics operations across a 20 km^2 area. The parcel locker network was dimensioned for a throughput of 32 locker transactions per day. Vehicle fleets are still fully diesel-powered (100 %), with no electric vehicles deployed to date. All cost and operational inputs for the scenario are as follows. Each locker costs € 7 000 to acquire, and its capital carries an annual opportunity cost of 8 %. Once in service, each locker incurs a fixed operational cost of € 10 per day. Delivery vehicles average 35 parcels per route and travel at 30 km/h; fuel is priced at € 1.50 per liter, with vehicles consuming 7 liters per 100 km. Drivers spend roughly 0.0667 hours (4 minutes) per drop, at an hourly labor rate of € 10. Finally, route distances for the Traveling Salesman Problem–based estimations use a β-constant of 2.5. The study compared two scenarios:

- Independent Networks: Each company operates its own separate parcel locker network
- Alliance Network: All seven companies share a unified locker network based on PI principles

***Table 1:** Daily Demand and Number of Depots by Company*

Company	Daily Demand	Number of Depots
Company 1	4 000 parcels/day	8 depots
Company 2	2 500 parcels/day	5 depots
Company 3	500 parcels/day	2 depots
Company 4	2 125 parcels/day	4 depots
Company 5	375 parcels/day	2 depots
Company 6	1 250 parcels/day	3 depots
Company 7	1 750 parcels/day	5 depots

The results of the implementation showed that total daily logistics costs across all operators fall from € 12 459.54 under independent operation to € 9 583.96 in the alliance—a saving of € 2 875.58, or 23.1 %. At the same time, the alliance streamlines infrastructure by reducing the optimal number of lockers from 225 to 199 units (−26 lockers, an 11.4 % cut) and yet increases effective locker throughput from 6 672 to 8 288 transactions (+1 616 lockers, a 24.2 % gain). Customer access also improves dramatically: average walking distance to a parcel locker drops from 0.278 km to 0.119 km (−0.159 km, a 57.2 % reduction), and the alliance achieves an average walking time of just 1.79 minutes—well below the 2.9–8.0 minute range seen in the independent networks. Overall, the cooperative model not only cuts costs but boosts capacity and service quality.
In addition to the 23.1 % aggregate cost saving, each individual carrier in Thessaloniki enjoys tangible benefits under the alliance model. For Company 1, daily logistics costs fall by € 543.50 (from € 3 610.00 to € 3 066.50), a 15.1 % reduction, while its effective locker throughput rises by 230 parcels (from 2 422 to 2 652, a 9.5 % gain) and average customer walking distance shrinks 38.3 % (0.193 km → 0.119 km). Company 2 cuts costs by € 471.28 (–19.8 %), boosts throughput by 267 parcels (+19.2 %), and halves walking distance (–53.0 %). The smallest operator, Company 3, sees the biggest proportional saving—€ 303.70 or 44.1 % off its € 689.22 baseline—more than doubles locker capacity (+100.5 %), and slashes walking distance by 76.6 %. Company 4 saves € 451.57 (–21.7 %), increases throughput by 274 parcels (+24.1 %), and cuts walking distance 57.5 %. Company 5, despite having no depots, halves its € 558.31 daily cost (–48.2 %), more than doubles locker usage (+116 %), and reduces customer walks 77.6 %. Company 6 enjoys a € 406.26 saving (–29.7 %), a 47 % rise in effective lockers, and a 68.3 % shorter walk. Even the aggregated “rest” of the network (Company 7) drops costs by € 430.10 (–24.3 %), gains +281 lockers (+32.0 %), and cuts walks by 62.6 %. Every operator thus not only pays less but also serves more customers with less effort and fewer assets under the shared locker alliance.

4. Conclusions

This paper introduced the Meta Model Suite (MMS) as an advanced orchestration tool to accelerate the adoption of the Physical Internet (PI) paradigm in urban logistics. Through its integrated approach of assessing digital maturity, recommending tailored PI-driven innovations like DISCO-X, and providing strategic planning tools, the MMS facilitates a systematic transition towards more sustainable and efficient urban freight systems. The Thessaloniki case study, particularly the analysis of a locker alliance network under the DISCOPROXI solution, demonstrated substantial real-world benefits, including significant cost reductions, enhanced operational efficiency, and improved customer service. These findings underscore the transformative potential of the MMS and PI principles in creating greener, more resilient, and digitally competitive urban environments by optimizing logistics operations and fostering collaborative resource sharing.

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