D3.5: Data-driven Impact Assessment Radar

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Executive summary

This deliverable (D3.5) presents the "Data-driven Impact Assessment Radar", *a web-based tool structured in 3 distinct levels,* developed within the URBANE project as a strategic response to the urgent demand for cleaner, smarter, and more resilient urban logistics. In a context where cities face increasing pressure to decarbonize and streamline freight transport, this work provides practical and scalable solution to help local authorities and logistics providers for making informed and evidence-based decision about new logistics services and scenarios in their cities and operations.

At its core **Impact Assessment Radar-Level 1** is a framework structured around six key pillars—ranging from governance and infrastructure to safety and environmental efficiency—further broken down into actionable sub-elements. This structured approach outlines a comprehensive methodology for evaluating both the readiness and performance of urban logistics ecosystems within cities as well as identify areas for improvement.

To support this transformation, the **Impact Assessment Radar Level 2** introduces three analytical models: a microhub-based delivery simulation that evaluates cost and operational efficiency of cargo-bike-supported locker systems; a fleet optimization module that helps identify the ideal vehicle mix to minimize emissions and operational costs; and a locker network design tool to optimize infrastructure deployment based on demand, geography, and user behaviour.

The **Impact Assessment Radar – Level 3** consolidates evidence from the URBANE Living Labs, as well as from other potential urban contexts, to illustrate the real-world application of green and digital logistics innovations and business models. It translates diverse case experiences into a harmonized set of Key Performance Indicators (KPIs), which are structured around URBANE's five strategic domains: Equity, Sustainability, Safety, Efficiency, and Digitization. By systematically assessing and visualizing these KPIs across different urban settings, the Impact Assessment Radar not only provides a robust basis for evaluation but also generates transferable insights, thereby supporting the extrapolation of impacts for future adopters.

Ultimately, the **Impact Assessment Radar** is a publicly available strategic tool designed to strengthen evidence-based logistics planning for policymakers and other relevant stakeholders in the logistics ecosystem. Structured in three levels, it provides enable cities to assess the maturity of innovations, study and compare different scenarios around innovative last mile logistic solutions as well as functions as a knowledge repository, consolidating insights that can guide future applications. Through this approach, Deliverable 3.5 contributes directly to the advancement of more integrated, sustainable, and intelligent urban freight systems.

Contents

List of Figures

List of Tables

Glossary of Terms and Acronyms

ACRONYM	DESCRIPTION
IAR	Impact Assessment Radar
LL	Living Lab
PI	Physical Internet
UCC	Urban Consolidation Centre
LSP	Logistics Service Provider
ADV	Autonomous Delivery Vehicle
eLCV	Electric Light Commercial Vehicle
DT	Digital Twin
ABM	Agent-Based Model
KPIs	Key Performance Indicators
GHG	Greenhouse Gas
CO_2	Carbon Dioxide

1. Introduction

Task 3.7 of the URBANE project focused on the development, integration, and operationalization of the Data-driven Impact Assessment Radar (IAR), a core innovation within the broader project tools to promote sustainable urban logistics. This task brought together conceptual foundations, analytical models, and performance indicators from previous work packages and translated them into a functional platform that enables stakeholders to evaluate, plan, and manage urban freight activities with a high degree of precision and contextual sensitivity. The outcomes of this task not only include the technical deployment of the Radar tool itself, but also its application in a set of diverse urban Living Labs, where it was tested and calibrated using real-world data.

As a result of Task 3.7, the Impact Assessment Radar now offers a consolidated suite of interactive tools and dashboards that visualize and quantify the performance of innovative logistics interventions across strategic, tactical, and operational planning levels. These tools are informed by KPIs aligned with the URBANE framework and provide meaningful insights into areas such as sustainability, safety, efficiency, equity, and digitalization. Importantly, IAR supports scenario testing and decision support for different urban contexts, allowing users to assess the impacts of logistics innovations such as cargo bikes, micro-hubs, parcel lockers, and low-emission zones.

Another major outcome of this task was the operational linking of the analytical tools developed in Tasks 3.3 to 3.6 including the microhub-based delivery model, fleet optimization module, and locker network optimizer into a Radar-inspired planning tool. This integration supports a seamless user experience, allowing planners and researchers to input contextual data, run optimizations, and immediately view the projected impacts. The interface was designed to be intuitive and customizable, with support for real-time adjustments and transparent assumptions to ensure usability across multiple stakeholder types. Field testing in Living Labs validated both the robustness of the tool's algorithms and the value it delivers for practical urban logistics planning.

Especially, Task 3.7 delivered a transferable, data-driven framework that can be applied by cities beyond the immediate scope of the URBANE project. By collecting and presenting intuitively empirical findings, best practices, and quantitative insights into a single public accessible tool, the Impact Assessment Radar serves as a strategic enabler for broader EU urban freight policy goals. It equips local authorities, logistics service providers, and urban planners with the capability to not only measure and monitor innovation performance but also to forecast the outcomes of their decisions based on verified use cases. This positions the Radar as a important contribution of the URBANE project, supporting scalable, evidence-based transformation toward more sustainable logistics ecosystems.

1.1 URBANE Outputs Mapping to GA Commitments

TABLE 2: DELIVERABLE ADHERENCE TO GRANT AGREEMENT DELIVERABLE AND WORK DESCRIPTION.

URBANE GA ITEM	URBANE GA ITEM DESCRIPTION	DOCUMENT CHAPTER(S)	JUSTIFICATION
	DELIVERABLE		
D3.5 Data-driven Impact Assessment Radar	*D3.5 will deliver the decision support system used in LLs and APIs, providing a single access point for decision makers to useful tools and information to assist the successful design, implementation, or upscaling of innovative urban logistics business models.*	Chapters 2 & 3	*This deliverable presents the architecture, functionalities and interoperability of the Data-Driven Impact Assessment Radar It also presents methodological framework, the different dashboards and explains the different outcomes and KPIs displayed. Finally, IAR is showcases it's practical application on two URBANE Wave 1 Living Labs and their respective Use cases.*
	TASK		
Task 3.7 Data-driven Impact Assessment Radar	*ST3.7.1 Developing an Impact Assessment Radar* *ST3.7.2 Developing a Data-Driven Planning & Monitoring Toolbox*	Chapters 2 & 3	• **Outcome 1:** Definitions of the PI-led city logistics ecosystem and the main impact areas. • **Outcome 2:** Design and development the Data-driven Impact Assessment Radar
ST3.7.1 Developing an Impact Assessment Radar	*An intermediation tool for holistic impact identification. By using this Radar, the project aims to comprehend how the various elements of a city logistics ecosystem and the main principles of a smart city concept affect the impact assessment process and set the ground basis of the impact assessment framework (Task 4.1) by proposing the main impact areas and categories that a city planner is invited to consider when assessing the effectiveness and efficiency of a new city logistics business model. The three dimensions of the sustainable development (economy, society, and environment) as well as the main principles of a life cycle analysis will be taken into consideration while the behavioural as well as the adaptation and transferability aspects of a city logistics innovation will also be included in the analysis.*	Chapter 3	*It identifies the main impact areas and categories. Based on the principles of the smart city concept, these areas are defined so that city planners can assess the effectiveness and efficiency of new business models. The impact assessment framework covers all the dimensions of sustainable development; economic, social, and environmental together with the main principles of life cycle analysis. A list of KPIs was selected for each LL considering the pilot goal and objectives together with the available data. These KPI lists were then fed into the ST3.7.2 and visualized for each city through the Impact Assessment Radar platform.*
ST3.7.2 Developing a Data-Driven Planning & Monitoring Toolbox	*This subtask will focus on creating a toolbox for facilitating the data-driven planning, decision making, and monitoring of new innovative city logistics business models. One of the main functionalities of the toolbox will be a live dashboard for providing a unified view on the key strategic, tactical, and operational assessment metrics that will be extracted from the project and becoming a central point for data gathering and extracting of valuable information. Additional functionalities will be the inclusion of capacity building and decision support tools that have either been developed*	Chapter 2, 3 & 4	*This sub tasked developed the Data-driven Impact Assessment Radar which is accessible through the platform in three main levels: strategic, operational, and impact assessment. Each level is described in detail covering its functionality, purpose, required inputs, expected outputs, and interoperability aspects.* *In addition, it defines the data specifications to allow seamless interaction between the IAR and the Living Labs to ensure the exchange of the necessary data. It also presents the dashboard*

as part of the project or were already available by previous EU initiatives. The aim of this task is to provide a single access point for any decision maker on useful tools and information that will help the successful design, implementation, or upscaling of an innovative urban logistics business model. The tools that will be incorporated in the URBANE Toolbox will be assessed in view of their applicability and usability in relation to the impact area and innovation they address, the level of capacity building, and their expected outcomes.

that visualizes the results from the different Living Labs and explains the KPIs displayed.

1.2 Deliverable Overview and Report Structure

The structure of the deliverable is organized to progressively introduce the logic behind, methodology, and application of the IAR. The deliverable thus serves as both technical documentation and a strategic roadmap for cities aiming to adopt sustainable and data-driven urban logistics solutions.

Chapter 2 opens with a contextual overview of the challenges currently facing urban logistics systems. It then introduces the IAR's core purpose and functionalities, providing a high-level understanding of how it supports structured decision-making and scenario-based planning.

Chapter 3 presents in depth the methodological framework that underpins the IAR's design, detailing its three functional levels ranging from an assessment of city readiness and maturity toward innovation, to a suite of planning models based on continuous approximation, and a benchmarking observatory that collects and shares results from real-life implementations. Each level corresponds to a key step in the planning process, offering users a stepwise path from strategic assessment to operational configuration and impact monitoring.

Chapter 4 focuses on practical application, presenting two use cases from Thessaloniki and Bologna Living Labs. These examples demonstrate how the IAR can be used to support pilot planning, infrastructure sizing, and operational strategy. The chapter also generalizes the application of the tool by providing a detailed documentation of its input parameters, generated outputs and reports, and implementation guidelines. These sections are intended to help other cities and logistics actors engage effectively with the IAR and integrate it into their planning processes.

Chapter 5 presents the conclusions of report. In more detail, it provides a complete narrative of the tool's purpose, design, and utility offering both a conceptual understanding and a practical guide for future users.

2. Data-driven Impact Assessment Radar

2.1 The challenges on implementing urban logistics ecosystems

The rapid growth of e-commerce has profoundly transformed supply chain structures, placing increased emphasis on the "last-mile" which refers to the final step in the delivery process from distribution nodes (depots, warehouses) to end consumers. This segment of the supply chain is notably complex and resource-intensive, accounting for approximately 10% to 20% of urban vehicle kilometres travelled, and contributing to roughly 15% of urban greenhouse gas emissions [1]. More critically, last-mile delivery operations are responsible for up to 40% of total logistics-related emissions, represents more than half of overall logistics costs[2]. These figures underscore the urgent need for sustainable and efficient solutions inspired by the Physical Internet (PI), a logistics paradigm advocating open, interconnected, and collaborative transport networks.

A major challenge in last-mile logistics is its environmental footprint. Traditional delivery methods often rely on inefficient routing and frequent stops, which exacerbate urban air pollution, greenhouse gas emissions, and noise. Congestion from freight vehicles further worsens these impacts, reducing urban residents' quality of life. At the same time, the lack of supporting digital and physical infrastructure- such as electric vehicle charging networks and delivery microhubs- slows the deployment of environmentally friendly solutions. These gaps highlight the need for strategic planning frameworks to evaluate readiness and guide sustainable logistics adoption.

Economic factors constitute another considerable barrier to implementing green, Physical Internet-inspired last-mile solutions. High operational costs, primarily driven by expenses related to fuel consumption, vehicle maintenance, and labour, often discourage logistics companies from transitioning toward more sustainable alternatives. Furthermore, the significant investment required for new technologies such as autonomous delivery vehicles, micro-hubs, and smart lockers can discourage stakeholders. Moreover, many logistics companies face uncertainties regarding the scalability of pilot solutions. While some innovative solutions have demonstrated promising results in isolated pilot scenarios, the challenge of scaling these implementations cost-effectively across entire urban areas

[1] European Commission. Recommendations on Urban Logistics – Sustainable Urban Logistics Planning (SULP). Expert Group on Urban Mobility, adopted 5 December 2024. Available at: https://transport.ec.europa.eu/document/download/b818ff86-2463-4949-9413-d3ca559f60b9_en (accessed 28 August 2025).

[2] Kayikci, Yasanur & Zavitsas, Kostas & Franklin, Rod & Cebeci, Merve Seher. (2023). Physical Internet-driven last mile delivery: Performance requirements across people, process, and technology.

remains substantial. Therefore, robust strategic planning and decision-support systems are necessary to address these economic concerns effectively.

Adopting advanced logistics solutions based on the Physical Internet concept introduces several technological and infrastructural difficulties also. A major challenge is the lack of interoperability between different logistics systems, limiting their integration into a seamless, interconnected urban freight network. Additionally, the maturity and reliability of emerging technologies, such as autonomous delivery vehicles, digital twins, and smart lockers, remain uncertain. These technologies require substantial investments and rigorous testing to ensure consistent and reliable operations. Moreover, existing urban infrastructure often lacks sufficient capacity, including limited urban space, insufficient power grid capability for electric vehicle charging, and inadequate digital infrastructure necessary to support sophisticated logistics platforms. These issues emphasize the importance of comprehensive planning frameworks capable of evaluating infrastructural readiness and guiding technological integration.

The implementation of innovative logistics solutions frequently encounters regulatory challenges, especially concerning novel technologies such as autonomous delivery vehicles and drone deliveries. Regulatory frameworks often lag behind technological advancements, resulting in uncertainty that hold back operational feasibility and delays wider adoption. Additionally, urban zoning regulations may restrict optimal placement and operation of logistics micro-hubs and locker stations, limiting their potential efficiency gains. Privacy concerns related to data sharing and user interactions with technologies such as smart lockers also raise important governance and public acceptance issues. These regulatory and governance-related challenges underline the necessity of tools that can navigate complex urban regulatory landscapes, facilitate stakeholder collaboration, and ensure compliance with local policies and regulations.

Several Physical Internet-inspired solutions, such as shared micro-hubs, smart lockers, autonomous delivery vehicles, and crowdshipping, face unique implementation challenges. Micro-hubs, which consolidate and redistribute goods closer to end consumers, encounter difficulties in location selection due to limited space availability, stakeholder coordination, and replication across different urban contexts. Shared smart lockers, though efficient, involve high initial installation costs and ongoing maintenance expenses, along with user privacy concerns and sharing mechanisms [3]. Autonomous delivery vehicles offer significant potential for sustainable delivery, yet their deployment is slowed by stringent regulatory approvals, safety concerns, liability questions, and public acceptance challenges. Each of these solutions demand targeted assessment mechanisms to evaluate risk, costs, and benefits before full-scale deployment.

Successful implementation of green logistics solutions inspired by the Physical Internet concept fundamentally relies on effective stakeholder collaboration. However, competitive pressures among logistics providers often create resistance toward cooperation and data sharing, limiting the efficiency gains achievable through interconnected and collaborative logistics networks. Additionally, the absence of standardized protocols and unified operational frameworks further complicates large-scale collaboration. Overcoming these organizational barriers requires careful planning, structured governance

[3] Beck, K., Esquillor, J., Zarei, M.M. *et al.* Making last mile logistics models aware of customer choices, demand sustainability and data economy. *Eur. Transp. Res. Rev.* **17**, 29 (2025). https://doi.org/10.1186/s12544-024-00683-9

mechanisms, and neutral platforms capable of facilitating multi-stakeholder partnerships, standardized communication, and data exchange.

Given the complexity of the challenges discussed, a comprehensive and structured planning tool is essential to facilitate the adoption of sustainable logistics solutions. The IAR Tool developed within URBANE addresses these needs across three integrated dimensions. Firstly, the tool evaluates urban areas' maturity and readiness to implement green, digital and Physical Internet logistics solutions. This assessment identifies critical gaps and areas requiring targeted improvement before sustainable solutions can be effectively deployed. Afterwards, the tool incorporates a strategical planning approach, leveraging continuous approximation modelling techniques to support decision-making at higher abstraction levels, thereby addressing economic viability, infrastructural constraints, and operational feasibility. Finally, the tool assesses the specific impacts and outcomes of implemented solutions across diverse urban contexts, providing stakeholders with empirical evidence of success factors, barriers, and effective practices. By integrating these dimensions, the IAR Tool significantly enhances stakeholders' ability to overcome identified challenges, strategically plan sustainable logistics implementations, and facilitate robust decision-making aligned with urban sustainability objectives.

2.2 Overview and architecture of the system

The Impact Assessment Radar brings together a range of new and existing tools from other EU projects to offer a comprehensive set of functionalities for data-driven planning, decision-making, and monitoring of innovative urban logistics business models. It is designed to support urban logistics stakeholders—particularly those involved in Living Labs—in making informed and structured choices when exploring last-mile delivery solutions.

By integrating three planning levels—strategic, tactical, and operational—the tool enables users to assess the maturity of their logistics ecosystem, anticipate the requirements of future interventions, and draw on concrete examples from other urban contexts. This layered approach helps cities design and test solutions more effectively within the broader URBANE Transferability Platform, serving as a bridge between high-level policy ambitions and data-driven implementation planning.

The aim is to provide a single access point for decision-makers to access tools and information that facilitate the successful design, implementation, and upscaling of innovative urban logistics business models. Specifically, the toolbox offers three levels of analysis:

- **Level 1/Readiness:** What should I improve in my ecosystem?
- **Level 2/Design:** What is the best solution to choose?
- **Level 3/Performance:** How does the operation of the innovative UL solution perform?

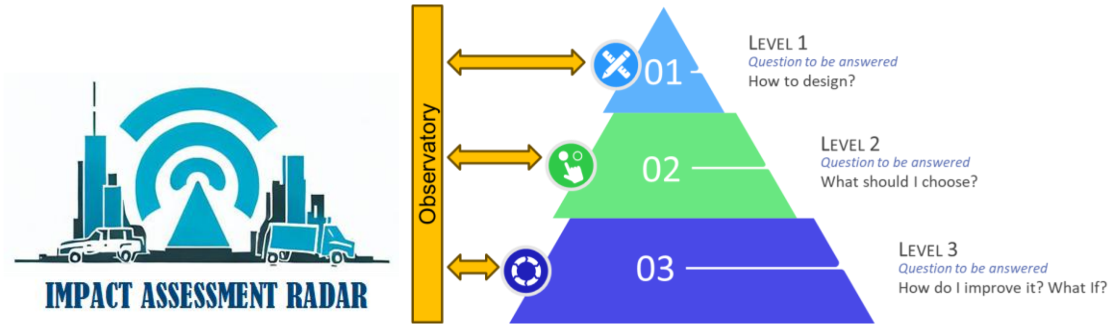

FIGURE 1: The Impact assessment radar and the levels of analysis

2.2.1 Level 1 – Strategic planning

This level is a *macro-scale* assessment and aims to address the question "What should I improve in my ecosystem?" or to understand the readiness level of a city to implement innovative urban logistics solutions. This level will help the planner to understand the city's Innovation Readiness for urban logistics and highlight the city's Insufficiencies that need improvement. It is designed to evaluate the organizational readiness of a city to implement city logistics innovations by assessing the capacity of the urban logistics ecosystems in terms of governance, sustainability, infrastructure, actors, accessibility, and safety. This will help the planner to design and implement more effective solutions that meet the needs and preferences of different stakeholders, such as customers, operators, authorities, and citizens. The primary goal of this tool is to inform and guide cities regarding the areas of the city that need to be strengthened to build a **Sustainable Urban Logistics Planning (SULP)**.

Figure 2: Illustrative result of the level 1 module

2.2.2 Level 2 – Tactical planning

This level is a meso-scale assessment which aims to address the question "What is the best solution to choose?" or to optimize the utilization of the selected urban logistics solution (designing PI-led urban logistics solutions). In this term, the Impact Assessment Radar will provide tools to maximize the impact of the selected solution.

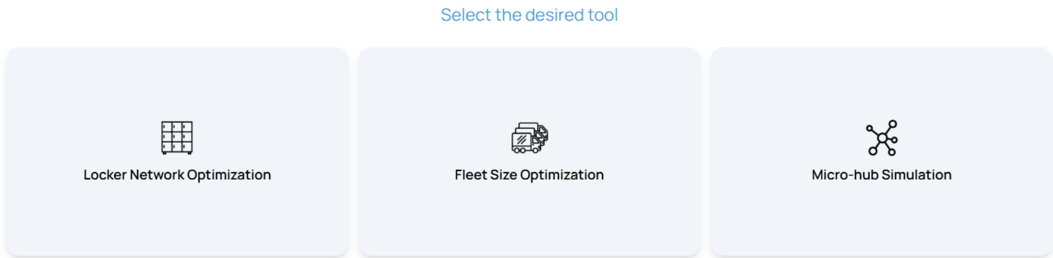

Figure 3: Level 2 available models landing page UI

One of the three key available scenarios supporting tactical planning within the Impact Assessment Radar is the **Integrated Locker Network Optimization model**. This tool enables decision-makers to determine the optimal number of parcel lockers for a given urban area, helping reduce the cost and environmental impact of last-mile delivery services. The model accounts for critical operational and economic variables such as daily parcel demand, service area size, locker capacity, capital and maintenance costs, delivery vehicle speed, fuel costs, labour time, and customer walking behaviour. By integrating these variables into a non-linear cost optimization framework, the tool identifies the configuration that minimizes the total cost per parcel while maintaining service quality and infrastructure feasibility.

The user interface provides an interactive platform where users can input real-world data and adjust parameters via sliders or direct entry fields. Once parameters are defined, the tool generates a curve plotting cost per parcel against the number of lockers deployed, clearly identifying the cost-minimizing locker count. In addition to highlighting the optimal point, the tool visually breaks down total costs into components (locker investment, maintenance, and home delivery costs), allowing for informed, data-driven evaluations. Users can explore how different strategies, such as increasing locker capacity or shifting delivery modes, affect both financial and environmental outcomes.

This optimization tool is grounded in the modelling framework developed in section 3.3, which conceptualizes customer behaviour using a distance-based quadratic function for self-pickup likelihood. It also incorporates spatial assumptions for uniform locker distribution and service area geometry. Embedded in the Impact Assessment Radar, the tool supports planners in evaluating realistic infrastructure deployment scenarios, balancing cost-efficiency with user accessibility.

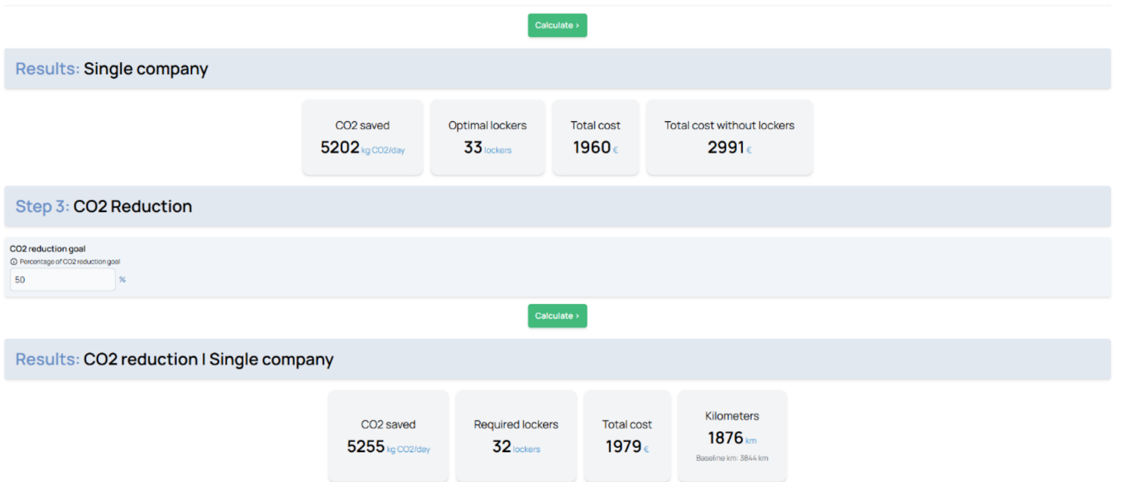

Figure 4: The output UI example of level-2 tools

Another central tool for tactical planning is the **Microhub-Based Urban Delivery Model**. This module quantifies and compares traditional van-based last-mile delivery with a hybrid micro-hub system that combines parcel lockers with cargo bike delivery. Users are guided through a set of adjustable parameters including depot numbers, service area size, parcel demand, vehicle capacities, cost factors, and self-pickup likelihood. The model uses a behaviour-based approach to divide demand between self-pickup and home delivery, depending on the customer's distance from lockers. By calculating investment, operational, and delivery costs for each scenario, the model highlights cost-optimal configurations while enforcing locker capacity constraints.

Likewise, the **Fleet Optimization Module** supports tactical fleet planning by recommending the optimal mix of vehicles to satisfy daily parcel demand while meeting environmental goals. Users can input city-specific parameters for area size, number of depots, delivery volumes, and details for each vehicle type, including fuel type, cost per kilometre, capacity, emissions factor, and acquisition cost. The model employs a numerical approach to allocate demand fractions across different modes and introduces a smooth ceiling approximation to estimate the required number of vehicles. It aims to minimize total operational cost while ensuring CO_2 emissions fall within a defined range.

2.2.3 Level 3 – Operational evaluation knowledge base

This level is a *micro-scale* assessment which aims to address the question "How does the operation of the innovative urban logistics solution perform?" or to present different operational scenarios for a city and identify the most effective one. Thus, Level 3 consolidates the empirical results derived from the application of the URBANE business models in the project's Living Labs. It bridges the gap between theoretical models and real-world execution by translating field-based insights into actionable intelligence for other cities and stakeholders.

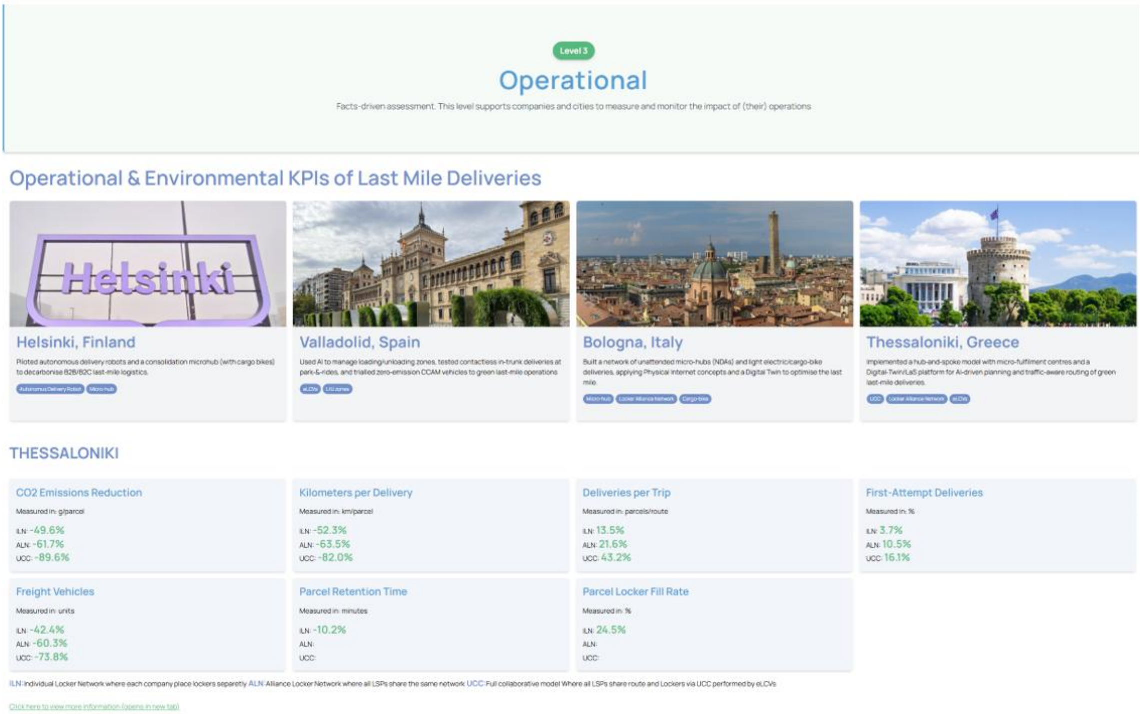

Figure 5:The UI of level-3 of IAR

2.3 URBANE Transferability Platform and Impact Assessment Radar Integration Framework

The Impact Assessment Radar has been designed to guide users and particularly urban planners and decision-makers through a seamless, intuitive process for assessing and planning last-mile logistics innovations. It mirrors the logical flow of a traditional planning study while significantly reducing the complexity and time investment typically required for such analyses. Rather than aiming to replace in-depth feasibility studies, the IAR serves as a decision-support accelerator, automating foundational tasks and structuring the planning process in a modular, data-driven manner.

The Level-2 tactical module of the Impact Assessment Radar (IAR) enables users to design and test system configurations for selected innovations. It allows planners to assess feasibility and develop optimized versions of innovative last-mile logistics services before full-scale simulation or deployment. Moreover, the Level-2 module serves as a gateway to the analytical models available within the URBANE Transferability Platform. Outputs from the IAR can be transferred to the URBANE Transferability Platform as illustrated in Figure 6, where more advanced models related to last-mile operations—such as facility location models, collaborative routing solvers and Agent-Based Models enable more sophisticated, micro-level scenario simulations or optimised logistic operations. Lastly, the updated results are then uploaded back into the IAR to support benchmarking, cross-city comparisons, and validation against previous case studies. This iterative process links high-level assessment with detailed modeling, ensuring robust, evidence-based planning of innovative last-mile logistics solutions.

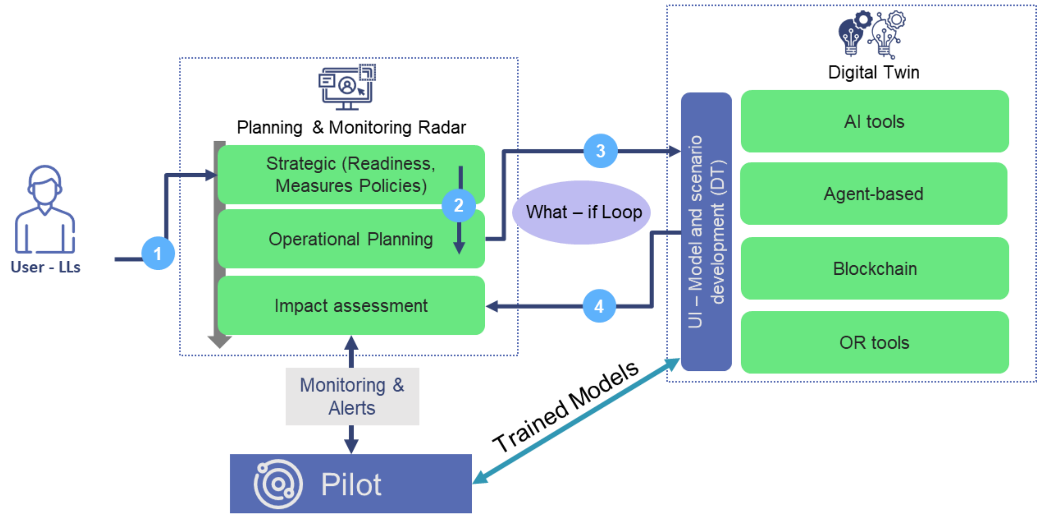

FIGURE 6: The Architecture of the Impact Assessment Radar

For example, one of the central Level-2 tools is the Locker Network Optimization Module, which provides estimates for the optimal number of parcel lockers required in a given area. It offers two configurations: one for individual service providers and one for collaborative locker alliance networks. These results can be directly fed into the URBANE facility location model, collaborative routing model, and Digital Twin module for detailed spatial and operational evaluation. Additionally, when assessing behavioural and network dynamics, these outputs can be enriched through the Agent-Based Model (ABM) to explore multi-actor scenarios. This approach was piloted in the Thessaloniki Living Lab, where the locker alliance configuration was used to evaluate cost efficiency and emissions reduction across stakeholders.

The Fleet Mixture Optimization Module assists planners in identifying the optimal fleet composition balancing diesel vans, electric vehicles, cargo bikes, and autonomous delivery vehicles (ADVs) to achieve specific sustainability targets (e.g., CO_2 reduction). These configurations are particularly effective when paired with the COPERT emissions model to calculate pollutant reductions or when used in the Digital Twin to simulate routing impacts under realistic demand and network conditions. The model can also estimate the number of ADVs needed to sustain operations, and its outputs can be coupled with the ABM to explore behavioural KPIs such as customer acceptance and service reliability. This methodology was deployed in the Valladolid and Helsinki Living Labs to support evidence-based fleet transitions.

Finally, the Micro-Hub Optimization Module addresses two-echelon logistics design by computing the optimal number and size of urban micro-hubs. In this model, the first delivery layer is served by conventional or electric vans, while the second echelon utilizes cargo bikes distributing parcels via locker-equipped hubs. The module’s outputs are designed to directly populate the Digital Twin for spatial simulation and to integrate with the collaborative two-echelon routing model offered by the URBANE platform. This configuration was applied in the Bologna Living Lab, where it supported both tactical resource planning and operational evaluation of a hybrid delivery network.

3. Methodological Framework of Impact – Assessment Radar

3.1 Introduction

The rapid pace of urbanization provides the context for the emergence of smart cities, where advanced technologies are used to improve residents' quality of life. However, this development carries environmental impacts. Urban centres, despite their innovations, have become major sources of increasing pollution. A large share of this pollution comes from transportation, industrial processes, and energy production from fossil fuels. The UNEP reports that urban areas are responsible for about 75%[4] of global carbon emissions, with cities contributing roughly 70%[5] of CO_2 emissions through fuel use in transport, heating, cooling, and power generation. Additionally, urban industries emit CO_2, various pollutants, and particulate matter.

In transportation (one of the primary emission sources) road traffic alone accounts for over 30% of urban emissions in one-third of the world's cities, while rail, waterways, and aviation together contribute less than 15%[6]. Urban transport is also responsible for more than half of all nitrogen oxide (NO_x) emissions and about 10% of non-methane hydrocarbons, both of which promote ozone and $PM_{2.5}$ formation through atmospheric reactions [7].

City logistics, critical to urban economies, also generates significant pollution. Transitioning to lower-emission logistics requires policies and incentives for electric or low-emission vehicles in last-mile delivery, cargo bikes or drones, and real-time tracking with route optimization. These measures can reduce carbon footprints while maintaining efficient freight movement.

The growth of e-commerce further strains urban logistics: last-mile deliveries are projected to increase delivery vehicles in cities by 36% by 2030 [8], worsening emissions and congestion and counteracting European environmental goals. Therefore, innovative solutions such as parcel lockers, crowdsourced

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[4] Silvia Vásquez-Sánchez, Aldo Alvarez-Risco, and Shyla Del-Aguila-Arcentales, "Sustainable Urban Form and Design," in *Building Sustainable Cities: Social, Economic and Environmental Factors*, ed. Aldo Alvarez-Risco, Marc A. Rosen, Shyla Del-Aguila-Arcentales, and Dora Marinova, 1st ed. (Cham: Springer, 2020), 137–147.

[5] Urban Climate Action Is Crucial to Bend the Emissions Curve | UNFCCC

[6] 52% of World's Greenhouse Gas Emissions Come From Just 25 Cities | World Economic Forum

[7] Ken Gwilliam, Masami Kojima, and Todd Johnson, *Reducing Air Pollution from Urban Transport*, Energy Sector Management Assistance Program (ESMAP) and International Bank for Reconstruction and Development / World Bank, June 2004

[8] World Economic Forum, *"Urban Deliveries Expected to Add 11 Minutes to Daily Commute and Increase Carbon Emissions by 30 % until 2030 without Effective Intervention"*, press release, January 10, 2020: "Growing demand for e-commerce delivery will result in 36 % more delivery vehicles in the world's top 100 cities.

delivery, shared distribution hubs, and smart lockers along with policies favouring low-emission vehicles and pedestrian- and cyclist-friendly streets are essential.

In academic research on sustainable urban logistics, the PI offers a novel paradigm. Analogous to the digital Internet, PI envisions an open, global logistics network with standardized containers and intelligent routing to optimize resources and minimize environmental impact. Although the ultimate aim is a PI-driven city logistics system, a clear framework for SULP is needed first. This framework establishes baseline principles of sustainability, efficiency, and resilience while it focuses on emission reduction, energy efficiency and greener transport modes in urban freight systems. Developing a SULP represents a prerequisite step toward a PI-based logistics ecosystem, leveraging technology, policy measures, and innovative practices to create a low-carbon, efficient urban freight network.

This phased strategy emphasizes building a solid foundation of sustainable logistics practices and technologies, which can later be expanded into the broader Physical Internet framework. By following this roadmap, cities can enhance logistics sustainability and efficiency before transitioning to a fully PI-enabled urban logistics ecosystem.

Thus, the questions that are raised within URBANE are:

- **Obj. 1:** *What should be done by a city authority to enable the development of a SULP?*
- **Obj. 2:** *How ready and mature is a city's urban logistics system to become innovative?*

3.2 Innovative green urban logistics ecosystem maturity evaluation methodology

The ecosystem approach in urban mobility research marks a sophisticated evolution in how planners and policymakers conceptualize and address the intricate dynamics of urban transportation systems. This methodology advocates for a comprehensive examination of urban mobility, viewing it as a complex network comprised of various interconnected elements. These elements span physical infrastructures like roads and transit systems, alongside technological advancements, regulatory landscapes, and the diverse behaviours of transport users. Contrary to traditional methodologies that might focus on singular modes of transport, such as buses, trains, or bicycles, the ecosystem approach encourages a broad overview, recognizing the symbiotic relationships and feedback loops within the broader urban transport system. Integral to this approach is the principle of collaboration and inclusive stakeholder engagement. Urban mobility challenges are inherently complex, necessitating a collaborative effort across a broad spectrum of stakeholders, including but not limited to academic researchers, governmental policymakers, local authorities, private sector actors, and community groups. This cooperative model facilitates the pooling of data, resources, and expertise, paving the way for the co-development of tailored, innovative solutions that are responsive to the nuanced demands of urban settings.

The advantages of employing an ecosystem perspective in urban transport research, foundational to understanding both passenger and freight movement, are significant. Firstly, it facilitates the diversification of revenue sources, blending traditional funding mechanisms with emerging models like data monetization and mobility-as-a-service platforms. Secondly, this approach stimulates innovation, offering fertile ground for the trial and adoption of novel mobility solutions, including but not limited to micro-mobility services, shared electric vehicles, and intelligent infrastructure projects. Lastly, and perhaps most critically, it champions the development of user-centric policies and solutions. By taking into account the full spectrum of the urban mobility ecosystem, the approach ensures that policies are designed with a keen focus on improving accessibility, affordability, safety, and environmental sustainability, thereby significantly enhancing the efficacy and resilience of urban transportation networks.

In more detail, this methodology which integrates physical infrastructures, technological innovations, regulatory landscapes, and transport user behaviour, represents a departure from the traditional focus on singular transport modes. It emphasizes the importance of understanding the symbiotic relationships and feedback loops within the urban mobility system (Karjalainen & Juhola, 2021). Karjalainen and Juhola (2021) criticize the current academic landscape for its narrow focus and call for a more inclusive and comprehensive assessment methodology that captures the full breadth of urban mobility ecosystems. This sentiment is echoed in the work of Flügge (2017), who discusses Smart Mobility as a critical design element for urban habitats, suggesting that sustainable urban transportation systems must thoughtfully integrate smart mobility solutions. Furthermore, Hakkarainen (2017) delves into the business ecosystem of Mobility-as-a-Service (MaaS), highlighting the potential of such models to innovate and diversify revenue sources within urban mobility. The principle of inclusive stakeholder engagement is central to this approach, advocating for collaboration across a spectrum of stakeholders, including academic researchers, policymakers, and community groups. This collaborative model is instrumental in co-developing tailored solutions that are responsive to the complex needs of urban environments (Avramakis et al., 2019).

Employing an ecosystem perspective in urban mobility research offers substantial advantages. It facilitates the diversification of revenue sources, stimulates innovation by providing a fertile ground for the trial and adoption of novel mobility solutions, and champions the development of user-centric policies and solutions. By taking into account the full spectrum of the urban mobility ecosystem, policies and solutions can be designed to improve accessibility, affordability, safety, and environmental sustainability, thereby enhancing the efficacy and resilience of urban transportation networks (Hakkarainen, 2017; Flügge, 2017; Avramakis et al., 2019).

The SPROUT methodology represents a pioneering approach in the comprehensive study of urban mobility by not only focusing on passenger transportation but also integrating the logistics sector into its analysis. This initiative marks the first time that efforts have been made to holistically capture both these aspects within the same framework. The significance of including logistics, alongside passenger mobility, stems from the understanding that both are critical components of urban mobility systems, deeply interlinked and affecting cities' efforts towards achieving climate-neutral and sustainable urban mobility goals. By employing a three-step approach that combined a systematic review of literature, lessons learned from participatory methods, and consensus-building techniques, along with prioritization and multi-criteria analysis techniques, SPROUT aimed to develop a robust framework. This framework was designed to assist municipal governments and policymakers in assessing a city's capacity and maturity for adopting and implementing innovative mobility solutions. These solutions encompass both passenger and freight dimensions, highlighting the interconnectedness of these sectors and the need for a unified strategy to address urban mobility challenges comprehensively. Through this innovative methodology, SPROUT has laid the groundwork for future urban mobility planning and policy-making, ensuring a more inclusive and integrated approach towards the development of sustainable and efficient transportation systems in cities.

Building on the pioneering work of the SPROUT methodology, URBANE plans to take these insights further by evolving and integrating them into an innovative urban logistics ecosystem. This strategic enhancement is aimed at capturing specifically the complexities of urban logistics, an area of increasing importance as cities worldwide strives for sustainability and efficiency in their transport networks. By focusing on urban logistics, URBANE seeks to address the critical challenges associated with freight systems within urban environments, both for planning, infrastructure, and actors' engagement, amongst others. The evolution of the SPROUT framework by URBANE signifies a dedicated effort to develop comprehensive, innovative solutions that not only encompass the entirety of urban mobility but also place a significant emphasis on the logistics sector. This targeted approach is expected to contribute significantly to the creation of more resilient, climate-neutral, and sustainable urban environments. Through this ongoing development, URBANE aims to provide municipal governments, policymakers, and stakeholders with the tools and knowledge necessary to foster a harmonious integration of passenger and freight transportation systems, thereby enhancing the overall quality of urban life.

3.2.1 The elements of the innovative urban logistics ecosystem

Cities need guidance to adopt an innovative city logistics system, and to achieve that, they need to:

- address how ready and mature a city logistics system is to introduce the Physical Internet concept.
- measure the city's performance at the current time. The first step toward this transformation is the definition of a general innovative urban logistics ecosystem.

While the ecosystem approach broadly describes the key elements of a transport system aimed at creating a more efficient, sustainable, and user-friendly mobility experience in urban areas, for the context of URBANE, this approach is specifically tailored to urban logistics. These kinds of focused approaches are important since they can help cities address the challenges and opportunities of urban freight transport in a more integrated, efficient, and sustainable way. The following six elements were defined based on the results of a comprehensive literature review and knowledge from previous EU programs, with a specific lens on their relevance to urban logistics.

SMART GOVERNANCE: is the strategic and operational backbone of the urban logistics ecosystem, integrating advanced planning, policy development, and stakeholder collaboration. It ensures that the ecosystem is guided by a clear vision, supported by adaptable regulations, and driven by data-informed decisions specifically for freight movement and last-mile delivery. This governance structure enables the ecosystem to respond dynamically to technological advancements, environmental challenges, and evolving urban demands in logistics operations (Xenou et al., 2022).

SMART & INNOVATIVE RESOURCES & INFRASTRUCTURE: represents the physical and digital foundation that enables innovative logistics solutions. It includes the deployment of smart infrastructure (e.g., dedicated loading zones, urban consolidation centres, smart traffic management for freight), regulatory environments conducive to innovation in logistics, and the integration of technologies such as IoT and AI for tracking, routing, and inventory management. By providing the necessary resources and infrastructure, it underpins the ecosystem's ability to support sustainable urban logistics practices, enhance operational efficiencies, and adapt to future logistics models (Khan et al., 2013).

SMART ACTORS: are the key drivers of innovation and collaboration within the urban logistics ecosystem. They encompass logistics service providers, city planners, technology developers, retailers, e-commerce platforms, and the community (as recipients of deliveries), all working together to implement and optimize smart logistics solutions. Through their collective expertise and use of advanced technologies, these actors foster a culture of continuous improvement, enabling the urban logistics ecosystem to thrive and evolve (Taniguchi & Thompson, 2015).

GREENESS & EFFICIENCY: reflects the integration of sustainable environmental management systems and low-carbon operations within the urban logistics ecosystem. It assesses the commitment of companies to minimizing their environmental impact by adopting clean energy sources, such as electric vehicles and renewable fuels, and by implementing strategies to reduce emissions from city logistics operations. This element also encompasses efforts to enhance operational efficiency, reducing waiting times, idle times, and empty runs, thereby optimizing resource use and decreasing the carbon footprint. It represents a holistic approach to achieving eco-friendly and efficient logistics practices, contributing to a more sustainable urban environment (Nasir S., 2022).

SMART & EASILY ACCESSIBLE CITY LOGISTICS NETWORKS: focuses on the connectivity and accessibility of logistics operations, facilitating the smooth flow of goods and information across the urban landscape. It emphasizes the development of multimodal transportation networks (e.g., integrating waterways, rail, and road for freight), standardized data exchanges for logistics operations, and collaborative platforms for last-mile delivery and freight consolidation. These networks ensure that the logistics ecosystem is flexible, resilient, and capable of supporting both current and future urban logistics needs efficiently (Khan et al., 2013).

SAFETY & SECURITY: describes commitment to how safety, security, and quality within the urban logistics ecosystem is fundamental to its success and sustainability. This element involves establishing rigorous standards, implementing advanced tracking and security technologies for goods in transit and logistics hubs, and ensuring regulatory frameworks are responsive to new challenges in urban freight movement. It guarantees that the logistics ecosystem not only meets but exceeds the expectations of its users, fostering trust and enabling high-quality service delivery of goods (Taniguchi & Thompson, 2014).

3.2.2 The sub-elements of an innovative urban logistics system

URBANE addresses these questions by building on the achievements of the H2020 SPROUT project, particularly its conceptual framework for assessing how prepared cities are to foster innovation and implement city-led policy responses. URBANE goes deeper into the analysis by specifically identifying the main elements of an innovative urban logistics ecosystem that affect the transferability and adaptability of city logistics innovations in other city environments. Since the overall goal of decarbonization is intrinsically connected to the PI concept, which is directly linked with the digital internet, it requires a higher level of smartness from the actors involved and the city’s system processes. Thus, this framework takes strongly into consideration the main pillars of the smart city concept and identifies six main PI-driven elements and 16 sub-elements, specifically tailored to the urban logistics context.

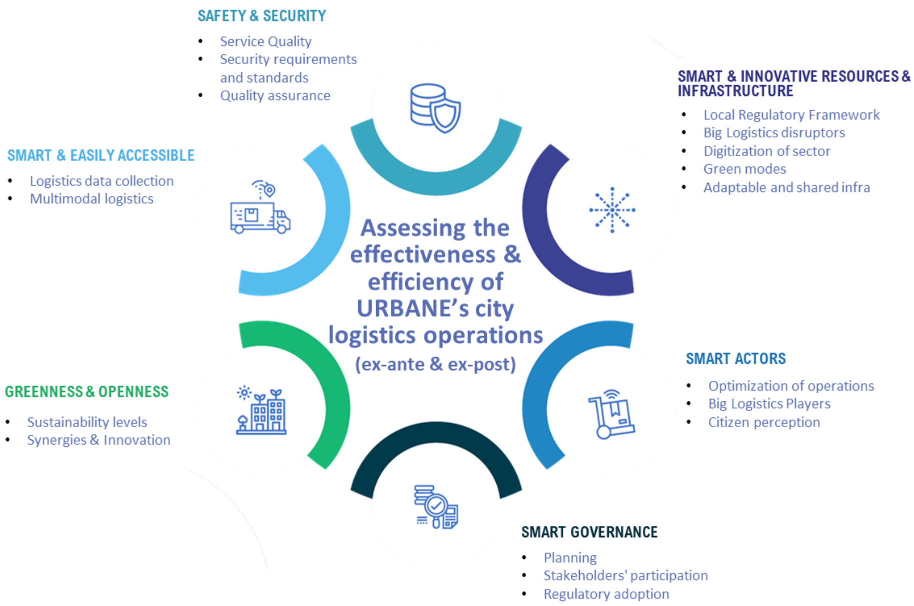

FIGURE 7: The readiness dimension of the city logistics ecosystem

SMART GOVERNANCE

1. **Planning:** The level of smartness in governance concerning city logistics planning, focusing on organizational agility, political stability, transparency, and cooperation among city departments regarding freight movement and goods delivery. It includes dedicated departments to innovation in urban logistics, experienced personnel, and long-term political support for sustainable strategies in urban freight.
2. **Stakeholders Participation:** The degree of involvement of various actors in the city logistics planning process, emphasizing collaboration, transparency, and engagement specifically for urban freight challenges. It includes building strong public-private relationships, fostering mutual collaboration, and utilizing tools like multi-stakeholder platforms and freight quality partnerships.
3. **Regulatory Adaptation:** The ability to adjust or develop policies and regulations to support decarbonized city logistics, considering innovation, flexibility, and data-driven approaches. It involves developing integrated, flexible, and data-driven regulatory frameworks, along with strategic plans like SULPs (Sustainable Urban Logistics Plan), to effectively manage and promote sustainable urban freight operations.

SMART & INNOVATIVE RESOURCES & INFRASTRUCTURE

1. **Local Regulatory Framework:** The set of rules, regulations, and ordinances established by local authorities to govern city logistics activities, addressing issues such as traffic management for commercial vehicles, emissions standards for delivery fleets, and infrastructure development to support logistics operations.

2. **Big Logistics Disruptors:** Innovative technologies, business models, or market trends influencing urban logistics, such as e-commerce advancements, autonomous vehicles for last-mile delivery, and shared mobility services (e.g., shared cargo bikes, micro-hubs), driving the transition towards decarbonized city logistics.
3. **Digitization of Sector:** The adoption and integration of digital technologies, data analytics, and information systems to optimize and streamline city logistics operations, enhancing efficiency, transparency, and decision-making in urban freight management.
4. **Green Modes:** Sustainable transportation alternatives reducing carbon emissions and environmental impact in city logistics, including electric vehicles, cargo bikes, and hydrogen-powered vehicles specifically for urban deliveries, supported by infrastructure (e.g., charging stations, bike lanes for cargo), and incentives.
5. **Adaptable and Shared Infrastructure:** Flexible and multi-purpose facilities and spaces supporting decarbonized city logistics activities, such as shared loading zones, urban logistics hubs (e.g., micro-consolidation centres, parcel lockers), and dynamic curb management systems for delivery vehicles.

SMART ACTORS

1. **Optimization of Operations:** Leveraging data, technology, and innovative practices to improve the efficiency, reliability, and sustainability of city logistics processes, including dynamic routing for delivery vehicles, real-time monitoring of freight movements, and demand forecasting for urban goods distribution.
2. **Big Logistics Players:** Major companies or organizations playing a significant role in urban logistics operations due to their scale, resources, and market influence, shaping the trajectory of decarbonization efforts within urban freight transport.
3. **Citizen Perception:** Attitudes, preferences, and behaviours of residents towards decarbonized city logistics solutions and initiatives (e.g., perception of delivery vehicles, noise, congestion), influencing the success and effectiveness of decarbonization efforts in urban goods movement.

SMART & EASILY ACCESSIBLE CITY LOGISTICS NETWORKS

1. **Logistics Data Collection:** Systematic gathering, processing, and analysis of information related to city logistics operations, providing valuable insights for planning, decision-making, and performance evaluation of urban freight systems.
2. **Multimodal Logistics:** Integration and coordination of different transportation modes to optimize freight movements and reduce carbon emissions in urban areas, facilitating efficient and comprehensive logistics operations (e.g., using rail or waterways for trunk haul and electric vans for last mile).

SAFETY, SECURITY & QUALITY

1. **Service Quality:** Level of satisfaction, reliability, and performance of city logistics services from the perspective of users and stakeholders (e.g., on-time delivery, condition of goods, professionalism of customer service), contributing to the effectiveness and competitiveness of decarbonized city logistics solutions.
2. **Security Requirements and Standards:** Establishment of measures and protocols to ensure the safety, integrity, and resilience of city logistics infrastructure and operations, addressing risks such as theft, vandalism, and cyber threats related to urban freight and delivery systems.
3. **Quality Assurance:** Monitoring, evaluation, and continuous improvement of decarbonized city logistics initiatives and interventions to uphold standards of excellence, reliability, and sustainability in urban logistics operations.

GREENESS & EFFICIENCY

1. **City Logistics System's Sustainability levels:** Assesses the environmental impact of logistics operations, focusing on reducing emissions, energy consumption, and waste from urban freight transport. This sub-element measures the adoption of sustainable practices and technologies, such as electric vehicles and renewable energy sources, in logistics operations within the city.
2. **City's Openness to Synergies & Innovation:** Evaluates the city's willingness to engage in innovative partnerships and adopt new solutions that enhance logistics efficiency and sustainability. It measures the city's proactive approach to fostering innovation, supporting pilot projects, and facilitating the integration of cutting-edge technologies in urban logistics systems.

3.2.3 Prioritization of the sub-elements

The allocation of specific weights to each sub-element was determined using the Analytic Hierarchy Process (AHP). Ten URBANE experts in urban logistics took part in this process. Their task was to prioritize 16 sub-elements of Innovation Readiness in urban logistics, based on inputs from ALICE, ITL, CERTH, EITUM, KLU, NORCE, VLTN, and TU Delft. To ensure robustness, it was assumed that all elements within the innovative urban logistics ecosystem carried equal weight. Therefore, a unique AHP was conducted for each sub-element of every component within the ecosystem.

The initial phase of the AHP involved constructing the A matrix (see Figure) based on feedback from URBANE experts. The 16 Innovation Readiness sub-elements were included as both rows and columns in the A matrix. Each weight (represented as w1, w2, w3, etc.) in the upper triangular portion of the A matrix corresponded to a pair of different sub-elements. URBANE experts were tasked with indicating:

i) which element they considered more significant, and
ii) how much more significant it was, using a scoring system ranging from 0 to 9 (refer to Table 1).

$$A = \begin{pmatrix} 1 & w1 & w2 & w3 & w4 & w5 & w6 & w7 & w8 & w9 & w10 \\ & 1 & w11 & w12 & w13 & w14 & w15 & w16 & w17 & w18 & w19 \\ & & 1 & w20 & w21 & w22 & w23 & w24 & w25 & w26 & w27 \\ & & & 1 & w28 & w29 & w30 & w31 & w32 & w33 & w34 \\ & & & & 1 & w35 & w36 & w37 & w38 & w39 & w40 \\ & & & & & 1 & w41 & w42 & w43 & w44 & w45 \\ & & & & & & 1 & w46 & w47 & w48 & w49 \\ & & & & & & & 1 & w50 & w51 & w52 \\ & & & & & & & & 1 & w53 & w54 \\ & & & & & & & & & 1 & w55 \\ & & & & & & & & & & 1 \end{pmatrix}$$

FIGURE 8: THE A MATRIX WHICH CONTAINS THE PAIRWISE COMPARISON OF ALL POSSIBLE COMBINATIONS OF CRITERIA

The score range can be described by the following table (Table 1):

TABLE 1: THE SCALE RANGE AND THE DESCRIPTION OF EACH VALUE, USED FOR AHP

Intensity of importance	Definition	Explanation
1	Equal importance	Two elements contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favour one element over another
5	Strong Importance	Experience and judgment strongly favour one element over another
7	Very strong importance	One element is favoured very strongly over another, its dominance is demonstrated in practice
9	Extreme importance	The evidence favouring one element over another is of the highest possible order of affirmation

** 2, 4, 6, 8 can be used to express intermediate values*

Then, the AHP was applied to the individual and consolidated expert responses. For each case, the consistency ratio and the weights of the sub-elements were calculated. The whole methodology is concluded in Figure 9.

- If the consolidated consistency ratio was calculated as lower than 10%, URBANE experts voted again (Step 1).
- When the consolidated consistency ratio was accepted (lower than 10%), the consolidated weights of the sub-elements were also selected.

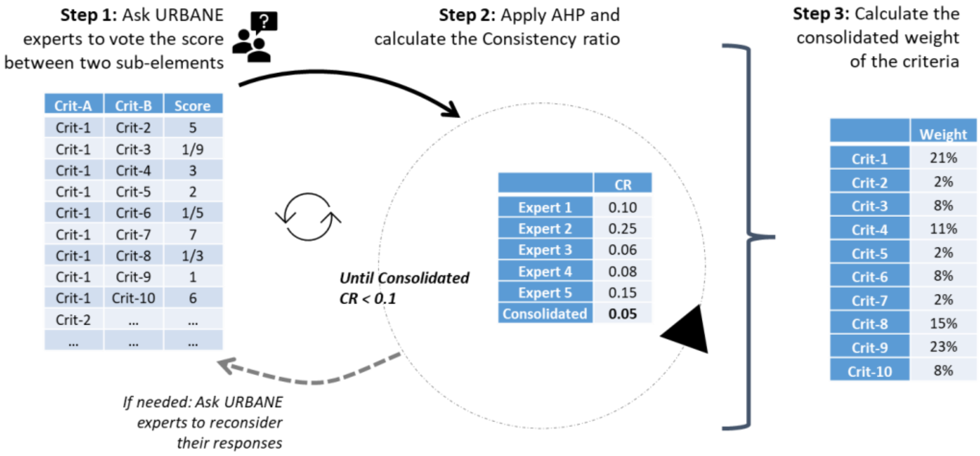

FIGURE 9. THE AHP PROCEDURE DEFINES THE WEIGHT OF THE SUB-ELEMENTS OF THE INNOVATIVE URBAN LOGISTICS ECOSYSTEM

3.2.4 An innovation readiness urban logistics self-assessment tool

In order to capture the current maturity level of a city to adopt innovative urban logistics solutions, a survey of 22 questions with a descriptive response scale was developed. This survey serves as a pivotal tool for cities, providing crucial support in the development of SULPs. Through this comprehensive questionnaire, cities can gather essential insights and data pertaining to various aspects of urban logistics, facilitating informed decision-making processes. The survey covers a wide range of topics crucial for the formulation and implementation of effective SULPs, including infrastructure, transport modes, environmental impact, and stakeholder engagement, among others. By engaging in this survey, cities can assess their current logistical landscape, identify areas for improvement, and tailor strategies to address specific challenges and opportunities. Moreover, the data collected through this survey enables cities to benchmark their performance against peers and gain valuable insights into best practices and emerging trends in urban logistics. Ultimately, the survey serves as a foundational step in the development of robust and sustainable logistical strategies that are tailored to the unique needs and priorities of each city, paving the way for enhanced efficiency, environmental sustainability, and liveability within urban environments.

SMART GOVERNANCE

Does the city have a vision for green and sustainable urban logistics plan?

- No Vision: The city has no defined vision for sustainable urban logistics.
- Basic Vision: The city recognizes the importance of sustainable urban logistics and has a general vision. However, this vision lacks detailed plans or quantifiable metrics for implementation and evaluation.
- Advanced Vision: The city's vision for sustainable urban logistics is detailed and measurable, targeting reduced emissions, better traffic flow, and more efficient deliveries by enforcing and supporting different stakeholders.

Does the city have strategic, long-term plans for sustainable urban logistics (e.g. SULP) to meet the visions, involving stakeholder co-creation?

- No Planning: No dedicated urban logistics planning.

- Plan Only: Plan for urban logistics exists, which considers the general vision of the city but no implementation yet.
- Developing & Implementing: SULP was developed and aligned with the quantified vision of the city with co-creation of stakeholders. It is partially implemented, and further development is ongoing.

How is the interrelation between SUMP and SULP articulated, and how is their alignment with national/local policies?

- Disconnected: No acknowledgment of SUMP and SULP interrelation. Plans operate independently without alignment with any policies.
- Developing Coordination: Initial efforts to coordinate SUMP and SULP are underway, with early stages of policy alignment visible.
- Fully Integrated and Aligned: SUMP and SULP are seamlessly integrated, complementing each other with strong alignment with national and local policies, showcasing comprehensive urban mobility and logistics planning.

Is there a dedicated team/department/responsible person for orchestrating and planning city logistics (infrastructure, operations)?

- No Dedicated Team: There is no dedicated team specifically assigned to sustainable urban logistics planning within the city.
- Emerging Team: A dedicated team for sustainable urban logistics planning exists, but it is in the early stages of development and may not be fully equipped or staffed.
- Robust Team: The city boasts a robust and well-established dedicated team for sustainable urban logistics planning, with experienced staff, clear objectives, and effective coordination mechanisms in place.

How data-driven is the current planning process, and to what extent are dedicated tools utilized?

- No Data Utilization: The current planning process lacks data-driven approaches, and there are no dedicated tools utilized.
- Minimal Data Utilization: Data-driven approaches are sporadically used in the planning process, with minimal utilization of dedicated tools.
- Comprehensive Data Utilization: The planning process is highly data-driven, with comprehensive utilization of dedicated tools at every stage, leading to sophisticated analysis and strategic decision-making.

How is communication facilitated among municipality departments and region, for coordinating and planning city logistics?

- Silos: Minimal communication, departments operate in isolation.
- Effective Internal Communication: Good communication and collaboration internally, but without external consultants.

- Joint Working Groups: Established joint groups with industry and academic advisors for collaboration and guidance.

How engaged were the stakeholders in the development and design of the urban logistics plan, and how is their ongoing involvement ensured?

- No Engagement: No stakeholder involvement in development or monitoring.
- Feedback: Stakeholders provide feedback through bilateral meetings but have no direct planning participation.
- Collaboration: Regular stakeholder meetings for discussing, designing, and amending logistics plans.

Is the current regulatory framework adaptive to changes in order to accommodate emerging trends for logistics activities?

- Inflexible: Slow adaptation to innovations, rigid regulatory framework.
- Limited Adaptation: Adapts to some innovations but faces limitations in conflicting interests.
- Open to Innovation: Actively adopts disruptive technologies, modifies regulations in line with global trends and innovations.

SMART & INNOVATIVE RESOURCES & INFRASTRUCTURE

Which of the following regulatory constraints are actively implemented in the city?

- Space access limitations
- Time access limitations
- Size and/or weight restrictions
- Loading/Unloading parking spaces
- Low emission zones
- Smart booking parking system
- ITS infrastructure for orchestrating operations
- Urban tolls for freight movements
- Night-Time access

How many last-mile delivery companies in the city have established their own innovative logistics infrastructure (e.g. private parcel lockers)?

- Limited companies: No last-mile delivery companies in the city have established their own innovative infrastructure (e.g., private parcel lockers).
- Few companies: A few last-mile delivery companies have established their own infrastructure for innovative urban logistics solutions, indicating early adoption of this innovation.
- Many companies: Many last-mile delivery companies in the city have their own infrastructure. This infrastructure is also used by other companies under agreements.

Which of the following smart city logistics initiatives have been implemented by the city's big LSPs?

- Urban Consolidation Centres (UCCs)
- Parcel lockers
- E-Commerce Micro-Hubs
- Cargo Bikes
- Mobility as a Service (MaaS) for Freight
- Crowdsourced Delivery
- Next day/Next hour delivery
- Blockchain for Logistics

To what extend do last mile companies use digital tools, smart technologies, and platforms for their operations?

- Limited Tools: Use of simple digital tools like spreadsheets.
- Advanced Tools: Utilization of advanced digital tools, e.g., cloud-based software and mobile apps.
- Fully Digital: Operations are fully digital, employing advanced technologies such as Blockchain and Digital Twins.

How widely do companies adopt green transportation modes (EVs, Cargo Bikes, hydrogen), and how do city infrastructure and incentives facilitate this?

- Limited Utilization: Companies rarely use green transportation due to the city's lack of public infrastructure, with existing facilities like EV chargers and hydrogen stations being privately owned. The absence of municipal incentives further diminishes adoption.
- Moderate Utilization: The city is beginning to establish public infrastructure for green transportation, including a growing number of EV chargers and some hydrogen stations. Limited public incentives exist, leading to an increase in company adoption supported by initial infrastructure and promotional efforts.
- High Utilization: The city boasts comprehensive public infrastructure for green modes, including widespread EV chargers and hydrogen stations, with strategic planning for location and quantity. Strong incentives such as tax breaks and priority lanes lead to widespread adoption by companies.

SMART ACTORS

To what extend do the last mile companies working with IoT, AI, and big data technologies to enhance operations or provide cost savings?

- Empirical Planning: LSPs rely on empirical methods, not data collection, for operations and planning.
- Next-Year Planning: LSPs use summarized data for large-scale, long-term planning (e.g., annually).

- Data-Driven: LSPs extensively collect IoT data and deploy AI and data-driven tools for dynamic, enhanced operations.

What is the presence and market dynamics of major LSP players in the city's last mile delivery ecosystem?

- Limited companies: Only small LSPs operate in the city; major players are present but only for deliveries. This indicates a nascent logistics ecosystem.
- Few companies: A few large LSPs have set up due to the limited market, showing a developing logistics ecosystem.
- Many companies: Numerous large LSPs operate in the city, reflecting a high demand for deliveries or a key role in the national distribution network, indicating a mature logistics ecosystem.

What was the response of the citizens of your city to the past city logistics solutions that have been implemented?

- Negative Response: Resistance to adopting new logistics solutions (e.g., parcel lockers).
- Slow Adoption: Positive towards new solutions but slow to adopt them.
- Positive Response: Quick and enthusiastic adoption of innovative logistics technologies.

SMART & EASILY ACCESSIBLE CITY LOGISTICS NETWORKS

To what extent do LSPs in the city adopt standardized data storage and participate in secure data exchange with other companies?

- Non-Standardized and Isolated: LSPs use proprietary data formats with no standardization. There are currently no interoperability actions in place.
- Transitioning with Limited Sharing: Some LSPs are adopting standardized data storage, yet data sharing is limited and cautious. Efforts towards common specifications and secure sharing are emerging.
- Standardized and Collaborative: LSPs adhere to standardized data formats (e.g., DatexIII) and actively engage in secure data exchange deploying innovative technologies such as blockchain, using common specifications.

What is the extend of public infrastructure utilization for multimodal transportation operations in the urban and peri-urban area of the city?

- Minimal Utilization: The existing infrastructure, while present, is significantly underutilized for multimodal transport purposes.
- Moderate Utilization: The infrastructure is regularly used for multimodal transport. However, it lacks efficient connections to public transport systems, limiting its effectiveness.
- Full Utilization: The infrastructure is fully leveraged for multimodal transportation and is seamlessly integrated with public transport systems, facilitating efficient and comprehensive multimodal operations.

To what extend do the last mile companies of your city provide a platform with live tracking of the parcel?

- No Live Tracking: No live tracking system available for parcels.
- Basic Access: Some companies have live tracking, but limited user access.
- Wide Access: Most companies offer live tracking with broad user access and options to change the delivery options.

How efficiently does the city's regulatory framework adapt to establish security requirements for new logistics infrastructure?

- Very Slow Adaptation: The city's regulatory process for implementing security requirements for new logistics solutions is significantly delayed, often taking several years to adapt to innovations.
- Moderate Adaptation: The city's adaptation to new logistics solutions and the establishment of security requirements is reasonably timed, usually within a year.
- Very Quick Adaptation: The city's regulatory framework is highly agile, rapidly adapting to innovative logistics solutions and establishing necessary security requirements in a very short time frame.

Which administrative level assumes primary responsibility for conducting environmental impact assessments related to urban logistics activities?

- Local Level - Municipality
- Regional Level - Region/State
- National Level - Country
- Collaborative Effort Across Multiple Levels
- N/A

Each question in the survey utilized a scale ranging from 0 to 3, with 3 representing the highest score for an element and 0 denoting the lowest. To ensure clarity and consistency in responses, detailed descriptions of each scale were provided along with concrete examples, thereby mitigating the risk of collecting misleading data or encountering conflicts in interpretation. The performance continuum of each scale was a key outcome derived from an extensive literature review conducted to define each sub-element.

A dedicated online survey incorporating these questions was developed and disseminated to representatives from various cities, with the survey accessible in https://ia-radar.imet.gr/readiness.

A brief statistical analysis involving measures such as Mean, Median, Standard Deviation, and Coefficient of Variation was conducted on the received responses. This analysis considered variations in responses to the same question across different respondents and variations in responses from the same city. The scoring mechanism for evaluating a city's performance involved calculating the average product of a sub-element's score with its corresponding weight, as expressed in Equation 1.

$$IR_{UL} = R_1.w_1 + R_2.w_2 + \cdots + R_i.w_i \quad (1)$$

Where IR_{UL}: is the Innovation Readiness for Urban Logistics score, Ri: is the average score of a sub-element (based on the corresponding questions) and w_i: is the weight of the sub-element.

3.3 Planning innovative urban logistics solutions

This section introduces three advanced optimization tools developed under the URBANE project, specifically tailored to enhance the efficiency and sustainability of urban logistics. First, a microhub-based urban delivery model is presented, utilizing parcel lockers and cargo bikes to optimize last-mile delivery by reducing costs and emissions. Next, the section details a comprehensive fleet optimization module, designed to identify an optimal mix of delivery vehicles that effectively balances operational expenses with stringent CO_2 emission targets. Finally, it discusses an integrated locker network optimization model, which strategically determines the optimal number of parcel lockers to minimize total delivery costs and improve customer convenience. Collectively, these models offer powerful, data-driven frameworks enabling city planners and logistics providers to design innovative and environmentally responsible logistics solutions.

3.3.1 A Microhub-Based Urban Delivery Model: Formulation, Analysis and Optimization

This section presents an in-depth quantitative framework for a microhub-based urban delivery model designed to optimize last-mile logistics. The proposed model routes parcels through a distributed network of micro-hubs (locker systems) rather than relying solely on traditional door-to-door (van-based) delivery. In this system, all parcels are first delivered to micro-hubs, from which they are either collected by customers (self-pickup) or delivered to homes via cargo bikes. The model incorporates customer behaviour through a distance-based choice function, calculates detailed operational and investment costs, enforces capacity constraints, and ultimately aims to minimize the cost per parcel. This paragraph explains the model's scope, methodology, variable definitions, equations, objective function, and provides a comprehensive analysis that supports its potential benefits over conventional delivery methods.

The microhub-based urban delivery model is constructed from a set of well-defined variables and parameters that capture both the logistical and economic aspects of the system. These variables fall into three main categories: company data, common operational parameters, and simulation settings.

At the company level, each courier company is characterized by its daily parcel demand (denoted by D) and the number of depots it operates (denoted by n_{depots}). The daily demand represents the total number of parcels that must be delivered, while the number of depots influences the baseline delivery cost since fewer depots may lead to longer routes.

Common parameters include the total service area (A) in square kilometers, which influences travel distances. For the traditional van-based (baseline) model, parameters include the van's capacity, a scaling factor β_{route} used to estimate route length, the van speed, and the additional delivery time per parcel. In addition, labour and transport costs for van operations (expressed in cost per hour and cost per kilometre respectively) are considered. These parameters ensure that the baseline model accurately reflects the costs associated with direct door-to-door delivery.

For the microhub-based system, additional parameters describe cargo-bike operations, such as bike capacity, a scaling factor $\beta_{\text{route\_bike}}$, bike speed, and delivery time per cargo-bike load. The associated labour cost and transport cost for cargo-bike operations are also included. Furthermore, microhub-specific parameters are defined: the fixed investment cost per micro-hub (F), the locker capacity of each microhub, and two capacity multipliers—one for self-pickup and one for home delivery. The self-capacity factor, for example, may indicate that each self-pickup parcel occupies only a fraction (e.g., $1/1.25$) of a locker unit, while the home capacity factor (e.g., $1/2$) indicates the locker usage for a home-delivered parcel.

Opportunity cost parameters include the opportunity cost rate r_o, the amortization period in years Y, and the number of working days per year W; these are used to calculate a daily amortized investment cost for the micro-hubs.

Finally, simulation settings define the candidate range for the number of micro-hubs, n_{mh}, over which the model is evaluated. This range allows the optimization process to identify the configuration that minimizes cost per parcel while satisfying capacity constraints.

3.3.1.1 Methodology

A central feature of the model is the dynamic assignment of the total daily demand D_{total} into two parts: self-pickup demand and home delivery demand. Customer behaviour is modelled by a quadratic function, which estimates the probability p_{self} that a customer opts for self-pickup based on the walking time to a microhub. The average walking time t is computed by assuming that micro-hubs are uniformly distributed over the service area, yielding:

$$t = 15 \times \left(\frac{2}{3} \sqrt{\frac{A/n_{\text{mh}}}{\pi}} \right)$$

This value converts the estimated distance into minutes, based on an assumed walking speed (15 minutes per km). The quadratic function then computes:

$$p_{\text{self}} = (a\,t^2 + b\,t + c - 0.2)$$

where a, b, and c are calibration constants, and the clip function ensures that the probability stays within [0, 1]. Consequently, the self-pickup demand D_{self} is given by:

$$D_{\text{self}} = p_{\text{self}} \times D_{\text{total}},$$

and the home delivery demand is:

$$D_{\text{home}} = D_{\text{total}} - D_{\text{self}}.$$

This split reflects the intuitive idea that customers closer to a micro-hub (resulting in lower walking time) are more likely to pick up their parcels, whereas those farther away will require home delivery.

3.3.1.2 Operational Cost Calculations

In the traditional delivery system, vans are used to deliver parcels directly from depots to customers. The route length L is estimated by the expression:

$$L = \beta_{\text{route}}\sqrt{\text{van\_capacity} \times A} + \frac{2}{5}\sqrt{\frac{A}{n_{\text{depots}}\pi}},$$

which incorporates both the influence of van capacity and depot density on travel distance. The number of routes needed is calculated as:

$$\text{routes} = \lceil D/\text{van\_capacity} \rceil,$$

so that the total effective route length is $L_{\text{total}} = \text{routes} \times L$. The route time T is then determined by:

$$T = \frac{L_{\text{total}}}{\text{van\_speed}} + \text{van\_delivery\_time} \times (\text{van\_capacity} \times \text{routes}).$$

The total cost for the baseline model is computed as the sum of the labour cost (time multiplied by labour cost per hour) and the transport cost (distance multiplied by transport cost per kilometre):

$$\text{Cost}_{\text{baseline}} = T \times D \times \text{labor\_cost\_van} + L \times \text{transport\_cost\_van}.$$

For the microhub-based system, the focus is on optimizing the delivery process by routing all parcels through micro-hubs. Here, only the home delivery portion incurs additional operational costs via cargo bikes; self-pickup incurs no extra delivery cost beyond the micro-hub investment.

First, the home delivery demand is distributed equally among the micro-hubs:

$$D_{\text{home, per km}} = \frac{D_{\text{home}}}{n_{\text{mh}}}.$$

The effective catchment area for each micro-hub is estimated by:

$$A_{\text{per km}} = 1.3 \times \sqrt{\frac{A}{n_{\text{km}}\pi}},$$

where the factor 1.3 adjusts the basic geometrical estimate to better reflect real-world conditions.

Cargo-bike operational costs for each micro-hub are computed by estimating both a route length L_{bike} and a route time T_{bike} using cargo-bike parameters. The route length is given by:

$$L_{\text{bike}} = \beta_{\text{route\_bike}}\sqrt{\text{bike\_capacity} \times A_{\text{per mh}}} + \frac{2}{5}\sqrt{\frac{A_{\text{per mh}}}{n_{\text{mh}}\pi}},$$

and the number of cargo-bike routes required is:

$$\text{routes} = \lceil D_{\text{home, per mh}}/\text{bike\_capacity} \rceil.$$

The effective route length is then $L'_{\text{bike}} = \text{routes} \times L_{\text{bike}}$ and the route time is calculated as:

$$T_{\text{bike}} = \frac{L'_{\text{bike}}}{\text{bike\_speed}} + 2 \times \text{bike\_delivery\_time} \times (\text{bike\_capacity} \times \text{routes}).$$

Therefore, the labour cost per micro-hub is:

$$C_{\text{labor, mh}} = T_{\text{bike}} \times D_{\text{home, per mh}} \times \text{labor\_cost\_bike},$$

and the transport cost per micro-hub is:

$$C_{\text{transport, mh}} = L_{\text{bike}} \times \text{transport\_cost\_bike}.$$

These costs are summed over all micro-hubs to yield the total operational cost for home delivery:

$$C_{\text{operational}} = n_{\text{mh}} \times \left(C_{\text{labor, mh}} + C_{\text{transport, mh}}\right).$$

Each micro-hub involves an upfront investment F that is amortized over its useful life. The daily investment cost per micro-hub is:

$$\text{Daily Investment Cost} = \frac{F \times (1 + r_o)}{Y \times W},$$

and with an additional 10% overhead for maintenance, the total investment cost for n_{mh} micro-hubs is:

$$C_{\text{investment}} = n_{\text{mh}} \times \left(\frac{F \times (1 + r_o)}{Y \times W} \times 1.1\right).$$

3.3.1.3 Capacity Requirements

Locker capacity is a crucial constraint in the micro-hub system. For each parcel, a fraction of a locker unit is required depending on the delivery mode. Specifically, each self-pickup parcel consumes $\frac{1}{\text{self\_capacity\_factor}}$ locker unit, and each home delivery parcel consumes $\frac{1}{\text{home\_capacity\_factor}}$ locker unit. The total required locker units are:

$$\text{Required Units} = \frac{D_{\text{self}}}{\text{self\_capacity\_factor}} + \frac{D_{\text{home}}}{\text{home\_capacity\_factor}}.$$

The available locker units are:

$$\text{Available Units} = n_{\text{mh}} \times \text{microhub\_capacity}.$$

If the available capacity is insufficient that is, if Available Units $<$ Required Units a heavy penalty is applied to the cost, disqualifying that configuration from being optimal.

The overall objective is to minimize the cost per parcel for the microhub-based delivery system. The total daily cost of the micro-hub system is the sum of the operational cost (which is based solely on the home delivery portion) and the investment cost of the micro-hub network:

$$C_{\text{total}} = C_{\text{operational}} + C_{\text{investment}}.$$

The cost per parcel is then calculated as:

$$\text{Cost per Parcel} = \frac{C_{\text{total}}}{D_{\text{total}}}.$$

The model evaluates various candidate numbers for the micro-hubs (n_{mh}) and selects the configuration that minimizes the cost per parcel while ensuring that the capacity constraints are met.

3.3.1.4 Analysis of the Model

The analysis of the model provides insight into the potential benefits of transitioning from a traditional van-based delivery system to a microhub-based system. In the baseline model, the total cost is determined by the efficiency of van-based routes, which are affected by factors such as van capacity, speed, and the geographical distribution of depots. These costs serve as a benchmark against which the micro-hub model is compared.

In the microhub-based model, all parcels are first delivered to a network of micro-hubs. The key innovation is the split of demand into two streams: self-pickup and home delivery. The self-pickup proportion is determined by a distance-based quadratic function that reflects customer behaviour customers closer to a micro-hub are more likely to collect their parcels directly, while those further away will opt for home delivery. For the home delivery component, cargo bikes are used, which are typically more efficient and less costly in urban environments. The operational cost for cargo bikes is computed by separately evaluating the labour cost (based on route time) and the transport cost (based on route length).

The model also accounts for the investment cost of installing micro-hubs, amortized over their useful life and adjusted with a maintenance factor. Additionally, capacity constraints are strictly enforced. Each self-pickup parcel and home delivery parcel consumes a fraction of a locker unit, and if the total required locker capacity exceeds the available capacity across all micro-hubs, the configuration is heavily penalized. This ensures that only feasible solutions are considered.

By evaluating different numbers of micro-hubs, the model identifies an optimal configuration that minimizes the cost per parcel. The analysis reveals not only the cost savings compared to the baseline system but also highlights the operational and infrastructural trade-offs involved in deploying a microhub-based system. Sensitivity analysis can further illuminate how variations in parameters (such as service area, cost factors, and capacity multipliers) impact overall performance, guiding decision-makers toward the most cost-effective and scalable solution.

This comprehensive model provides a detailed, quantitative framework for evaluating a microhub-based urban delivery system. By integrating a demand-splitting mechanism, operational cost calculations for cargo-bike delivery, investment cost amortization, and capacity constraints, the model offers a robust means to optimize last-mile logistics. The objective is to minimize the cost per parcel, and through simulation, the optimal number of micro-hubs can be identified. This framework enables a direct comparison with traditional van-based delivery systems and supports informed decision-making regarding the adoption of micro-hubs to improve cost efficiency, scalability, and environmental sustainability in urban logistics.

3.3.2 Fleet Optimization Module Deliverable

3.3.2.1 Scope of the Module

This module is designed as a decision support tool for optimizing a logistics fleet by balancing operational cost and CO_2 emissions. The primary purpose is to determine an optimal vehicle mix that satisfies a given daily delivery demand while ensuring that environmental targets are met. The system estimates the number of routes required, calculates detailed cost components, and forecasts CO_2 emissions for each vehicle type whether it is part of the current fleet (e.g., diesel or hybrid vehicles) or a new alternative (e.g., automated robots, cargo bikes). The final recommendations provide actionable figures, with the number of vehicles for each mode rounded to the nearest integer, making the results directly implementable. This module is especially relevant for companies that must navigate both economic pressures and environmental regulations.

3.3.2.2 Methodology and Model

In developing this optimization model, our approach begins with a deep understanding of the real-world constraints of fleet management. Intuitively, any logistics operation must ensure that vehicles are not only cost-effective but also sustainable. The core challenge lies in allocating a fixed daily delivery demand across various types of vehicles. Each vehicle type has its own operational characteristics such as capacity, speed, fuel consumption, and CO_2 emission factors which affect both its cost and its environmental impact. Thus, the model is built upon a detailed representation of these characteristics.

The methodology starts by breaking down the problem into two interrelated components: the economic performance and the environmental performance. Economically, the objective is to minimize the total cost of operating the fleet. This cost includes fuel and energy consumption, labour, depreciation, and where applicable, the additional costs associated with acquiring new technologies such as robots. Environmentally, the goal is to ensure that the fleet's CO_2 emissions achieve a specified reduction compared to a baseline scenario. This dual objective naturally leads us to formulate a constrained optimization problem.

A significant modelling decision was to allocate the overall delivery demand among the different vehicle types using fractions that add up to one. In the model, these fractions represent the share of the total demand that each model will serve. To enforce this requirement in a mathematically convenient way, the fractions reparametrize. Instead of directly optimizing the fractions, the model optimizing over a positive vector z and then compute the fractions y as the normalized version of z (i.e., $y_i = \frac{z_i}{\sum_{j=1}^{n} z_j}$). This method inherently satisfies the allocation constraint and simplifies the optimization process.

Another challenge is the discrete nature of the decision regarding the number of vehicles. Since vehicles come in whole numbers, a direct formulation would involve non-differentiable functions (like the ceiling function). However, to take advantage of continuous optimization techniques, a smooth approximation of the ceiling function introduced. This approximation allows us to generate continuous estimates for the number of vehicles during the optimization phase, which can later be rounded to the nearest integer.

Before presenting the mathematical formulations, it is important to emphasize that our model is built on two primary pillars: cost modelling and CO_2 emissions modelling. The cost model quantifies the various operational expenses for each vehicle type, while the CO_2 model estimates the environmental impact. Together, these models provide a comprehensive picture that supports informed decision-making. The optimization problem then seeks to minimize cost while ensuring that the candidate fleet's CO_2 emissions remain within a predetermined interval relative to a baseline scenario. This interval is defined by lower and upper bounds corresponding to maximum and minimum acceptable reductions, respectively.

Global Parameters:

Let
A denote the service area in km²,
D denote daily deliveries,
n_d denote the number of depots,
β denote the route-estimation constant,
t_d denote the delivery time per parcel (in hours, e.g., $\frac{4}{60}$),
s_0 denote the default speed (km/hr),
c_{lab} denote the labor cost per hour,
w denote the working days per year,
δ denote the depreciation rate,
γ denote the opportunity cost rate,
T_{opp} denote the opportunity cost amortization period (years), and
M denote the available minutes per vehicle per day.

Mode-Specific Parameters:

For each vehicle mode i, let
c_i be the capacity (parcels per route),
s_i be the vehicle speed (km/hr),
f_i be the fuel consumption per 100 km,
κ_i be the cost factor for energy,
A_i be the acquisition cost,
σ_i be the software cost (if applicable),
e_i be the CO_2 emission factor (kg CO_2 per km), and
b_i be a binary flag indicating if the mode is part of the baseline fleet.

The total new demand to be served, D_{new}, is allocated among the candidate modes via demand share fractions y_i such that:

$$y_i \geq 0 \quad \text{and} \quad \sum_{i=1}^{n} y_i = 1.$$

Reparametrize by introducing a positive vector z with:

$$y_i = \frac{z_i}{\sum_{j=1}^{n} z_j}.$$

Route Length and Time:

The estimated route length for mode i is given by:

$$L_i = \beta\sqrt{c_i\,A} + \frac{2}{5}\sqrt{\frac{A}{n_d \pi}}.$$

The route time is:

$$T_i = \frac{L_i}{s_i} + c_i\,t_d.$$

Number of Routes and Vehicles:
For allocated demand $D_i = y_i D_{\text{new}}$, the number of routes required is:

$$r_i = \lceil D_i / c_i \rceil.$$

The total operating time (in minutes) is:

$$M_i = r_i \times T_i \times 60,$$

and the number of vehicles required is approximated as:

$$v_i = \lceil M_i / M \rceil,$$

with a smooth approximation $\tilde{v}_i$ used during optimization.

Cost Components:
The per-vehicle cost for mode i comprises:

Fuel cost:

$$\text{FuelCost}_i = \frac{f_i}{100}\,\kappa_i\,L_i.$$

Labor cost:

$$\text{LaborCost}_i = c_{lab}\,T_i.$$

Depreciation cost:

$$\text{DepCost}_i = \frac{A_i\,\delta}{w}.$$

For non-baseline (new) modes, additional costs include:

$$\text{OppCost}_i = \frac{A_i\,\big((1+\gamma)\,T_{opp}\big)}{T_{opp}\,w} \quad \text{and} \quad \sigma_i.$$

Thus, the per-vehicle cost is:

$$C_i^{\text{baseline}} = \text{FuelCost}_i + \text{LaborCost}_i + \text{DepCost}_i,$$

and

$$C_i^{\text{new}} = C_i^{\text{baseline}} + \text{OppCost}_i + \sigma_i.$$

The total cost for mode i is then:

$$\text{TotalCost}_i = \tilde{v}_i C_i.$$

CO_2 Emissions:

For mode i, the total CO_2 emissions are estimated by:

$$E_i = r_i L_i e_i.$$

The overall candidate fleet's emissions are:

$$E_{\text{candidate}} = \sum_{i=1}^{n} E_i,$$

while the baseline emissions E_{baseline} are computed based on a provided baseline mixture.

Objective Function:

The optimization problem seeks to minimize the total operational cost:

$$\min_{z \in \mathbb{R}^n_{>0}} \sum_{i=1}^{n} \tilde{v}_i(z)\, C_i,$$

$$\text{subject to } y_i = \frac{z_i}{\sum_{j=1}^{n} z_j}.$$

CO_2 Emission Constraints:

The candidate fleet must satisfy:

$$E_{\text{candidate}} \le E_{\text{baseline}} \times (1 - \text{min\_co2\_reduction}),$$

$$E_{\text{candidate}} \ge E_{\text{baseline}} \times (1 - \text{max\_co2\_reduction}).$$

The model combines detailed operational cost and emissions calculations into a single framework. The cost structure accounts for fuel, labour, depreciation, and, where applicable, additional costs for new technology. CO_2 emissions are derived from route calculations and the vehicle-specific emission factors. By allocating the demand among various vehicle types using a reparametrized vector, the model automatically satisfies the demand-split constraint, simplifying the optimization process.

One key innovation is the use of a smooth surrogate for the ceiling function. In practice, the number of vehicles must be an integer, however, modelling it as such would result in a highly non-differentiable problem. The smooth approximation enables the use of continuous optimization techniques, which are computationally more efficient. Once the optimal solution is obtained, the continuous vehicle numbers are rounded to the nearest integer to ensure practicality.

Furthermore, the environmental constraints are incorporated as nonlinear constraints that ensure the candidate fleet's CO_2 emissions remain within a prescribed range relative to the baseline. This dual constraint is essential, as it prevents the solution from either over-investing in new technology (resulting in excessive reductions) or falling short of the required environmental improvements. The use of Differential Evolution (DE) facilitates the global search of the solution space despite the nonconvexities introduced by these constraints and the smooth approximations.

Overall, the model successfully balances cost minimization with environmental considerations. It is robust, modular, and capable of providing actionable fleet recommendations based on comprehensive operational and environmental data.

While the model currently offers a robust solution framework, several avenues exist for future improvement. One potential enhancement is refining the smooth approximation for the ceiling function to further reduce approximation error, thereby improving the accuracy of vehicle count estimates. Additionally, incorporating dynamic and stochastic elements—such as variations in daily demand or fuel prices—could make the model more responsive to real-time conditions. Another area for development is extending the model to a multi-objective optimization framework that simultaneously considers service reliability and customer satisfaction alongside cost and emissions. Finally, further integration with real-time data sources and visualization tools would enhance the practical utility of the model, providing fleet managers with interactive decision support capabilities.

3.3.3 Integrated Locker Network Optimization for Last-Mile Delivery

The design of an optimal locker network requires a careful balance between investment costs and operational savings. Installing a large number of lockers increases capital expenditure and maintenance costs, yet too few lockers may force the delivery network to revert to more expensive door-to-door service. Therefore, a quantitative model is needed that can determine the optimal number of lockers such that the total cost of service (comprising both home delivery and locker-related costs) is minimized, while still meeting customer demand.

This work presents a comprehensive model that estimates the optimal number of parcel lockers based on a set of inputs including the service area, daily delivery demand, and the spatial configuration of depots. In addition, the model integrates a probabilistic choice function to capture customer behaviour regarding locker versus home delivery. The resulting optimization model is non-linear, owing to the spatial distribution assumptions and the square root dependency of route distance on area. In what follows, the methodology section describes, mathematical formulation, and sensitivity analysis in detail.

3.3.3.1 Methodology

The proposed locker optimization model is developed in several key steps. First, mathematical derivation functions to estimate the average distance and route time for deliveries performed. Next, the integrations of these functions into a cost model that differentiates between home delivery and locker delivery. The central trade-off lies in the fact that increasing the number of lockers reduces the average distance a customer must walk (thus lowering labour and transportation costs for home delivery), but it also increases the capital investment and operational cost of the locker network. Finally, the model is solved by enumerating over potential numbers of lockers and identifying the configuration that minimizes the overall daily cost.

3.3.3.2 Mathematical Functions for Distance and Time

The first step in our modelling approach is to characterize the spatial dimensions of the service area and their impact on delivery operations. Assuming that the service area A (in km²) is uniformly covered by the locker network. If n lockers are deployed, then, on average, each locker is responsible for a service area of $\frac{A}{n}$. Approximating this service area as a circle, the radius R of each circle is given by

$$R = \sqrt{\frac{A}{n\pi}}.$$

Because customers are randomly distributed within this circle, the average distance from the centre (locker) to a customer is approximately

$$d_{\text{avg}} = \frac{2}{3}R = \frac{2}{3}\sqrt{\frac{A}{n\pi}}.$$

Converting this distance into walking time (assuming an average walking speed of 4 km/hr or 15 minutes per km) yields the average walking time t_{walk}:

$$t_{\text{walk}} = 15 \times d_{\text{avg}} = 15 \times \frac{2}{3}\sqrt{\frac{A}{n\pi}}.$$

In addition to the spatial component, the extra distance incurred by depot stops took into account. AssumING that the extra distance is given by

$$d_{\text{extra}} = \frac{2\sqrt{A}}{n_{\text{depots}}},$$

where n_{depots} is the number of depots available.

For home delivery operations, the vehicle route length is modelled using a heuristic derived from the Traveling Salesman Problem (TSP). Specifically, the baseline route length for a vehicle that delivers C parcels is approximated as

$$L_{\text{base}} = \beta\sqrt{C \times A},$$

where β is a TSP constant (typically around 2.5). The total route length L is then given by

$$L = L_{\text{base}} + d_{\text{extra}}.$$

The route time T is the sum of the travel time and the service time (the time required to deliver each parcel). Formally,

$$T = \frac{L}{s} + C \times t_{\text{delivery}},$$

where s is the vehicle speed (in km/hr) and t_{delivery} is the time required to deliver a single parcel.

3.3.3.3 Cost Modelling

The overall cost function for the locker network model comprises two primary components: the cost of home deliveries and the cost associated with the locker network. The home delivery cost is modelled based on the remaining parcels that are not handled by lockers, while the locker cost includes both the capital investment and operational expenses.

3.3.3.4 Home Delivery Cost

Let D denote the total daily deliveries and q_{locker} be the capacity of each locker (i.e., the maximum number of parcels that can be handled per locker per day). As not all deliveries can be shifted to lockers; I the probability $P(n)$ that a customer opts for locker delivery as a function of the average walking time. For instance, a quadratic model is used:

$$P(n) = a\,t^2 + b\,t + c,$$

where t is the average walking time computed earlier, and the coefficients a, b, and c are calibrated to yield realistic probabilities (with a slight downward adjustment to reflect customer inconvenience). Thus, the effective number of locker deliveries is given by

$$D_{\text{locker}} = \min\{P(n) \times D,\ n \times q_{\text{locker}}\}.$$

The remaining deliveries must be handled by home delivery, so that

$$D_{\text{home}} = D - D_{\text{locker}}.$$

The home delivery cost is then computed as the product of the number of routes required (which is $\frac{D_{\text{home}}}{\text{vehicle\_capacity}}$) and the cost per route. The cost per route includes fuel cost and labour cost, which are functions of L and T.

Locker Cost

The locker cost has two components. The first is the capital cost (or acquisition cost) of installing the lockers. The model assumes that the locker investment is evaluated over a long horizon (e.g., 10 years). The locker capital cost is given by

$$\text{Daily Locker Capital Cost} = \frac{I \times r}{W},$$

where I is the purchase cost per locker, r is the annual opportunity (or capital) cost rate, and W is the number of working days per year (typically 260). Additionally, there is a fixed operational cost per locker per day, denoted by C_{op}. Thus, the total locker cost is

$$C_{\text{locker}}(n) = n \times \left(\frac{I \times r}{W} + C_{\text{op}}\right).$$

The total daily cost function for the locker network is then defined as

$$F(n) = C_{\text{home}}(n) + C_{\text{locker}}(n),$$

where $C_{\text{home}}(n)$ is the cost of home deliveries when n lockers are installed, and $C_{\text{locker}}(n)$ is the cost of operating the locker network. The optimal number of lockers n^* is found by solving

$$n^* = \underset{n}{\operatorname{argmin}} F(n).$$

Due to the non-linearity introduced by the square root term in the route length and the piecewise nature of the effective locker delivery function, the overall cost function $F(n)$ is non-convex and non-linear. Standard linear programming methods are not directly applicable. Instead, a brute-force enumeration method using SciPy's optimization tools (e.g., scipy.optimize.brute) to search for the optimal integer n that minimizes $F(n)$ mobilized.

For each candidate number of lockers n (in a reasonable range, say 1 to 500), the model computes:

1. The average walking time and its impact on the probability $P(n)$ of choosing locker delivery.
2. The effective locker capacity $\min\{P(n) \times D, n \times q_{\text{locker}}\}$.
3. The cost of home deliveries based on the remaining deliveries and the cost per route.
4. The capital and operational cost of the locker network.
5. The algorithm then selects the n that minimizes $F(n)$.

Even though the optimization is performed via enumeration, the behaviour of $F(n)$ take place by examining its mathematical structure. Consider the term associated with the average walking time:

$$t_{\text{walk}}(n) = 15 \times \frac{2}{3}\sqrt{\frac{A}{n\pi}}.$$

The derivative of $\sqrt{\frac{1}{n}}$ with respect to n is

$$\frac{d}{dn}\sqrt{\frac{1}{n}} = -\frac{1}{2}\frac{1}{n^{3/2}}.$$

Thus, as n increases, the average walking time decreases but with diminishing returns. This in turn increases the locker adoption probability $P(n)$ but with a similar diminishing effect. On the cost side, the locker cost increases linearly with n. The optimization problem thus seeks to balance the decreasing home delivery cost (as more lockers reduce the distance and, hence, the fuel and labor costs) against the increasing locker capital and operational costs. The optimal solution is achieved when the marginal savings in home delivery cost is approximately equal to the marginal increase in locker cost.

The model is highly sensitive to parameters such as the service area A, the number of depots n_{depots}, and the operating costs (fuel and labour). For example:

Increase in Area A: Leads to longer route lengths and higher walking times, thus reducing locker adoption. In this case, more lockers may be needed to offset the increased home delivery cost.

Increase in Depot Efficiency (higher n_{depots}): Reduces the extra distance and, hence, the route time for home deliveries, which can lower home delivery costs and shift the balance toward fewer lockers.

Higher Fuel or Labor Costs: Increase the home delivery cost, thereby favouring a locker network solution that can shift more deliveries from home to locker.

These trade-offs must be considered when calibrating the model for a particular urban environment.

This document has presented a comprehensive mathematical model for optimizing a parcel locker network as part of a last-mile delivery system. At first the spatial and temporal aspects of delivery routes, deriving expressions for average walking time and route length. Then integrated these functions into a cost model that combines home delivery costs (derived from fuel, labour, and operational considerations) with locker investment costs (capital plus operational expenses).

The resulting total cost function $F(n)$ is non-linear and non-convex due to the square-root dependency of route length on the number of lockers and the probabilistic model for locker choice. To solve this problem, a brute-force enumeration approach using SciPy's optimization tools considered, thereby finding the optimal number of lockers that minimizes total daily cost.

The derivative analysis of the underlying functions provides intuition about the trade-offs: as the number of lockers increases, the marginal benefit in terms of reduced walking time and home delivery cost diminishes, while the capital cost increases linearly. Sensitivity analysis further reveals how variations in key parameters—such as the service area, depot efficiency, fuel prices, and labour costs—affect the optimal solution.

In summary, the integrated locker network optimization model provides a robust quantitative framework for determining the optimal infrastructure investment in locker networks, balancing customer service improvements with economic efficiency. This model can serve as a decision-support tool for logistics operators aiming to reduce operational costs and environmental impacts in the context of urban last-mile delivery.

3.4 The innovative urban logistics solutions performance repository

This comprehensive framework outlines a novel approach to assessing and advancing innovative urban logistics. It commences with identifying key impact areas crucial for sustainable urban development, leading to the conceptualization and definition of relevant KPIs and their associated sub-elements. Subsequently, the framework establishes a critical connection between these defined KPIs and the array of innovative business models and technological solutions emerging within last-mile logistics. Finally, it details a robust methodology for integrating real-world use cases and their corresponding KPI data into a dynamic knowledge observatory, facilitating evidence-based learning and the transferability of successful urban logistics innovations across diverse city environments.

3.4.1 Identification of the main impact areas and categories for impact assessment

Building upon the broader ecosystem approach described in Section 3.2.1, this section delves into the specific impact areas critical for evaluating the performance of innovative urban logistics solutions within the URBANE framework. The CIVITAS Evaluation Framework is a set of guidelines and practical advice for the evaluation of urban mobility measures implemented in European cities. The framework aims to assess the impact and the process of these measures, as well as to provide feedback and recommendations for future improvements. The scope of the framework covers all types of mobility measures that are part of the CIVITAS Initiative, which focuses on sustainable and innovative solutions for urban transport. The objectives of the CIVITAS Evaluation Framework are to measure and compare the effects of mobility measures on various aspects of urban life, such as environment, economy, society, transport, and energy; identify and analyse the factors that influence the success or failure of mobility measures, such as barriers, drivers, risks, and opportunities; provide evidence-based knowledge and best practices for policymakers, practitioners, and researchers in the field of urban mobility; and support the learning process and the transferability of mobility measures across different contexts and cities. The impact evaluation component of the CIVITAS Evaluation Framework focuses on measuring and analysing the changes that occur because of implementing mobility measures. The impact evaluation is based on a set of indicators that are grouped into five impact areas: transport, environment, economy, society, and energy (Table 2) according to Engels et al., 2017.

URBANE Framework Impact Areas
Equity
Sustainability
Safety
Efficiency
Digitization

TABLE 2: The urbane framework impact areas

Thus, based on URBANE Framework Impact Areas, 13 sub-elements regarding the performance of the innovative urban logistics ecosystem were defined aligned with the Impact Areas of the URBANE Framework.

Element	Sub-element	URBANE Framework
SMART & EASILY ACCESSIBLE	Accessibility	Equity
	Affordability	Equity
GREENNESS & OPENNESS	Sustainability	Sustainability
	Energy consumption	Sustainability
SAFETY & SECURITY	Road Safety	Safety
	Cargo safety	Safety
SMART & INNOVATIVE RESOURCES & INFRASTRUCTURE	Level of service	Efficiency
	Efficiency	Efficiency
	IT, infrastructure and technology integration	Digitization
SMART ACTORS	Consumer behaviour	Digitization
	Flexible employment	Equity
	Business efficiency	Efficiency
	Quality of life & Working environment	Equity

TABLE 3: The innovative urban logistics ecosystem elements

In the context of the URBANE Framework, the sub-elements are analysed from a perspective that emphasizes structural integrity and societal advancement. Equity is manifested through the provision of services that are accessible and affordable, which is deemed essential for inclusivity across varying socioeconomic strata. The tenets of sustainability are actively pursued by adopting practices that prioritize energy conservation, reflecting a strategic alignment with the framework's guiding principles.

Attention to safety is articulated through measures aimed at road and cargo security, principles which are intrinsically tied to the URBANE framework's emphasis on Safety. In terms of resources and infrastructure, an emphasis is placed on the evaluation of service levels and operational efficiency, signifying a direct correlation with the Efficiency principle espoused by URBANE. The incorporation of IT and technology within infrastructural development is observed as a vital component that propels the Digitization principle forward within the framework.

The role of smart actors is scrutinized under the URBANE Framework, where patterns of consumer behaviour and the adaptation of employment structures are seen as indicative of shifts toward Digitization and Equity. The efficient management of business operations reflects a larger trend towards optimization and resource management, aligning with the Efficiency principle of the framework. Considerations for improving the quality of life and the work environment are recognized as key factors in upholding the principle of Equity, ensuring a distributive approach to the advantages engendered by technological and operational advancements. The conceptualization of these impact areas and their associated sub-elements forms the foundational step, providing the necessary lens through which the performance of various urban logistics innovations, as discussed in the subsequent section, can be systematically assessed.

3.4.2 The main innovation categories and business models in last mile logistics

Following the identification of key impact areas and performance sub-elements in Section 1.1.1, this section shifts focus to the core of urban logistics transformation: the innovative categories and business models driving efficiency and sustainability in last-mile delivery. The transformation of last-mile logistics is centred around reconfiguring traditional delivery flows through innovative operational and business models. These models are designed to reduce congestion, emissions, and inefficiencies, while leveraging shared infrastructure and digital tools. Among the most prominent innovations are open locker networks, locker alliance networks, electrified delivery fleets (notably cargo bikes and autonomous delivery vehicles), and micro-hubs supporting two-echelon delivery systems. All these models align with the Physical Internet paradigm, emphasizing interoperability, modularity, and openness in both infrastructure and data flows.

Within the framework of the URBANE project, the Impact Assessment Radar developed a comprehensive taxonomy and generalization of the key innovations implemented across the pilot sites. This methodological approach enables the IAR to attribute site-specific impacts to broader categories of innovation, facilitating a structured understanding of the outcomes generated. As a result, the impacts observed in each pilot are contextualized within overarching innovation typologies, thereby allowing third-party stakeholders and urban planners to interpret the results through the lens of the corresponding innovation context. This contributes to a more robust and transferable impact assessment framework.

3.4.2.1 Locker Networks and Locker Alliance Models

Locker networks are decentralized out-of-home parcel collection and drop-off points placed across urban environments. They operate either as closed systems (proprietary to one logistics provider) or as open/shared infrastructure in what is known as locker alliance networks. The latter adopts a business-to-infrastructure (B2I) model, where municipalities or third-party operators host lockers that are accessible by multiple carriers, facilitating interoperability.

Mechanically, lockers function as end nodes in the delivery chain, replacing home addresses. Couriers consolidate parcels at a depot and distribute them across lockers on optimized multi-drop routes. Consumers receive digital access codes to retrieve parcels. In locker alliances, digital platforms ensure access control, time-slot booking, and data security for multiple carriers.

The business model of locker alliances emphasizes shared CAPEX and OPEX (installation, maintenance, space rental), improved delivery density, and reduced failed delivery rates. Municipalities benefit through reduced traffic and emissions. However, operational barriers include the need for governance frameworks, integration of backend systems, fair cost/revenue distribution, and optimal locker placement based on land use, accessibility, and demand density.

3.4.2.2 Electrification and Cargo Bikes

Electrified transport models, especially involving e-cargo bikes and electric vans, address both emission reduction and operational flexibility. These models target urban centres where vehicle restrictions, congestion, and environmental zones hinder traditional vans.

E-cargo bikes operate with a hub-and-spoke mechanic: parcels are transferred from a central or satellite hub to the bike, which performs high-density deliveries in pedestrian or semi-pedestrian areas. A bike can carry up to 100-150kg of goods and access narrow streets with minimal disruption. Route optimization and telematics platforms help balance payload and distance.

Business-wise, these models support lower OPEX compared to vans (fuel, maintenance, parking), and provide service differentiation in zero-emission zones. Riders may be employed directly or contracted via gig platforms. However, limitations include limited range, weather dependency, and constraints on parcel volume. Scalability hinges on integration with micro-hubs and regulatory support for dedicated infrastructure.

3.4.2.3 Micro-hubs and Two-Echelon Distribution

Micro-hubs are local transshipment nodes located within or near urban delivery zones. Their primary role is to break bulk flows from regional depots and support last-mile delivery via smaller, low-emission vehicles. These hubs are central to two-echelon models:

- Echelon 1: Goods are moved from a main depot to micro-hubs using trucks or vans.
- Echelon 2: Parcels are dispatched from the hub to final destinations using cargo bikes, e-vans, or by depositing them in lockers.

These hubs may be fixed structures, temporary setups in modular containers, or mobile units. Services may include parcel sorting, fleet parking and charging, battery swapping, and in some cases, returns handling.

From a business perspective, micro-hubs offer consolidation benefits, reduce time spent in traffic, and enable the use of more sustainable vehicles. They also enable shared use between logistics operators, forming part of urban logistics-as-a-service (ULaaS) models. Real-world deployments in cities like Berlin and Bologna demonstrate collaborative use among competitors. However, challenges include finding real estate, coordinating operations among multiple stakeholders, zoning constraints, and ensuring economic viability when delivery volumes are low.

3.4.2.4 Autonomous Delivery Vehicles (ADVs)

ADVs aim to automate last-mile deliveries through small sidewalk robots, semi-autonomous pods, or fully automated vans. Their operational model involves dispatching the vehicle from a depot or micro-hub to a destination route, either door-to-door or locker-to-door. Most ADVs follow fixed, geofenced paths and rely on human teleoperation when needed.

The process includes: order aggregation at the hub, loading into the robot, path navigation with customer notifications, and secure drop-off or PIN-based handoff. Some ADVs integrate with lockers or micro-depots.

Their business models are built around reducing labour costs, offering 24/7 service availability, and supporting scalable unit economics through modular hardware. Pilots in Helsinki and the United States show improved service coverage and customer acceptance. Yet, ADVs face high upfront R&D costs, regulatory hurdles, public safety concerns, and complex urban navigation requirements.

3.4.2.5 The Physical Internet dimension of innovative logistics models

The above models are often implemented in silos, each addressing specific operational or infrastructural challenges within the last-mile logistics landscape. However, there is a growing emphasis on promoting cross-operator collaboration and shared resource utilization. For example, cargo bikes are increasingly deployed from micro-hubs to supply locker networks that are accessible to multiple logistics providers; autonomous delivery vehicles can complement conventional delivery services during off-peak periods or to manage overflow; and locker alliances serve as shared urban assets, offering neutral delivery points to various stakeholders. The integration and interoperability of these systems are typically orchestrated through digital platforms that manage booking, access rights, routing, and data exchange, thereby enhancing coordination and unlocking economies of scale across the logistics ecosystem.

The principles of the Physical Internet provide a unifying framework by advocating for openness, modularity, and systemic interoperability. As asset sharing, operational synergies, and streamlining of service channels increase, networks benefit from enhanced utilization, scalability, and robustness. The shift toward open, collaborative logistics infrastructures—mirroring the design of digital networks—enables more efficient, adaptive, and resilient urban delivery ecosystems. Consequently, advancing PI-aligned models represents not merely a technological evolution, but a systemic reconfiguration of last-mile logistics to address environmental, operational, and spatial challenges at scale. The insights derived from the implementation of these innovative models, as further detailed through empirical data, are crucial for populating the performance repository.

TABLE 4: Mapping of urban logistics innovations and technology enablers to wave-1 LLs

City	Parcel Locker Network	ADVs	Micro-Hubs	Cargo-Bikes	UCC	Blockchain	L/U Zones	Digital Twin	eLCVs
Bologna			✓	✓		✓		✓	
Helsinki		✓	✓	✓		✓		✓	
Valladolid				✓		✓	✓	✓	✓
Thessaloniki	✓				✓	✓		✓	✓
Barcelona				✓	✓	✓		✓	
Karlsruhe		✓						✓	

This cross-city mapping of implemented innovations, captured within Level 3 of the Impact Assessment Radar, directly feeds into the robust integration framework described in the following section, ensuring a systematic approach to knowledge transfer and benchmarking. Table 44 presents a **cross-city mapping of innovations** implemented and reported by the Living Labs participating in the URBANE project, as captured in Level 3 of the Impact Assessment Radar. It illustrates the diversity of last-mile logistics solutions tested across six European cities, highlighting both the heterogeneity and complementarity of approaches. For instance, **Bologna** demonstrates a highly integrated approach, piloting multiple innovations across the logistics chain—including micro-hubs, cargo bikes, blockchain integration, and digital twin simulation reflecting a mature ecosystem capable of supporting multi-layered interventions. In contrast, **Thessaloniki** focused on specific solutions such as parcel locker networks, eLCVs adoption and blockchain, representing a targeted intervention strategy. **Helsinki**, **Valladolid**, and **Barcelona** emphasized new vehicle technologies, such as ADVs and cargo bikes, alongside partial infrastructure deployment with UCCs, while **Karlsruhe** implemented lighter pilots, testing ADVs and digital twins. The matrix structure of this table not only facilitates a comparative understanding of solution adoption but also supports knowledge transfer between cities by identifying which innovations have been piloted under similar urban contexts. This structured reporting enhances the IAR's ability to serve as a scalable observatory, enabling cities to benchmark their efforts and draw lessons from existing implementations.

3.4.3 Continuous Enrichment Process for the IAR Observatory

Building on the conceptualization of impact areas and KPIs and the identification of key urban logistics innovations this section details the third and final pillar of the framework: the integration mechanism for new results through the Impact Assessment Radar. The third level of the Impact Assessment Radar is designed as a knowledge observatory that systematically captures and organizes insights from real-world implementations of green last-mile logistics solutions inspired by the Physical Internet. Its primary function is to provide cities and stakeholders with contextual benchmarks, derived from prior use cases across diverse urban environments. This layer enables cities to compare their projected impacts with empirical results and learn from the operational realities of similar innovations implemented elsewhere. As more cities engage with the IAR and contribute their data, the platform evolves into a self-enriching ecosystem, supporting generalization and evidence-based planning at the EU level.

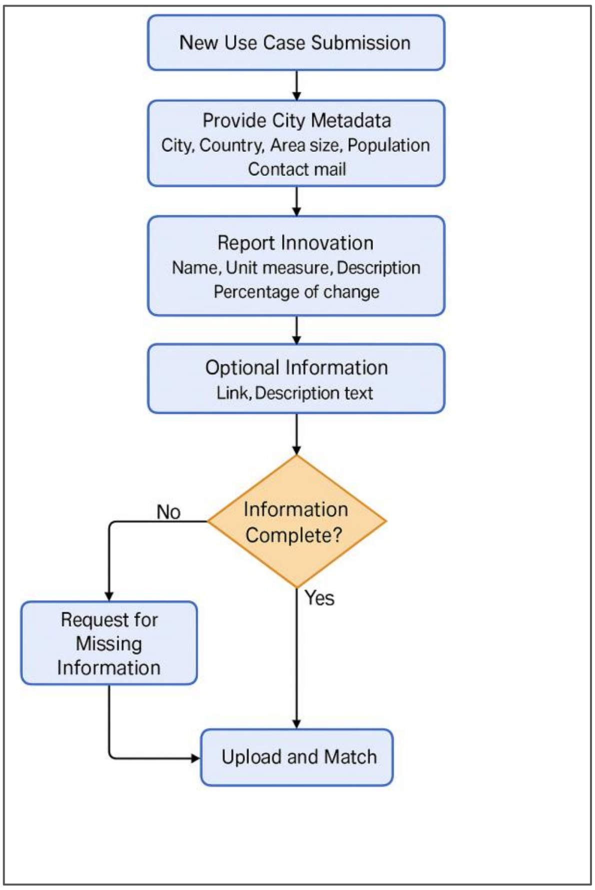

FIGURE 10: New use case integration process flow

To maintain the scientific integrity and interoperability of the platform, the IAR incorporates a structured data submission and validation workflow for each new use case. When a city intends to contribute new data to Level 3, it must begin by submitting a standardized set of metadata that ensures consistent categorization and geo-contextual framing. These mandatory fields include: City name, Country, Area size (in sq km), Total population, and a contact email address for verification and follow-up. This foundational information allows the system to situate the new data spatially and demographically, which is critical for comparative analytics across pilot sites.

Following the metadata submission, the city must identify the innovation it implemented by selecting from an existing list of solution types (e.g., locker networks, micro-hubs, cargo bike schemes, ADV deployment) or by defining a new innovation category if necessary. The core of the submission is the KPI reporting section, where the city provides a list of key performance indicators. Each KPI entry must include:

- name of the KPI,
- unit of measurement,
- description of the indicator, and
- reported percentage change (either improvement or deterioration).

This structured format enables integration with existing KPI ontologies within the URBANE platform, ensuring that newly submitted data can be processed for aggregation, comparison, and visualization alongside existing cases.

Once the submission is received, the platform initiates a data processing protocol. In routine cases, where all required fields are complete and clearly defined, the system may validate and publish the new use case automatically. In cases where discrepancies, ambiguities, or missing data are detected, the submission is routed to a manual review process conducted by designated URBANE evaluators. The contact person is notified via email and asked to provide clarifications or missing information. Only once all criteria are met and the data integrity is confirmed is the new case uploaded to the platform. The case is then automatically mapped to comparable entries in the database based on context parameters (e.g., population size, innovation type, density profile) and made available for benchmarking. This ensures that the IAR Level 3 observatory remains both scalable and scientifically robust, offering a dynamic playground of learning and exchange among EU cities committed to sustainable urban logistics transformation. This robust data integration and validation process ensures that the IAR remains a dynamic and scientifically sound observatory, effectively connecting the conceptual framework to real-world performance, and thereby fulfilling the overarching aim of assessing and advancing innovative urban logistics.

4. Demonstration examples of Impact Assessment Radar

This section provides a set of practical implementation guidelines intended to support future adopters such as local authorities, planners, and logistics stakeholders in effectively utilizing the Impact Assessment Radar within real-world planning processes and innovation modelling studies. By walking through two representative use cases from the Thessaloniki and Bologna Living Labs, both part of the Wave 1 deployment, the section illustrates how the IAR can be applied across its three levels to inform data-driven decision-making and strategic planning. These examples have been selected to demonstrate the full spectrum of functionalities offered by the tool, highlighting how the IAR can support everything from initial maturity assessment and conceptual design to quantitative modelling and impact benchmarking.

Specifically, the first part of this section presents computational results derived from the use of the IAR's Level 1, Level 2, and Level 3 modules in each of the two cities. This serves as a concrete example of how different cities can approach the deployment of green last-mile logistics solutions using the same structured methodology. Following that, Section 4.3 outlines the fundamental components of the IAR framework, with a particular focus on the critical input parameters and model configurations that users must carefully consider when initiating a new assessment or simulation study.

The purpose of this section is to bridge the gap between abstract tool functionalities and practical application. By providing both real-world use cases and documentation of the underlying building blocks, future users will gain a comprehensive understanding of how to configure and scale the IAR according to their local needs. This ensures that the tool is not only transferable across different urban contexts, but also practical in supporting planning studies, pilot evaluations, and long-term strategy development for green and efficient last-mile logistics.

4.1 The Thessaloniki se case

4.1.1 Level 1 Results and Analysis

The analysis of Thessaloniki's Innovation Readiness for Urban Logistics reveals an overall score of 51%, indicating a moderate level of maturity with substantial scope for enhancement within its urban logistics ecosystem. This 51% score is a quantifiable measure of the city's current capacity and preparedness to adopt and implement innovative, green urban logistics solutions, placing it roughly in the middle of a theoretical maturity continuum.

FIGURE 11: the innovative urban logistics readiness score for the case of Thessaloniki

While the city demonstrates particular strengths in its SMART ACTORS, notably in the positive Citizen perception of logistics solutions and robust Security requirements and standards, several critical areas require focused attention to achieve a truly innovative and sustainable system. Digging deeper into the SMART ACTORS element, the positive Citizen perception (Q17) suggests a generally receptive public, willing to engage with new logistics initiatives, which is a significant asset for pilot projects and solution adoption. Furthermore, the strong emphasis on "Security requirements and standards" indicates that the city has established or is actively developing frameworks to ensure the safety and integrity of its urban freight operations, fostering trust among users and providers. This strength is complemented by robust performances in SMART GOVERNANCE and SMART & INNOVATIVE RESOURCES & INFRASTRUCTURE, suggesting a solid strategic backbone and foundational physical and digital assets supporting logistics innovation. Quantitatively, this is evidenced by strong scores in Stakeholder participation (Q7), pointing to active collaboration in planning, and Logistics data collection (Q12), indicating that LSPs are adopting standardized data storage and secure data exchange, which are crucial for data-driven optimization. Additionally, high marks in Service Quality (Q18) and Quality Assurance (Q20) suggest that the city's logistics services generally meet user expectations and that processes for continuous improvement are in place.

However, the ecosystem's weakest element is SAFETY,SECURITY & QUALITY, which, despite individual strong points like Q20, highlights a significant disconnect in practical implementation. More analytically, a critical area of underperformance is Electrification (Q14), where the city shows low adoption of green transportation modes. This is a clear quantitative deficiency, likely due to insufficient public infrastructure (such as EV chargers and hydrogen stations) and a lack of compelling municipal incentives. This directly impacts the GREENNESS & EFFICIENCY of the urban logistics system. Another significant weakness lies in the implementation of Regulatory Constraints (Q9). The low score here implies that essential regulatory measures, such as space/time access limitations, low emission zones, or smart parking systems for freight, are either not actively or effectively enforced, creating a barrier to desired operational shifts. Furthermore, when compared to other cities, Thessaloniki exhibits a significant weakness in the Digitization of the sector (Q13), suggesting that last-mile companies are not fully leveraging advanced digital tools, smart technologies, and platforms for optimizing their operations. The report also highlights a comparative weakness in Citizen Perception (Q17), indicating that while internal perception might be good, it doesn't stand out as strongly when benchmarked against other leading cities. Finally, the articulation and alignment between SUMP and SULP (Q3) is identified as a weak point, implying a fragmented approach to urban mobility and logistics planning, which could hinder comprehensive and integrated policy development.

In essence, while Thessaloniki has established a commendable base in stakeholder engagement, governance structures, and the perceived quality of its logistics services, its path to a truly innovative green urban logistics ecosystem hinges on addressing critical gaps in electrification infrastructure and incentives, strengthening regulatory enforcement, advancing the digital maturity of its logistics sector, and fostering a more cohesive planning approach across urban mobility and logistics domains. Overcoming these challenges will be paramount for Thessaloniki to significantly elevate its innovation readiness score and achieve its climate-neutral and sustainable urban mobility goals.

4.1.2 Level 2 Results and Analysis

The Level 2 module of the IAR was employed in the Thessaloniki Living Lab to identify the optimal configuration for a parcel locker network under varying demand levels and infrastructure settings. The first stage of the analysis assumed a locker size of 32 units and tested the influence of depot availability comparing four versus eight depots (that are available in the baseline scenario) across escalating parcel demand scenarios (2000 to 5000 parcels). This phase aimed to determine how depot decentralization affects network cost-efficiency. Results clearly indicated that a more consolidated depot strategy (four depots) consistently outperformed the decentralized setup (eight depots) in terms of cost reduction. For instance, with 5000 parcels, the four-depot configuration achieved a 50.03% cost reduction versus 41.1% in the eight-depot case.

Following this insight, the next stage focused on optimizing the locker unit size. The planner evaluated three configurations: small lockers of 16 units, large lockers of 32 units, and a mixed-size configuration equivalent to 28 units (modelling a 75%-25% combination of 32 and 16-unit lockers). For each size, the system tested demand levels from 2000 to 5000 parcels, keeping the depot count fixed at 4. The analysis revealed that even smaller lockers (16 units) required significantly more installations to serve the same demand (208 lockers for 5000 parcels) the resulting cost reductions were limited (~21.8%). Conversely, the 32-unit configuration showed superior performance, requiring only 98 lockers to serve the same volume with a 50.03% cost reduction. The intermediate locker size (28 units) struck a balance, offering 38.61% cost savings for 113 lockers at 5000 parcels. This trade-off analysis highlights how selecting an appropriate locker capacity can substantially affect both infrastructure needs and service cost efficiency.

From this process, the most efficient and scalable solution was identified: a configuration of 101 lockers of approximately 28 units capacity. This design was chosen not only for its favourable cost-performance profile but also for its long-term viability. It was estimated suitable to accommodate projected parcel volumes through 2026 (approx. 4500 parcels). The IAR results were subsequently integrated into the URBANE Platform’s facility location model, which processed the quantitative output and returned specific geospatial coordinates for locker deployment across Thessaloniki. This result was also used in the collaborative routing module and Digital Twin simulation to assess the broader implications on delivery performance and environmental impact.

Locker Size	Demand	Depots	Optimal Lockers	Total Cost with Lockers	Total Cost Baseline	Cost Reduction (%)	Cost per parcel after
32	2000	8	33	1968	2991	34.2	0.98
32	3000	8	54	2784	4486	37.94	0.93
32	4000	8	76	3596	5981	39.88	0.9
32	5000	8	98	4404	7477	41.1	0.88
32	2000	4	39	1738	2991	41.89	0.87
32	3000	4	55	2416	4486	46.14	0.81
32	4000	4	76	3079	5981	48.52	0.77
32	5000	4	98	3736	7477	50.03	0.75
16	2000	4	76	2406	2991	19.56	1.2
16	3000	4	119	3555	4486	20.75	1.19
16	4000	4	163	4703	5981	21.37	1.18
16	5000	4	208	5847	7477	21.8	1.17
28	2000	4	39	2011	2991	32.76	1.01
28	3000	4	64	2882	4486	35.76	0.96
28	4000	4	88	3737	5981	37.52	0.93
28	5000	4	113	4590	7477	38.61	0.92

TABLE 5: Demonstration of level 2 results for Thessaloniki LL

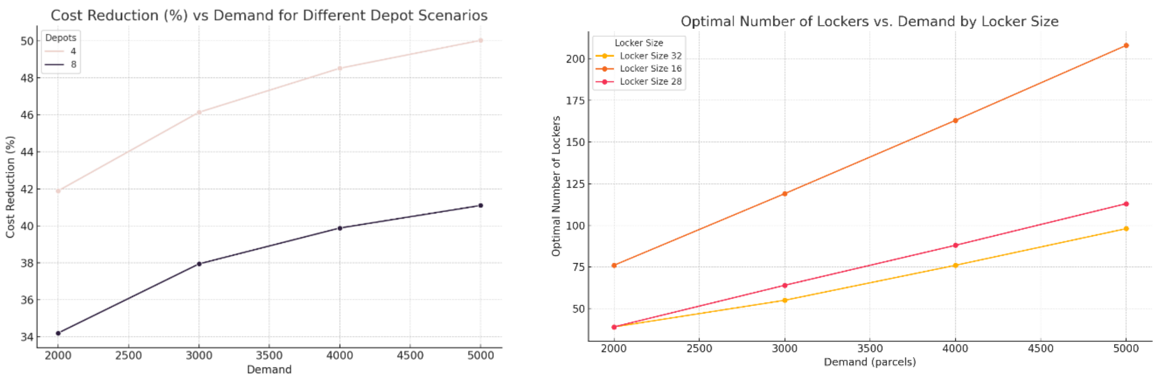

FIGURE 12: Demonstration of data generated from level 2 module for the locker network model

In summary, the Thessaloniki use case showcases the full potential of the IAR's Level 2 capabilities. It demonstrates how planners can iteratively test demand scenarios, infrastructure configurations, and asset types to converge on an optimal last-mile solution. The methodology also emphasizes the value of combining analytical outputs with spatial decision-making models, ensuring results are both cost-effective and implementation ready.

4.1.3 Level 3 Results and Analysis

The Level 3 module of the Impact Assessment Radar captures and highlights the outcomes of real-world demonstrations, offering valuable feedback for future replication. In the case of the Thessaloniki Living Lab, the results derived from Level 2 were directly applied to shape the pilot activities. Specifically, the optimal number of parcel lockers identified through the Locker Network Optimization model was implemented as part of the physical deployment. Additionally, the Fleet Mixture module provided actionable insights into the appropriate mix of eLCVs needed to meet the city's operational and environmental targets. The Micro-Hub Network Optimization model further supported decisions regarding the number and scale of consolidation points required in the target area.

By integrating these outputs, the Thessaloniki Living Lab was able to proceed with a data-informed strategy for both its field tests and its extended digital demonstrations using the URBANE Transferability Platform. The Digital Twin module allowed for the validation of these decisions in a controlled environment, simulating system behaviour at scale. As these decisions were grounded in structured, quantitative insights from Level 2, the Level 3 repository now reflects not only the adopted configurations but also their real-world performance and impacts. This enables other cities to reference concrete results when assessing similar solutions for their local contexts.

The Thessaloniki use case exemplifies how the IAR can function as an end-to-end planning and evaluation tool. From early-stage configuration analysis to large-scale deployment and impact benchmarking, it offers a coherent and replicable pathway for adopting green last-mile logistics solutions. The stored outcomes in Level 3 provide a valuable resource for stakeholders seeking guidance on performance expectations, system design, and strategic alignment with broader sustainability objectives.

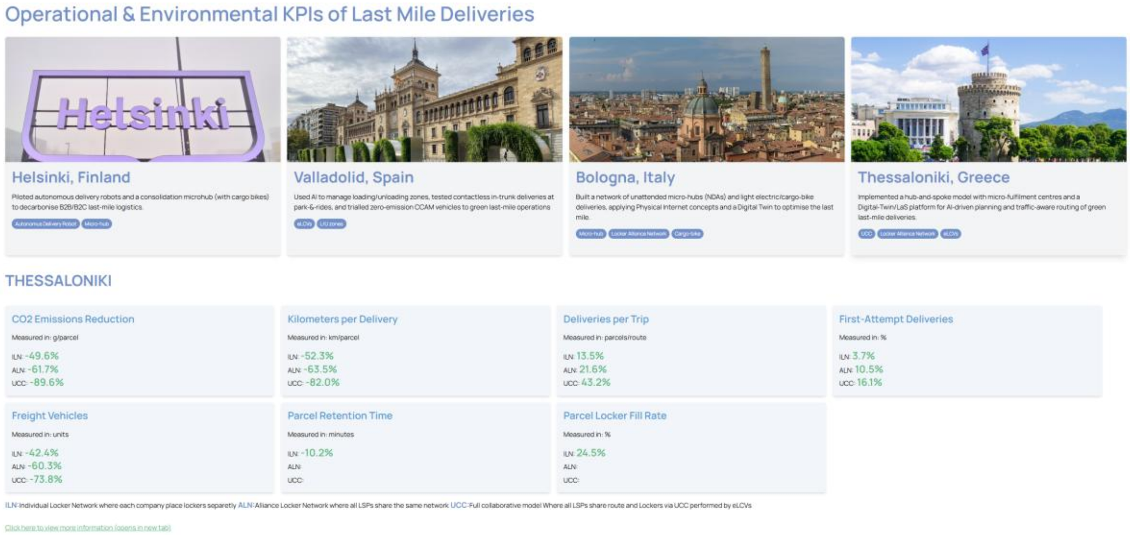

FIGURE 13:Demonstration of Level 3 Results In IAR

4.2 The Bologna use case

4.2.1 Level 1 Results and Analysis

The analysis of Bologna's Innovation Readiness for Urban Logistics reveals an overall score of 52%, indicating a moderate level of maturity with substantial scope for enhancement within its urban logistics ecosystem. This 52% score serves as a quantifiable diagnostic, positioning Bologna at a mid-range point on the maturity continuum for adopting and implementing innovative, green urban logistics solutions.

FIGURE 14: The innovative urban logistics readiness score for the case of Bologna

The city's strongest element is undeniably SMART GOVERNANCE, suggesting a robust administrative framework for urban logistics. This strength is particularly evident in its Planning and Stakeholder participation, which are highlighted as strong points of the system. This implies that Bologna has well-developed, long-term Sustainable Urban Logistics Plans (SULPs) that are actively co-created with diverse stakeholders (Q2 and Q7). Furthermore, a significant advantage for Bologna lies in the seamless articulation and alignment between its SUMP and SULP, and their strong integration with national and local policies (Q3). This integrated approach is crucial for cohesive urban transport development. Bologna also demonstrates considerable strength in SMART & INNOVATIVE RESOURCES & INFRASTRUCTURE and SMART & EASILY ACCESSIBLE CITY LOGISTICS NETWORKS, indicating a solid foundation of physical and digital assets, and effective network connectivity for urban freight. Other strong points include an advanced vision for green and sustainable urban logistics (Q1) and efficient communication channels among municipal departments and regional entities for coordinating and planning city logistics (Q6).

However, the ecosystem's weakest element is identified as SAFETY,SECURITY & QUALITY, signifying an area requiring significant improvement to bolster the reliability and sustainability of urban logistics. More analytically, Bologna shows underperformance in Multimodal logistics (Q15), suggesting that while its networks may be accessible, the effective integration and coordination of different transportation modes (e.g., rail, waterways, road) for optimizing freight movements and reducing emissions are not yet fully realized. This represents a key quantitative deficiency. A deeper dive reveals that Security Requirements and Standards (Q19) are also a weak point for Bologna, indicating a need for more robust measures, protocols, and potentially advanced technologies to ensure the safety and integrity of its logistics infrastructure and operations. Additionally, the weakness in Prospective infrastructure implies that Bologna might struggle with infrastructure designed specifically for future-oriented or highly innovative logistics models. Despite these internal weaknesses, a notable positive finding is that, when compared to other cities, Bologna was found to be "very weak in none element(s)" and "underperforms in none point(s)". This suggests that while challenges exist, they are not unique to Bologna and are likely common hurdles faced by many urban areas in their journey towards innovative logistics.

In essence, Bologna's commendable strengths in governance, planning, and stakeholder engagement, along with its robust basic infrastructure and network, provide a strong springboard for future advancements. However, to significantly enhance its innovation readiness and achieve a truly sustainable and secure urban logistics ecosystem, Bologna must prioritize addressing its quantitative weaknesses in multimodal logistics integration and the establishment of comprehensive security requirements and standards. Leveraging its strong foundational elements to tackle these specific areas will be crucial for Bologna to progress further in its innovative green urban logistics journey.

4.2.2 Level 2 Results and Analysis

In the Bologna Living Lab, the Level 2 micro-hub optimization module of the Impact Assessment Radar was used to formulate and plan urban delivery network configurations under different operational scenarios. The tool enabled city planners to explore how variations in total demand shared between two logistics providers considering locker hub capacities influence the required number of micro-hubs and delivery strategy split between cargo bike deliveries and self-pickups.

The test area of 4.3km² (the Bologna city centre ring) was used as a reference. Initially, stakeholders modelled scenarios with locker hub capacity fixed at 128 parcels per hub. As demand grew from 200 to 600 parcels, the number of required micro-hubs increased to maintain a service balance between delivery and pickup efficiency. Subsequently, alternative scenarios were evaluated using larger 256-capacity hubs. This significantly reduced the number of hubs required while shifting the balance of parcel handling more heavily toward cargo bike deliveries, illustrating the scaling potential of higher-capacity infrastructure.

The diagrams illustrate these dynamics. Figure 15 shows how hub count scales differently with demand depending on locker size, while the right plot depicts the relation between delivery modes. Notably, larger lockers allowed for a more centralized setup (fewer hubs), with a corresponding increase in cargo bike last-mile deliveries and a reduced need for self-pickup points.

Overall, the Bologna Living Lab used the IAR tool as a aggregated scenario simulation-based planning environment, allowing for flexible experimentation with urban logistics configurations before implementation. This supports both efficient infrastructure use and tailored green last-mile delivery services based on local demand and operational preferences.

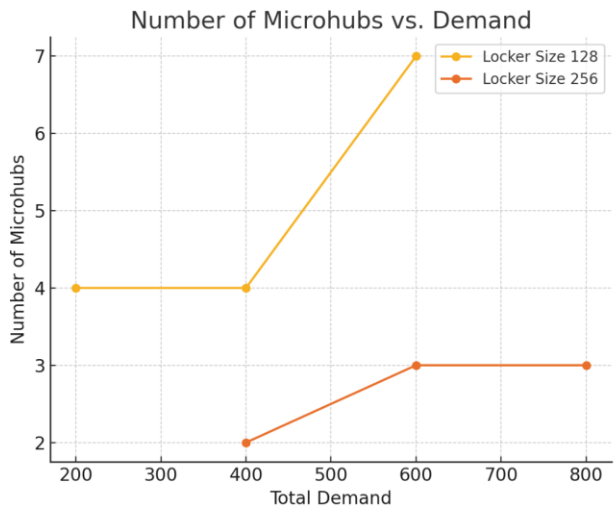

FIGURE 15: Demonstration of data generated from level 2 module for the micro-hub model of Bologna

During the Bologna pilot, three micro-hubs were physically deployed to support the operational testing of a two-echelon delivery model combining urban hubs and cargo bikes. While these implementations validated the concept on the ground, the Level 2 module of the IAR was employed as a complementary planning tool to guide future network expansions. Rather than relying on simulation, the module uses closed-form analytical models to estimate optimal configurations under varying demand and infrastructure assumptions. Specifically, it allowed stakeholders to test how the network should scale in response to future increases in parcel volumes, and how locker size, hub capacity, and spatial deployment affect performance and delivery mode balance.

This functionality was especially useful for identifying the transition point beyond which larger hub capacities become more efficient, reducing the need for additional infrastructure while enabling greater use of cargo bike delivery. By quantifying these trade-offs in a structured and transparent way, the tool helped city planners and service providers in Bologna to anticipate operational needs and prepare for scaling the service sustainably and cost-effectively.

4.2.3 Level 3 Results and Analysis

In the Bologna Living Lab, the planning process was driven by the insights generated from the Level 2 modules of the IAR. The analytical models were used to determine the optimal number and size of micro-hubs needed to support a two-echelon delivery network combining urban hubs and cargo bikes. The Fleet Mixture module also helped define the required fleet size of cargo bikes to serve different demand levels. These outputs were instrumental in informing the pilot design and scaling strategy. Using the URBANE Transferability Platform, the Bologna team integrated these configurations into the collaborative green routing tools, the Digital Twin environment, and the two-echelon delivery models to evaluate performance under realistic urban constraints.

The results from these combined assessments were documented and uploaded into Level 3 of the IAR, providing a stable record of how the selected solution performed in the Bologna case. This structured documentation enables future adopters to understand the relationship between infrastructure configurations and delivery outcomes. It also serves as a reference point for other cities interested in replicating similar last-mile logistics models. By capturing both planning and evaluation data, the Level 3 observatory supports knowledge sharing and promotes wider adoption of sustainable urban logistics practices.

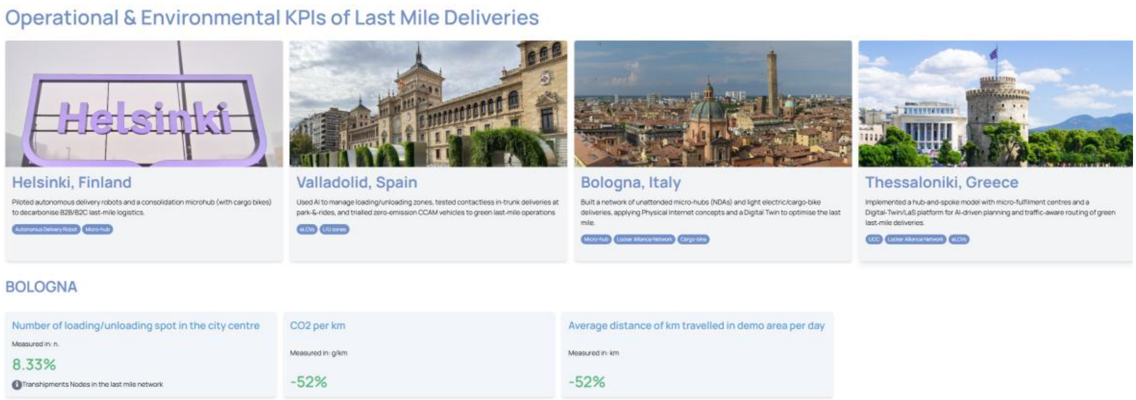

FIGURE 16: Demonstration of Level 3 Results for Bologna LL

4.3 Adoption and Transferability Framework for European Cities: Guidelines for Replication, Local Adaptation, and Uptake

4.3.1 Capacity Building and stakeholders' engagement for maturity evaluation

The successful adoption and widespread transferability of innovative urban logistics solutions across European cities hinge not only on the intrinsic quality of robust methodological frameworks but, more critically, on the inherent capacity of individual cities to effectively embrace, implement, and integrate such innovations into their urban fabric. While the European Union consistently promotes the development of SULPs as a vital mechanism for fostering greener and more efficient freight movement, many cities encounter a significant practical challenge: the pervasive absence of dedicated logistics departments and, consequently, a substantial lack of specialized knowledge. This deficit often directly impedes their ability to orchestrate multi-stakeholder discussions effectively, a process that is crucial for understanding the diverse needs and complex problems articulated by various users and for facilitating the conflict resolution necessary to design solutions that are both effective and broadly acceptable within the urban environment.

At this critical point, the IAR , is meticulously designed to systematically assess multiple dimensions of innovation within the urban logistics ecosystem, emerging as an exceptionally capable instrument. Far from serving merely as a diagnostic survey, this tool is strategically conceived to function as a catalytic platform for genuine co-creation, actively triggering and structuring essential dialogues that might otherwise prove elusive. By providing a comprehensive agenda through its 22 precisely formulated questions, thoughtfully categorized under the six overarching elements of the innovative urban logistics ecosystem (Smart Governance, Smart & Innovative Resources & Infrastructure, Smart Actors, Greenness & Efficiency, Smart & Easily Accessible City Logistics Networks, and Safety & Security), the tool effectively addresses the initial challenge of "where to begin" for cities lacking specialized logistics expertise. This structured approach is instrumental in guiding productive conversations, enabling a diverse assembly of stakeholders to convene in a roundtable setting. These stakeholders include LSPs, various city authorities from departments spanning transport, planning, environment, and economic development, law enforcement agencies, academic institutions, and citizen representatives as the ultimate recipients of deliveries. Within this collaborative environment, each question prompts an ecosystem-oriented response, allowing varied perspectives, nuanced needs, and potential points of contention to surface organically. This process fosters a deeper, shared understanding of interdependence and promotes a truly holistic view of urban logistics challenges and opportunities.

The analytical insights derived from the survey's qualitative and quantitative measurements, combined with the AHP-derived weights assigned to each sub-element, empower cities to objectively identify their weakest areas in terms of innovation readiness. For instance, a low score in Regulatory adaptation, coupled with a high AHP weight emphasizing its significance, would clearly signal a critical priority area demanding immediate intervention and focused effort. This data-driven clarity provides city authorities with actionable intelligence required to strategically allocate resources and channel capacity-building efforts precisely where they are most needed, thereby maximizing the impact of their initiatives. Furthermore, the roundtable format, central to the effective utilization of this assessment tool, naturally cultivates an environment conducive to conflict resolution. As stakeholders articulate their positions and engage with each survey question, disparities in current practices or divergences in future aspirations inevitably become apparent. In such instances, the overarching objective of enhancing the city's collective "Innovation Readiness for Urban Logistics" score serves as a unifying force, guiding participants towards the discovery and adoption of mutually acceptable solutions. This process fosters a sense of shared ownership and collective responsibility for the urban logistics landscape.

Beyond its crucial role in initial assessment and strategic planning, the Innovative Urban Logistics Readiness Tool is designed to function as a dynamic, long-term monitoring instrument. By periodically re-administering the survey (typically every 18 months to three years, allowing sufficient time for implemented changes to manifest) the established multi-stakeholder task force can systematically track the city's progress. This recurring assessment enables quantification of improvements in specific elements and sub-elements over time, providing concrete evidence of the efficacy of implemented policies and initiatives. It also enables timely identification of emerging barriers or shifts in stakeholder priorities, necessitating adaptive adjustments to SULPs or other urban logistics strategies. Crucially, this consistent monitoring provides valuable opportunities to celebrate successes, offering tangible proof of advancements made. This serves to motivate all involved stakeholders and builds momentum for continued innovation and sustained efforts in transforming urban logistics. The tool also facilitates benchmarking against other European cities using the same framework, enabling peer learning and knowledge transfer across municipal boundaries.

In essence, the Innovative Urban Logistics Readiness Tool transcends the traditional confines of a diagnostic instrument; it evolves into a comprehensive facilitator for continuous learning, collaboration, and systematic improvement. It is this robust capacity-building function that is paramount for the effective replication, intelligent local adaptation, and widespread uptake of green urban logistics solutions across European cities. The tool empowers cities with limited prior logistics expertise to initiate essential dialogues, cultivate a shared vision for sustainable urban logistics futures, and systematically chart their transformative journey toward becoming more innovative and resilient urban environments. Through this approach, the tool addresses the fundamental capacity gap that often hinders SULP development and implementation, transforming it from a regulatory requirement into a collaborative opportunity for urban logistics ecosystem advancement.

4.3.2 The design and conduction of planning solutions

This section outlines the detailed input parameters and corresponding output interpretations for each of the models included in the Impact Assessment Radar Level 2 planning suite. The aim is to support future users in replicating the presented analyses in new urban contexts by providing clear guidance on model configuration and application. These guidelines build upon the examples discussed in previous sections and are structured to enable straightforward transferability of the planning logic.

The first subsection describes the Locker Network Optimization module, which operates in two distinct modes. The baseline mode allows a single logistics service provider to estimate the approximate number of parcel lockers required within a specified service area. An extended mode supports scenarios involving multiple operators sharing a common locker infrastructure, thus promoting collaborative logistics strategies. The second model focuses on the Fleet Mixture Optimization, enabling planners to determine the optimal vehicle mix by balancing environmental and economic criteria. This model is particularly useful for evaluating transition strategies from conventional fleets to greener alternatives, such as cargo bikes and electric delivery vehicles or ADVs.

The third model synthesizes the previous two, forming a 2-echelon micro-hub based delivery model. It estimates the optimal number and placement of micro-hubs while integrating second-layer delivery operations carried out by cargo bikes. This model supports planning for multi-modal and decentralized last-mile logistics networks and is particularly aligned with Physical Internet principles.

All three models are designed to work with aggregated and easily accessible input data, minimizing data collection barriers for cities and logistics stakeholders. Moreover, the models share several common parameters, allowing users to experiment with multiple configurations and solutions across the suite with minimal redundancy.

4.3.2.1 The Locker Network Optimization module

The Locker Network Optimization module is designed to determine the optimal number of parcel lockers in a city logistics setting, considering cost-efficiency with CO_2 reduction. The user begins by specifying the number of logistics companies involved and the characteristics of the service area, such as total demand (parcels/day), the number of depots, and the area size in square kilometres. Key locker-related inputs include locker capacity (parcels per locker), acquisition cost, and operational cost per locker. Additional vehicle related inputs such as average delivery speed, vehicle capacity, fuel cost, and labour cost also used to simulate and compare the cost and emissions impacts of locker deliveries versus traditional home deliveries Table 7.

Category	Parameter	Value	Units
Step 1: Companies	Number of companies	The number of companies in the service (2+ for locker alliance network)	Companies (scalar)
Step 2: Area & Demand	Area of interest	The area the demand covers	km²
	Locker capacity	The number of units in each Locker	parcels/locker
	Demand (Company n.)	The demand per day in parcels each company have in the study area	parcels/day
	Depots (Company n.)	The number of depots (The final station before last mile, also called warehouses in some cases)	depots
Advanced Parameters	Locker acquisition cost	The cost of acquisition of one locker	€
	Annual opportunity cost rate	The yearly investment opportunity cost	-
	Operational cost per locker per day	Maintenance, IT and other costs locker have	€/day/locker

	Vehicle capacity	The average number of parcels delivered on a single route	parcels/route
	Vehicle speed	The average speed in this area	km/h
	Fuel price	The fuel price in this area approximately	€/litre
	Fuel consumption	The per 100km travelled consumption of fuel	litre/100km
	Delivery time	The time takes to park unload deliver and get back for a single parcel	hours/delivery
	Labor cost hourly	The average hourly wage of a single employee	€/hour
Step 3: CO_2 Goal	CO_2 reduction goal	The reduction expected to achieve by this innovation	%

TABLE 6: INPUT PARAMETERS FOR THE LOCKER NETWORK OPTIMIZATION MODULE

Once all inputs are provided, the model calculates the optimal number of lockers needed to minimize costs and/or reach a specified CO_2 reduction target. The results include the total cost of operations using lockers, the baseline cost without lockers, and the corresponding CO_2 savings in kilograms per day. In an extended step, users can input a desired CO_2 reduction percentage, and the model will then return the number of lockers required to achieve that reduction. The underlying engine is based on cost estimation using distance-based delivery models, energy consumption, and demand split across the delivery zone.

Scenario	CO_2 Saved	Lockers	Total Cost (€)	Baseline Cost (€)
Base Optimization	CO_2 kg that will be saved by installing this number of lockers	The optimal number of Lockers	The total operational cost if optimal lockers adopted	The original cost before Locker adoption
With 50% CO_2 Reduction	CO_2 kg that will be saved by installing this number of lockers	The optimal number of Lockers considering CO_2 reduction goal	The total operational cost if optimal lockers adopted considering CO_2 reduction goal	The original cost before Locker adoption

TABLE 7: Output Results for the Locker Network Optimization Module

4.3.2.2 The Fleet Size Optimization module

The Fleet Size Optimization module helps logistics planners determine the ideal mix and quantity of delivery vehicles (diesel and electric, hybrid, bike, ADV) needed to meet demand while satisfying environmental goals. Users provide the area of interest, daily parcel demand, number of depots, and a minimum CO_2 reduction goal. Fleet composition can be configured by assigning percentage shares to diesel and electric vehicles. Each vehicle type is characterized by parameters such as capacity, acquisition cost, consumption, CO_2 emission per km, and cost factor. Additional advanced inputs include delivery time per parcel, depreciation, opportunity cost, labour cost, and working days. Table 8 summarizes the variables of the Fleet Mixture Model excluding the variables already reported in Table 7.

Category	Parameter	Value	Units
	Minimum CO_2 reduction goal	The CO_2 reduction expected to achieve by this innovation	%
Fleet Composition	Diesel share	The share of diesel vans on the fleet	%
	Electric share	The share of electric vans on the fleet	%
Advanced Parameters	Working days per year	The working days per year (e.g. 260 usually)	days
	Depreciation rate	The rate that the existing fleet depreciates the value per year	%
	Default speed	The average speed in this area	km/h
	Delivery time	The time takes to park unload deliver and get back for a single parcel	hours

TABLE 8: Input Parameters for Fleet Size Optimization Module

The model computes the optimal fleet mix that minimizes operational costs while achieving the specified CO_2 reduction target. It outputs the number of vehicles per type, daily CO_2 emissions (absolute and baseline), and the total daily operational cost. The algorithm balances the higher upfront cost of electric vehicles against their lower per-kilometre emissions and cost factors. It also adjusts the number of vehicles needed to fulfil demand depending on the capacity and efficiency of trade-offs. The tool is particularly useful for decision-makers exploring electrification scenarios, carbon budgeting, and cost-sensitive fleet expansion strategies.

Vehicle Type	Capacity	Consumption	Acquisition Cost	CO_2 Emission	Speed
The engine/fuel type	The average parcel capacity	The consumption per 100km	Total purchase cost of one unit	The kg per km driven	The average speed

TABLE 9: Vehicle configuration for Fleet Size Optimization Module

Metric	Value
CO_2 reduction	The % of reduction achieved after new fleet mixture proposition
Total CO_2 emissions	The value in kg per day of reduction achieved

Total cost	The new total daily operational cost
Optimized diesel share	The share of diesel vans in the new setting
Optimized electric share	The share of the proposed mode (electric in this example)
Vehicles (Diesel)	The total fleet size of the baseline vehicle
Vehicles (Electric*)	The number of new vehicles need to acquire

TABLE 10: Output Results for Fleet Size Optimization Module

4.3.2.3 The Micro-hub Optimization module

The Micro-hub module is aimed at estimating the cost and infrastructure requirements for deploying micro-hubs to support two-echelon last-mile delivery systems. The model supports multiple companies and allows users to input per-company demand and depot information, in addition to area size. Micro-hubs act as intermediate facilities where parcels are transferred from vans to smaller, low-emission vehicles like cargo bikes for last-mile delivery. Advanced parameters include micro-hub capacity, fixed and opportunity costs, home/self-pick-up capacity multipliers, and courier specific values (e.g., labour cost, delivery time, and transport cost for vans vs. bikes).

Parameter	Value	Units
Micro-hub Fixed Cost	The acquisition cost of a single micro hub unit	$
Micro-hub Capacity	The number of parcels can be hosted in a single micro-hub	Parcels per micro-hub
Bike Capacity	The average number of parcels delivered by cargo-bike in a single route	Parcels per route
Bike Speed	The average speed of the cargo bike in this area	km/h
Bike Delivery Time	The average delivery time using cargo bike	hours
Labor Cost (Bike)	The hourly labour cost for the cargo-bikers	$/hour
Transport Cost (Bike)	The transport cost per km for cargo bike (due to maintenance and depreciation, accidents costs). A value near zero does not affect significantly the results	$/km

TABLE 11:Input parameters Micro-Hub Optimization Module

The tool calculates the optimal number of micro-hubs required, the resulting aggregated delivery cost per parcel, and how parcel demand is split between home delivery and on-foot (bike) delivery. The optimization seeks to balance setup costs (e.g., micro-hub operation and vehicle labour/transport) with routing and emissions efficiencies. It considers two delivery legs: from depot to micro-hub (via van) and from micro-hub to customer (via bike), estimating total demand coverage while respecting delivery capacities and service constraints. This module is particularly useful in dense urban areas where vehicle access is limited and local authorities encourage shared delivery infrastructure.

5. Conclusions

The IAR has been designed as a comprehensive planning and evaluation tool that supports urban logistics stakeholders in identifying, assessing, and projecting the impacts of innovative green last-mile delivery solutions. Developed within the URBANE project, the IAR serves as a foundational element of the broader URBANE Transferability Platform, enabling cities across Europe to systematically explore the maturity, feasibility, and effects of adopting PI oriented solutions, such as parcel lockers, microhubs, green and digitally supported delivery vehicles, and asset sharing schemas. In the continuously evolving landscape of urban logistics, where policy directives, environmental sustainability targets, and digital transformation converge, the IAR proposes an emerging methodological structure that helps decision-makers plan sustainable interventions based on evidence, best practices, and robust scenario evaluation.

The deliverable presents the IAR across three interconnected levels, each structured to align with the stages of real-world urban planning processes. The first level assesses a city's readiness to adopt green and digital logistics innovations by evaluating the maturity of its existing ecosystem and infrastructure. The second level offers a set of continuous approximation models that generate high-level but actionable planning outputs including optimal fleet mixes, parcel locker networks, and microhub layouts, using easily accessible aggregated data. The third level functions as an observatory, aggregating use case data and performance outcomes from pilot implementations across the EU. This progression mirrors the typical logic of planning studies: from situational analysis to solution design, to benchmarking and replication. The structure of the deliverable reflects this logical flow, helping the reader follow how a user interacts with the IAR platform, accesses the models, interprets outputs, and leverages shared experiences to support evidence-based decision-making.

From a planning and policy perspective, the IAR addresses a critical gap by enabling cities to prototype logistics interventions without incurring the financial and operational cost of full-scale pilots. Its lightweight modelling approach offers flexibility for initial planning, while its connection to the Digital Twin and Agent-Based Modelling modules within the Transferability Platform allows for deeper evaluation when more information is needed. Moreover, its cross-city benchmarking functionality at Level 3 promotes harmonization and transparency in the way urban logistics strategies are evaluated across Europe. As a result, the IAR is positioned not only as a technical instrument but also as a governance enabler promoting policy alignment, data standardization, and long-term resilience planning.

The successful demonstration of the IAR in Wave 1 & Wave 2 Living Labs further confirms its practical relevance. In Thessaloniki LL, the tool was used to estimate the optimal number of parcel lockers, support fleet restructuring planning for electric vehicles, and guide UCC network design. These results were later applied in both real-world pilot activities and digital twin simulations. In Bologna LL, the Level 2 modules were used to define the microhub network and optimal cargo bike fleet composition, which were then integrated with collaborative routing and two-echelon delivery models to assess impact at scale. These case studies illustrate the full value chain of the IAR moving from strategic assessment to tactical configuration, to operational impact evaluation so that validating its use in diverse urban contexts.

Looking forward, the IAR will serve as a continuously evolving platform that grows as more cities contribute data, share results, and benchmark their progress. This collaborative knowledge base enhances the transferability of best practices and provides a replicable foundation for future planning. In the long run the vision is to position the IAR as a unified standard in the EU for assessing the readiness, planning the deployment, and evaluating the outcomes of sustainable urban logistics systems. By fostering a culture of shared learning and open evaluation, the IAR will not only support cities in making informed, context-rich decisions but also accelerate the broader policy goals of the European Green Deal, Sustainable Urban Mobility Plans, and digital transformation in the freight and logistics sector.

In conclusion, the IAR establishes practices that extent beyond a technical toolbox. It is a strategic enabler of change, empowering cities to translate ambition into action, reduce uncertainty in planning, and collaborate across borders to advance a shared vision for clean, efficient, and inclusive last-mile logistics. The continuous expansion, improvement, and institutionalization of the IAR within the URBANE platform and beyond will be essential in building a resilient logistics ecosystem that meets the needs of people, businesses, and the city-logistics ecosystems in general.

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