D4.1: Barcelona Demonstrator

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Executive summary

The purpose of this document is to provide a detailed description of the tasks performed at the Barcelona Living Lab (LL), part of WP4 of URBANE. The LL was jointly implemented by the Universitat Oberta de Catalunya (UOC), the Metropolitan Area of Barcelona (AMB), and the last-mile operator Vanapedal, combining research, public-sector coordination, and real operational practice. Barcelona LL was designed to improve the efficiency of sustainable city logistics practices through the optimization of the operations carried out in micro-consolidation centres and by a cargo-bike operators. Lastly, the report presents the definition of the LL, the description of the Use Cases, the operations performed and the different assessments methodologies conducted.

In more detail, the LL pursued had a twofold aim. The first was the development, implementation and validation of an RFID-based system to improve operational efficiency, automation, and traceability in last-mile processes. RFID readers installed in cargo-bikes enables real-time parcel identification, automated data collection, and seamless integration with a cloud-based server and Blockchain services. The second aim was to replicate URBANE tools and solutions to support the optimisation of urban logistics operations, generating transferable knowledge through the application of instruments such as the Digital Twin and the Impact Assessment Radar, and enabling replication in other European urban contexts.

Finally, the Use cases and testbeds were designed to validate the RFID system before full deployment, and a set of KPIs was defined to compare baseline (AS-IS) and technology-enabled operations (TO-BE) . The results showed reductions in handling times at the micro-consolidation centre, improvements in delivery efficiency and staff productivity, and the successful introduction of real-time parcel traceability, confirming the potential of RFID-enabled, cargo-bike-based logistics as a scalable solution for sustainable urban freight distribution.

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Glossary of Terms and Acronyms

Abbreviations	DESCRIPTION
AMB	Metropolitan Area of Barcelona
API	Application Programming Interface
AWS	Amazon Web Server
B2B	Business to Business
B2C	Business to Consumer
BPMN	Business Process Model and Notation
CNMC	(Spanish) National Commission of Markets and Competition
DT	Digital Twin
EV	Electric Vehicle
IAR	Impact Assessment Radar
ICE	Internal Combustion Engine
ICT	Information and Communication technology
IT	Information Technology
KLU	Kühne Logistics University
KPIs	Key Performance Indicators
LSB	Logistics Sector Board
LEZ	Low Emission Zone (ZBE in Catalan)
L/D	Loading and Unloading zones
LL	Living Lab
LRP	Location Routing Problem
LSP	Logistics service providers
MCC	Micro-Consolidation Centre
MMP	Mobility Master Plan
MQTT	Message Queuing Telemetry Transport
MUMP	Metropolitan Urban Mobility Plan
NMG	National Mobility Guidelines (DNM in Spanish)
RFID	Radio Frequency Identification

SLA	Service Level Agreement
SIMMB	Integrated Metropolitan Mobility System of Barcelona
SKEMA	Skema Business School
UCC	Urban Consolidation Centre
UDS	Urban Distribution of Services
UE	European Union
UFD	Urban Freight Distribution
UHF	Ultra High Frequency
MUFDS	Municipal Urban Freight Distribution Strategy
UFDC	Urban Freight Distribution Centres
UFDS/EDUM	Urban Freight Distribution Strategy (EDUM in Catalan)
SIM	Subscriber Identity Module
SUMP	Sustainable Urban Mobility Plan (or UMP)
UOC	Universitat Oberta de Catalunya
VAN	Vanapedal – Solucions Ultima Milla
VRP	Vehicle Routing Problem
WP	Work Package

1. Introduction

This present deliverable report documents the development, implementation, and evaluation of the Barcelona Living Lab (LL), a key component of Work Package 4 (WP4) within the URBANE project. The Barcelona LL aims to enhance the efficiency and sustainability of last-mile logistics operations by testing and validating innovative operational and digital solutions. The LL is structured around three complementary innovation areas:

1. **Assess the environmental benefits of electrifying first-mile operations.**
   To evaluate the potential reduction in CO_2 emissions and other environmental impacts achieved by replacing conventional internal-combustion vehicles with electric alternatives in the first-mile transport of consolidated goods from the Zona Franca logistics area to the micro-consolidation centre serving Ciutat Vella.

2. **Replication of URBANE digital tools and solutions.**
   A central objective is the implementation and validation of the Digital Twin and the Impact Assessment Radar. These tools are used to simulate processes and different last-mile innovative scenarios as well as to optimize real life urban logistics operations, providing a data-driven framework for decision-making. By testing these solutions in Barcelona, the project creates a scalable blueprint designed to support adoption in other European urban contexts.

3. **RFID-enabled automation of last-mile operations.**
   RFID readers are installed at a Vanapedal's cargo bikes to automate parcel detection, reduce manual handling, and generate continuous operational data. A Blockchain system tracks real-time data flows, ensuring compatibility and traceability. Pilot tests validate system performance, identify operational issues, and report future recommendations.

The main purpose of this deliverable is to provide a detailed mapping of the current operational context, identify opportunities for optimisation, and outline the methodologies guiding the implementation and evaluation of the Barcelona LL. These foundations ensure coherence with the broader objectives of WP4 and support the replicability of the results in future Living Labs. The key objectives of this deliverable include:

1. Present and analyse the results obtained from the implementation of the Barcelona LL, including the RFID-enabled last-mile pilots and the application of URBANE digital tools.

2. Describe the operational context and baseline conditions of Barcelona's last-mile logistics system.

3. Evaluate the impact of the implemented solutions through a structured set of KPIs, focusing on operational efficiency, transparency, and parcel traceability.

4. Justify the replication potential of URBANE tools and methodologies, generating transferable insights to support their adoption in other areas.

By documenting the use of URBANE digital tools in a real-life urban logistics setting, the report contributes to the objectives of WP4 and provides a structured evidence base to support the optimisation, replication, and scaling of sustainable last-mile logistics solutions.

1.1. URBANE Outputs Mapping to GA Commitments

The table below summarises how the outputs and activities of Barcelona LL correspond to the commitments outlined in the GA. This ensures transparency regarding the alignment, status, and contribution of each deliverable and task.

Table 1. Outputs Mapping to GA Commitments

URBANE GA	URBANE GA DESCRIPTION	DOCUMENT CHAPTERS	JUSTIFICATION
	DELIVERABLE		
D4.1 – Barcelona demonstrator	D4.1 consolidates the results of the implementation of the Barcelona demonstrator and lessons learned. It will demonstrate the implementation of RFID parcel handling of a cargo-bike hub and complementary locker solutions. It will also deliver the algorithms developed to facilitate the operations in the micro-hub and models and simulations of new process of RFID in ciclo-logistics.	Chapters 3 - 9	These chapters document the full implementation of the demonstrator, starting with the LL context (Ch. 3), the LL framework including DT and Blockchain integration (Ch. 4), the setup and technical development of the RFID system (Ch. 5), the use cases implemented including DT simulation and RFID pilots (Ch. 6), and the evaluation through KPIs (Ch. 7), and the tactical assessment (Ch. 8), lessons learned, and recommendations (Ch. 9). Together, they provide a complete account of the demonstrator's outcomes as required by the GA.
	TASK		
Task 4.1. - Barcelona Living Lab Implementation	ST.4.1.1. LLs Community Setup. UOC, VAN and AMB will map operational needs and schedule all the potential tasks. Coordinate with other LLs, especially those involved in the first wave, such as Helsinki and Thessaloniki to obtain firsthand knowledge on their activities and results and identify areas of innovation that can be adopted. A	Chapters 3 - 9	The report chapters collectively cover all Task 4.1 subtasks: Ch.1 introduces the task's position in WP4; Ch. 2 explains the methodologies for data collection and RFID information capture; Ch. 3 defines the LL context and stakeholders; Ch. 4 presents the LL framework and simulations; Ch. 5 describes the LL setup including RFID technical development; Ch. 6 presents the use cases (first-mile simulation and last-mile

benchmarking and selection of RFID readers and tags will be done.

ST.4.1.2. Algorithms developed to facilitate the operations in the micro-hub. Develop algorithms to process the data received from the RFID tags building on open-source principles basis, for the identification of the parcels coming into the micro-hub, their sorting and classification into standardised containers and the design of the delivery routes. This activity will look into results from Task 3.5 and explore reuse of algorithms.

ST.4.1.3. Modelling and simulation of new process of RFID in ciclo-logistics. Before carrying out the physical implementation of the system, simulations will detect any possible weaknesses or failures (DT-enabled). The simulation will help to test the requirements of vehicles using the new RFID system and estimate the expected reduction of operating times.

ST.4.1.4. Implementation of RFID technology. Implement the RFID system, the operational algorithms, and adapt the traditional micro-hub processes for parcels management. Evaluate the changes in the way goods are sorted, loaded onto the cargo-bikes, and delivered to the customer. New protocols will be defined and personnel training to become familiar with the new technology will be carried out in the context of the LL. Implement a small scale 6-month pilot with a limited number of bikes and riders, and then extend it to evaluate performance.

ST.4.1.5. End-User feedback and Impact Assessment. Tasks and activities will be properly documented to assess how much RFID technology improved the operational efficiency and cost. Technical workshops with other metropolitan public authorities (preferably with policy officers) will be carried out and outputs will be disseminated.

pilots); and Ch. 7 provide KPI performance results, Ch. 8 provides tactical-level evaluation; and Ch. 9 outline the conclusions, with the lessons learned and recommendations. This fully corresponds to ST4.1.1–ST4.1.5 and demonstrates completion of the Task.

1.2. Deliverable Overview and Report Structure

This section provides a comprehensive overview of the structure of the report, which is organised into nine chapters, each addressing a key dimension of the Living Lab:

- **Chapter 1** introduces the scope, objectives, and structure of the deliverable and situates it within the framework of WP4 and the broader URBANE project.

- **Chapter 2** describes the data sources and methodologies employed, including stakeholder mapping, operational data collection, and RFID-enabled information capture.
- **Chapter 3** outlines the context and characteristics of the Barcelona LL, including the city's logistics landscape, policy environment, stakeholders, and challenges.
- **Chapter 4** details the Living Lab framework, including existing infrastructure and the integration of the Digital Twin, Blockchain, and Impact Assessment Radar.
- **Chapter 5** presents the Living Lab setup, including stakeholders, technical development of the RFID system, infrastructure, and preparation processes.
- **Chapter 6** explores the use cases implemented: the first-mile simulation via the Digital Twin and the series of last-mile RFID pilots.
- **Chapter 7** presents the performance results of the Barcelona Living Lab, reported through a set of key performance indicators (KPIs).
- **Chapter 8** describes the tactical-level evaluations conducted for the Barcelona Living Lab, firstly, detailing the simulations done using Level 2 of the Impact Assessment Radar and, secondly, presenting the findings of one of the project's outputs.
- **Chapter 9** presents the conclusions of the deliverable, summarising the main findings in the form of lessons learned and key recommendations, all derived from the Barcelona Living Lab activities.

Together, these chapters present a coherent and detailed narrative of the Barcelona LL's implementation and findings, contributing to the URBANE project's goal of establishing innovative, scalable, and sustainable urban logistics solutions.

2. Data Collection and Analysis

This chapter describes the data collection strategy adopted in the Barcelona Living Lab. The collected data also supports replication activities for Wave 4 Living Labs by providing a clear empirical basis for comparison and transferability.

Data was obtained through a combination of qualitative and quantitative methods, selected according to the resources and specific conditions of the Barcelona LL. The main data collection approaches applied are summarised below:

- **Stakeholder mapping:** It identifies the individuals, organisations, and institutional actors directly or indirectly affected by the LL interventions. Entities are grouped by type and level of influence, enabling a clearer understanding of local dynamics and helping to anticipate opportunities, risks, and collaboration needs.

- **Desk research:** Consists of reviewing existing documentation, including project databases, reports, scientific literature, municipal plans, and online open-data resources. It also includes research carried out through workshops, events and congresses, as well as the two project outputs in the form of scientific articles.

- **BPMN diagrams of AS-IS and TO-BE situations:** Business Process Model and Notation (BPMN) diagrams were used to map current (AS-IS) and improved (TO-BE) logistics processes. These diagrams highlight operational bottlenecks, manual workloads, and inefficiencies before the intervention, and later illustrate the redesigned workflow after RFID technology integration.

- **Operational data gathering**: The implementation of RFID technology enabled direct extraction of real-time operational data from the last-mile environment. These data serve as the foundation for evaluating the improvements achieved in the TO-BE scenario. Key variables collected include:
  1) Number of daily deliveries.
  2) Time spent de-consolidating, re-consolidating, and loading.
  3) Vehicle load level on each trip.
  4) Delivery routes.
  5) Distance traveled by delivery vehicles.
  6) Delivery times.
  7) Incidence rate.

Data collection was coordinated by UOC with the operational support of Vanapedal and the analytical assistance from other URBANE partners. The RFID system enabled automated, continuous data transmission to a cloud-based server, where records were stored and processed. Additionally, Blockchain technology ensured the immutability and traceability of key parcel-handling events.

The combination of stakeholder input, desk research insights, BPMN modelling, and operational metrics provides a robust empirical foundation for assessing both the baseline scenario and the improvements achieved through the Living Lab interventions.

3. Barcelona Living Lab Context

This chapter provides an overview of the urban, regulatory, and operational environment in which the Barcelona Living Lab operates. Understanding this context is essential for evaluating the feasibility, challenges, and scalability of the innovations introduced in the LL. The chapter is organised into three sections: the characteristics of the city of Barcelona, the governance and policy framework, and the specific vision and challenges addressed by the Barcelona LL.

3.1. The city of Barcelona

3.1.1. Location and characteristics

Barcelona is situated in the north-east of the Iberian Peninsula (Figure 1) and serves as the capital and most prominent city of Catalonia. The city covers an area of 101.35 km² and is a major European centre, ranking as the second most populous city in Spain and the tenth in the European Union. As of January 2024, the total population is 1,655,956 inhabitants, with a high population density of approximately 16,340 inhabitants/km². Its metropolitan area is one of the largest and most densely populated urban agglomerations in the EU, encompassing 5,879,198 inhabitants.

The city is a crucial logistics node, seamlessly integrated with national and international transport networks (airport, port, motorways, railways), and is a key component of the TEN-T Core Network via the Mediterranean Corridor.

Figure 1. Location of Barcelona in Europe and Spain

The Barcelona LL specifically focuses on Ciutat Vella, the historic city centre characterised by narrow medieval streets, restricted access for motorised vehicles, limited space for loading/unloading activities, high pedestrian density, high commercial connectivity, and strict regulatory controls on vehicle circulation. These urban constraints strongly influence last-mile delivery efficiency and highlight the need for zero-emission logistics solutions sustained by micro-consolidation centres.

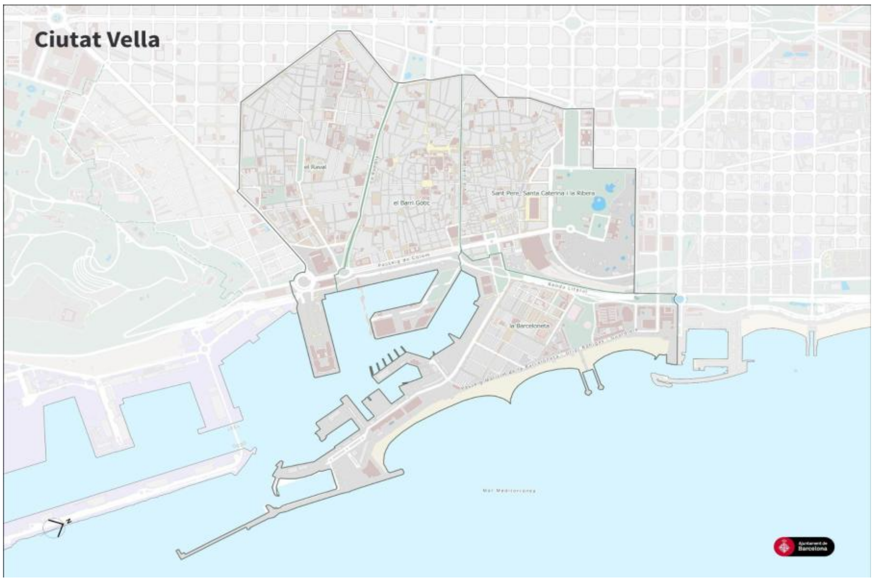

Figure 2. Location of the Ciutat Vella District in Barcelona (Source: Ajuntament de Barcelona)

3.1.2. Regional and economic context

E-commerce in Spain continues to grow, with 84,7% of online purchases delivered to customers' homes (Comisión Nacional de los Mercados y la Competencia, 2025). This intensifies pressure on the last-mile delivery segment, which faces high rates of failed deliveries, returns, congestion, and rising environmental impacts, including increased traffic, air pollution, noise, accidents, and greenhouse gas emissions.

In Barcelona, motorised traffic is estimated to contribute approximately 52 % of all pollutant emissions, with over 70 % of these emissions attributable to private cars, many of which are diesel-powered. This reflects the heavy influence of road traffic on the city's air quality, where vehicles, and particularly private cars with diesel engines, remain a major source of nitrogen dioxide and other harmful pollutants, prompting the City Council to implement policies like the ZBE to reduce emissions and protect public health (Ajuntament de Barcelona, 2023).

To foster more sustainable last-mile logistics, Barcelona is promoting intermodality, including Urban Consolidation Centres and Micro-Consolidation centres. These enable goods consolidation and allow the replacement of large trucks with cargo bikes, small electric vehicles, and other low-emission modes, improving both environmental and acoustic conditions in dense urban areas. The city is also advancing the digitalisation of urban logistics. For instance, through the SPRO[1] app, loading and unloading areas are digitised, enabling operators to book kerbside space. Complementary actions include expanding an Open Data portal that provides information on logistics infrastructure and incidents, supporting more efficient and transparent last-mile operations.

3.2. Governance Analysis

Barcelona LL's deployment is influenced by the city's regulatory framework, including laws, decrees and other regulations. These policies are aimed at promoting digital transformation and accelerating its transition towards sustainable mobility, smart innovation, climate neutrality, and zero emissions. The following are the most relevant regulations, each according to the competent authority:

A. Laws at the regional level

   a. Decree 134/2024 approves the Air Quality Plan, Horizon 2027, which defines the current framework for addressing air pollution in Catalonia. The plan identifies areas where air quality limit values are exceeded and establishes measures to reduce emissions, including actions related to traffic management and sustainable mobility, replacing previous air quality action plans.

   b. On October 3, 2006, the National Mobility Guidelines (NMG) were approved by Decree 362/2006, applicable throughout the territory of Catalonia. These guidelines have a territorial planning nature and are intended to be used for the development of various mobility instruments established by Law 9/2003: mobility master plans, specific plans, and urban mobility plans.

   c. Law 9/2003, of June 13th, of the Regional Government of Catalonia, concerning mobility. This law, pioneer at the national level, aims at defining the principles and objectives of passenger and freight transport management, but also identifying those instruments needed to ensure the sustainability of the system.

B. Laws at the national level

[1] SPRO is the application which professionals should use to book slots in DUM parking places in the Barcelona Metropolitan Area (Ajuntament de Barcelona, n.d.-a).

a. On October 8, 2025, the Sustainable Mobility Law was approved in the Spanish Congress. This law aims at prioritizing decarbonization and digitalization. It forces the acceleration of clean fleets and enables municipalities to impose access fees within Low Emission Zones (LEZ), it also mandates that cities include specific regulations for Urban Freight Distribution (UFD) in their mobility plans, which refers to the system and process by which goods are collected, transported, and distributed within urban environments.

b. Law 7/2021, on climate change and energy transition, establishes the obligation to implement Low Emission Zones (LEZ), becoming a legal obligation for large cities such as Barcelona. Their development must comply with the criteria set out in the regulatory instruments governing LEZs that are in force at the time of approval of the corresponding regulatory framework.

c. Law Decree 970/2020, of November 10, which modifies the General Traffic Regulations, approved by Law Decree 1428/2003, of November 21, and the General Vehicle Regulations, approved by Law Decree 2822/1998, of December 23, regarding urban traffic measures.

d. Law Decree 339/2014, of May 9, which establishes the requirements for the marketing and putting into service of bicycles and other cycles and their parts and pieces, and which modifies the General Vehicle Regulations, approved by Law Decree 2822/1998.

e. Law 1/2006, of March 13, which regulates the Special Regime of the municipality of Barcelona, Law 22/1998, of December 30 and the Municipal Charter of Barcelona, and the rest of the European, state and regional regulations that are applicable. This document develops the powers attributed to Barcelona City Council in matters of traffic, circulation, parking and road safety on urban roads and on crossings declared urban roads, as well as on any space open to the free movement of people, animals and vehicles.

f. Article 12 of Law Decree 1428/2003, of November 21, which approves the General Traffic Regulations for the application and development of the articulated text of the Law on traffic, circulation of motor vehicles and road safety, approved by Law Legislative Decree 339/1990, of March 2.

C. Regulations at UE level

a. Regulation (UE) 2024/1679 requires big urban areas (urban nodes) to elaborate and implement a Sustainable Urban Mobility Plan (SUMP), which has to include specific measures for Urban Freight Distribution (UFD), leading to implementation of logistics hubs, access restrictions, and incentives for the use of vehicles such as cargo bikes.

b. Regulation (UE) N° 168/2013 of the European Parliament and of the Council, dated January 15, 2013, concerning the approval and market surveillance of two- or three-wheel vehicles and quadricycles.

c. The EU Transport White Paper 2011 is a strategic document that defines EU transport policy until 2050. Its objective was to build a competitive, resource-efficient system by cutting transport emissions by 60% and reducing oil dependence. Key targets included phasing out conventionally-fuelled cars from cities by 2050 and shifting 50% of medium distance freight from road to rail or water.

3.2.1. Planning instruments and policies for last-mile logistics

Barcelona's Municipal Strategy for Urban Goods Distribution (EDUM) details that the city currently has 94,748 establishments requiring approximately 145,000 daily deliveries under the B2B model, and 98,000 daily deliveries encompassing housing, offices, pickup points, logistics, and reverse logistics under the B2C model. Most of the loading and unloading operations (L/U) occur on public spaces, namely streets, with a minority using interior docks in buildings and Urban Freight Distribution Centres (UFDC). The city offers approximately 10,000 free loading and unloading spaces. Of these, around 8,500 are located within the regulated parking area and require telematic validation through the SPRO application, a key axis for management.

The most relevant instruments are described hereunder:

A. Planning instruments for sustainable mobility:

- The Mobility Master Plan (PdM) translates the National Mobility Guidelines into territorial strategies. Its purpose is to plan mobility within the Integrated Metropolitan Mobility System of Barcelona (SIMMB), considering all modes of transport, passengers, and freight. The PdM covers 12 counties, encompassing 75% of Catalonia's population, ensuring coordinated mobility planning at a metropolitan and regional scale (Autoritat del Transport Metropolità, 2020).

- The Metropolitan Urban Mobility Plan (MUMP) 2019-2024 outlines a model for future metropolitan mobility based on four strategic pillars: healthy, sustainable, efficient, and equitable mobility. Its objectives are aligned with those established in the Climate and Energy Plan 2030 of the Metropolitan Area of Barcelona (AMB), the Paris

Agreement on climate change, and the United Nations Sustainable Development Goals (Institut d'Estudis Regionals i Metropolitans de Barcelona, 2019).

- The city of Barcelona has the Urban Mobility Plan 2024 (SUMP) as a planning instrument defining the action lines governing urban mobility for the coming years. The PMU 2024 sets four main challenges aimed at addressing the mobility needs of both people and freight: Ensuring the right to mobility; ensuring the health and safety of individuals; contributing to the recovery of economic and commercial activities; and combating the climate crisis while improving air quality (Ajuntament de Barcelona, 2024).

B. Planning instruments for sustainable logistics:

- As these figures have been gradually growing over the last years, Barcelona City Council has launched the Municipal Strategy for the Urban Distribution of Goods Horizon 2030 (EDUM in Catalan). This strategy aims to advance towards a city model where UFD can develop in the most efficient, sustainable, and safe manner (Ajuntament de Barcelona, n.d.-b).

C. Planning instruments for climate neutrality:

- The Climate Agreement of the City of Barcelona is a document outlining a series of measures aimed at achieving climate neutrality by 2030 and promoting decarbonization. It is a necessary step to qualify for the European mission's label 'One hundred smart and climate-neutral cities by 2030', which provides advantages in financing through European funds (Ajuntament de Barcelona, 2021).

3.2.2. Specific policies, measures and actions for sustainable logistics

- **Establishment of the Logistics Sector Board (LSB):** The LSB has been set up as a permanent platform for structured dialogue and collaboration among stakeholders, aimed at developing and implementing logistics-related measures.

- **Optimization of public market infrastructure:** Use of indoor spaces in publicly owned markets has been promoted for logistics operations, improving last-mile delivery efficiency.

- **Regulation of loading/unloading zones in Barcelona:** As of 2025, there are over 10,500 designated loading and unloading zones are managed under the AREA regulation, ensuring consistent logistics operations city-wide.

- **Extension of L/U hours:** L/U time slots have been standardized across the city, now operating uniformly from 8:00 to 20:00.

- **Expansion of night-time distribution:** Night-time UFD is being promoted, with a goal to increase available night delivery points to 500.
- **Deployment of pickup point network:** A dense network of pickup points is being established, ensuring access within 200 meters across the city.
- **Click & Collect systems:** In accordance with commerce law, there is a legal obligation to provide click-and-collect systems.
- **Promotion of shared cargo platforms:** Initiatives are in place to support platforms that enable the sharing of cargo capacity among operators.
- **Support for cycle logistics:** Legal adjustments to the Pedestrian and Vehicle Traffic Ordinance are proposed to expand opportunities for cycle-based freight transport.
- **E-commerce taxation measures:** A new fee is proposed for large e-commerce operators to reflect their intensive use of public space for deliveries.
- **Enhancement of consolidation centres:** Micro-consolidation centres are being strengthened to improve logistics efficiency and reduce inner-city congestion.
- **Development of rail freight hubs:** Rail-connected hubs are being planned to support multimodal freight transfer, storage, and distribution.
- **Logistics zoning in urban planning:** New industrial developments will include designated logistics spaces to ensure long-term sector integration.
- **Parking incentives for zero-emission vehicles:** Zero-emission freight vehicles will be allowed to park in UFD spaces for up to 30 minutes, beyond standard signage limits.
- **Expansion of B2C distribution centres:** Small-scale centres (100–300 m²) are being developed to enable sustainable last-mile parcel delivery to consumers.
- **Expansion of B2B distribution centres:** Centres (approx. 250–300 m²) for business deliveries are being expanded to facilitate off-peak goods reception and low-emission distribution.

3.2.3. Business models and strategies related to last-mile logistics

Barcelona also engaged in a process of transformation of its public space to improve urban life and sustainability. It is intrinsically linked to new mobility and urban space management paradigms. Urban Freight Distribution is clearly affected by such policies, and therefore must be properly analysed to identify ways of improvement. In general terms, UFD models are divided into different categories based on the type of goods transported, regional dynamics, delivery times, delivery frequencies, and types of services offered.

The urban distribution of goods provides services to both professionals and citizens through three different models: distribution business to business, the delivery of products to the end consumers, and the provision of services to business and citizens.

- **B2B UFD** (Business to Business): It includes the supply to different types of establishments, such as food stores, hotels and restaurants, large chains in the textile sector, or educational and health centres.
- **B2C UFD** (Business to Consumer): Distribution to the end customer encompasses e-commerce. This model adds a new stage to the distribution chain known as the last mile.
- **UDS** (Urban Distribution of Services): It is the model that encompasses service provision activities that, in a complementary manner, include the transportation of freight (moving, construction and renovation of buildings, technical assistance, among others).

Some indicative business practices and strategies followed by the logistics operators to make last-mile delivery more sustainable are as follows:

1. **Optimizing traditional logistics.** Logistics operators plan shipments in advance using consolidated goods, considering load grouping, routes, shared facilities, and demand forecasting. Fleet management software supports efficient routing, scheduling, and real-time tracking. Supplier-customer collaboration further improves efficiency. Benefits include cost reduction, operational optimization, and lower environmental impact.
2. **Deliveries with two-stage delivery systems.** Deliveries are split into collection/consolidation at regional or micro-hubs and final distribution using smaller vehicles and optimized routes. This increases efficiency, reduces costs, lowers environmental impact, and improves customer service.
3. **Deliveries using sustainable (zero-emission) vehicles.** Electric vehicles, cargo bikes, and other zero-emission vehicles reduce environmental impact. Success requires charging infrastructure and route optimization to maximize efficiency.
4. **Deliveries that involve consolidation in destination**. Strategies like Click & Collect, smart lockers, convenience store pickups, and smart mailboxes consolidate deliveries at customer-accessible points, improving efficiency and reducing costs.

5. **Returns management and reverse logistics.** Clear return policies, strategic collection points, optimized routes, and tracking software ensure efficient, cost-effective, and environmentally friendly returns processing.

Understanding these contextual conditions is essential for designing realistic, scalable pilots in the Barcelona LL.

3.3. Vision and challenge to be addressed in the Barcelona LL

Barcelona faces rapidly intensifying pressures on its urban logistics system, driven by the growth of e-commerce, increasing service demands in dense historic areas, stringent environmental goals, and evolving mobility regulations. E-commerce deliveries in the city have grown strongly in recent years, with more than 100,000 daily deliveries generated since 2020 and peak periods such as Christmas 2024 seeing 5.6 million home deliveries, reflecting a sustained annual increase of around 10 % in parcel volumes (Ajuntament de Barcelona, 2024).

These trends accentuate long-standing challenges in the last-mile segment: congestion, inefficiencies in parcel handling, fragmented delivery processes, limited space for logistics infrastructure, and the absence of real-time visibility of goods as they move through the city.

Within this context, the URBANE Barcelona Living Lab seeks to address two interconnected challenges that directly affect the sustainability and efficiency of urban freight distribution:

1. **Inefficient and resource-intensive last-mile operations in dense urban areas.** The historic centre of Barcelona, particularly Ciutat Vella, presents severe spatial constraints: narrow streets, restricted vehicle access, high pedestrian density, and limited loading and unloading spaces. These constraints increase the operational burden for last-mile operators, resulting in longer handling times, unreliable parcel identification, and difficulties in coordinating deliveries. Traditional manual processes intensify these inefficiencies.

2. **Lack of digitalisation and traceability across the urban logistics chain.** Last-mile operators rely heavily on manual verifications and non-automated registration methods, generating delays, errors, and incomplete operational datasets. This limited the ability to optimise routes, evaluate performance, and integrate logistics activities into broader urban mobility strategies. Challenges observed in early pilots, such as missed readings, incomplete records, and unsynchronised data, highlight the need for a robust, automated, and traceability-enhancing system.

The vision of the Barcelona LL is to transform these challenges into an opportunity to demonstrate a data-driven, low-emission, and digitally integrated last-mile logistics model. By combining micro-consolidation and cargo-bike operations, RFID-enabled automation, blockchain-based traceability, and Digital Twin simulations, URBANE aims to show how historic European cities can adopt scalable, greener, and more resilient freight systems. This vision aligns with Barcelona's ongoing transformation of public space, its Municipal Urban Freight Distribution Strategy 2030, and its objectives for cleaner, more efficient mobility.

3.3.1. LL Objectives

Building upon the challenges outlined above, the Barcelona Living Lab establishes a set of objectives that guide the design, implementation, and evaluation of the interventions. These objectives are expanded here to reflect their full strategic scope and their integration with the project's overall vision.

- **Optimise city logistics through digitally enabled micro-consolidation and cargo-bike operations.** The LL aims to enhance the efficiency of last-mile delivery processes by improving parcel handling, routing, and operational workflows within micro-consolidation centres and cargo-bike fleets. This includes reducing loading and unloading times, minimising errors in de-consolidation and re-consolidation, and supporting operators as they navigate dense and highly regulated urban environments.

- **Use digital modelling tools to support assessment and transferability.** The LL uses URBANE's Digital Twin and complementary digital tools as analytical and learning instruments to test scenarios, interpret results, and structure evidence generated by the interventions. The LL focuses on providing these tools with real operational data and using them to compare baseline and pilot conditions, identify key performance drivers, and support knowledge transfer. This approach strengthens the replicability of the LL by translating local results into indicators, and methodological guidance that can be reused by other cities.

- **Deploy and validate an RFID-based system to enhance traceability and automate last-mile operations.** A major goal of the LL is to design, implement, test, and validate an RFID-enabled workflow for sustainable delivery operators. This increases transparency, reduces manual checking, and improves delivery accuracy.

- **Support the transition to cleaner, multimodal, and scalable urban freight solutions.** Through its combination of electric vehicle simulations for first-mile operations and zero-emission cargo-bike logistics in last-mile operations, the LL aims to demonstrate how greener multimodal ecosystems can be operationalised. The findings are intended to support Barcelona's broader sustainability policies, encourage the expansion of micro-consolidation centre networks, and inform future strategies for low-emission freight distribution.

- **Establish a replicable model for digitalised, sustainable last-mile logistics.** Beyond local improvements, the LL defines clear methodologies, KPIs, and validated insights that can be used as lessons learned for other European cities. By documenting the lessons learned and recommendations, the project contributes to the long-term URBANE objective of creating replicable, interoperable solutions for smart urban freight distribution.

4. Living Lab Framework

4.1. Existing infrastructure

The existing physical infrastructure in Barcelona provides a robust foundation for implementing advanced urban logistics solutions. This section outlines the physical infrastructure used within the Barcelona LL. Existing physical infrastructure relates to those elements needed for the implementation of the pilot that do not need a formal acquisition or adaptation. This infrastructure encompasses various facilities and assets that support efficient logistics operations and last-mile delivery services. Most of them refer to public spaces or specific infrastructure owned or operated by the partners of this project:

Table 2. Existing physical infrastructure

	DESCRIPTION
City infrastructure	
Streets	Streets where to circulate.
Loading and unloading areas	Loading/unloading areas distributed along the city of Barcelona.
Last mile operator infrastructure	
Micro-consolidation centre	Micro-consolidation centre of Vanapedal, located next to Estacio de França, in Ciutat Vella.
Vehicle fleet	Fleet of cargo bikes operated by Vanapedal.
Customer infrastructure	
Pickup points, lockers and convenience stores	Micro-hubs where to consolidate deliveries in destination.
B2B Business deliveries	Business receiving deliveries from Vanapedal in their premises.
B2C Home deliveries	Addresses of customers receiving deliveries from Vanapedal.

Figure 3. The cargo-bikes in the streets of Ciutat Vella

Figure 4. L/U zone in Ciutat Vella

Figure 5. L/U sign in Ciutat Vella

4.2. Data Sources and Interconnectivity

The successful implementation of the Barcelona Living Lab relies on the collection and integration of diverse operational datasets that enable both the evaluation of last-mile performance and the deployment of the RFID-enabled workflow. Most of the required data is generated directly within the Living Lab through real-life operations, providing a robust empirical foundation.

To establish the baseline (AS-IS) scenario, delivery operations are first conducted without the RFID system in place. During this phase, a comprehensive set of planning and operational data is collected, including delivery addresses, consolidation and loading times, route starting points, delivery points, delivery durations, and parcel-level timestamps. Once the digital tools and the RFID readers are introduced, the same indicators continue to be captured, complemented by real-time tracking data automatically generated by RFID events. These data streams are used to compare the AS-IS and TO-BE configurations and to support the integration of Blockchain-based event recording and validation.

Beyond operational data, the Living Lab requires a limited set of external datasets. In particular, a detailed street-network shapefile of the Ciutat Vella district is obtained from the Barcelona Open Data Portal. This dataset is essential for routing optimisation, integration with the Digital Twin, and the development of dynamic Vehicle Routing Problem (VRP) models.

The combination of internally generated operational data and externally sourced spatial data ensured a seamless interconnectivity between the RFID system, cloud-based data management, Blockchain services, and routing models, enabling comprehensive analysis, traceability, and performance evaluation across all phases of the project.

4.3. URBANE Innovation Transferability Platform

To analyse, optimise, and monitor the operations implemented in the Barcelona Living Lab, the project relies on a set of digital models and technological tools that support data-driven decision-making. These tools enable logistics scenario simulation, real-time performance assessment, and secure delivery data management, forming an integrated framework for both the strategic evaluation of greener logistics alternatives and the operational validation of RFID-enabled last-mile processes.

The Barcelona Living Lab builds on tools and methodologies developed and validated in the URBANE Lighthouse Living Labs. While RFID technology is a novel solution not previously tested in any Lighthouse LL, and therefore not directly transferable, the other key digital components, which are the Digital Twin, the Impact Assessment Radar, and the Blockchain Technology, have been adapted and applied in Barcelona from Wave 1's LL.

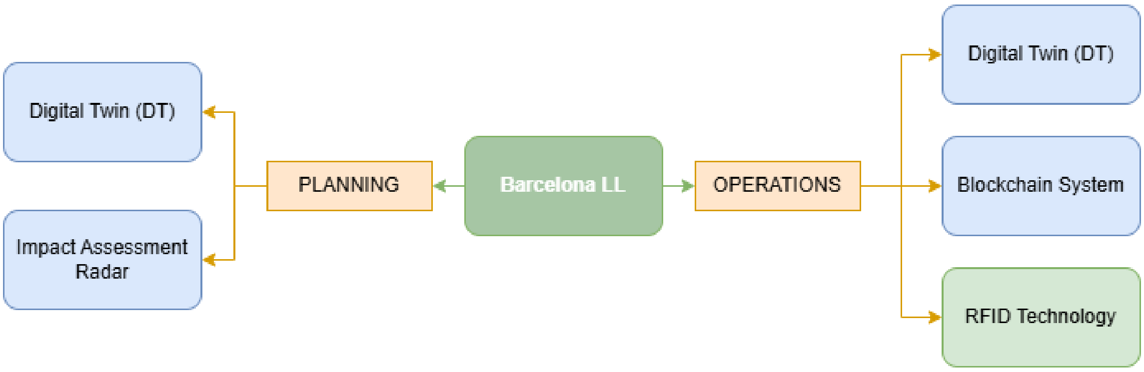

Figure 6. Transferability of URBANE tools and models

The following subsections describe the key instruments in the Barcelona Living Lab.

4.3.1. Digital Twin

The Barcelona Living Lab utilizes the URBANE Digital Twin (DT), developed under Work Package 3 and operationalized through the CitIQore application, to support operations as well as to simulate and analyse last-mile logistics operations. The DT provides a dynamic, data-driven environment that integrates models, historical datasets, and real-time data streams from the Living Lab's operations to evaluate innovative logistics interventions in the city.

Through CitIQore's visual and interactive interface, stakeholders can design and test "what-if" scenarios that replicate real operational conditions, enabling data-informed decisions and policy development for sustainable urban logistics.

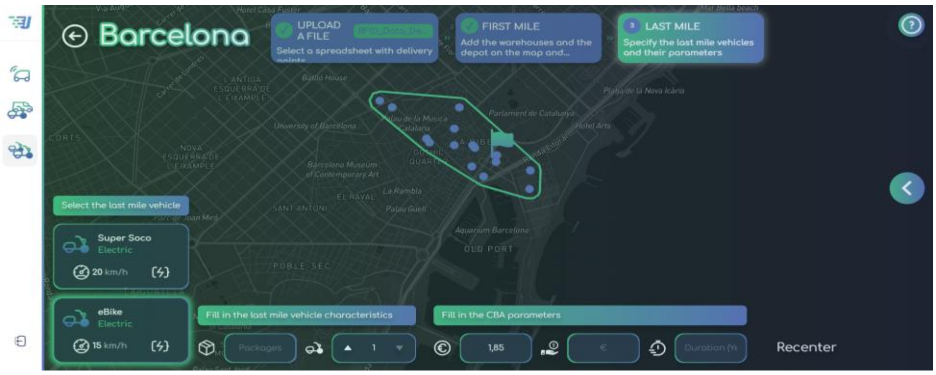

Figure 7. Example of the Digital Twin tool in the Barcelona LL

The Digital Twin used in Barcelona is directly based on the DT framework demonstrated in other Living Labs, such as the Bologna Lighthouse LL, where it was first used to simulate logistics scenarios and assess the impacts of alternative delivery configurations.

Thanks to its modular structure and model library, the DT could be adapted to the Barcelona context with minimal restructuring. Barcelona now applies the same simulation logic to evaluate first-mile electrification and support the last-mile cargo-bike operations.

The technical architecture of the URBANE DT combines three main components:

- **Simulation & Modelling:** Integrated models from the URBANE Model Library allows execution of planning, optimisation, and simulation workflows. For the Barcelona case, these include routing optimisation for cargo bikes and electric vans, demand estimation models, and cost-benefit analyses of sustainable delivery schemes.
- **Real-Time Data Processing & Analytics:** The DT ingests both real-time and batch data through secure ingestion connectors and processes them. For Barcelona, these data sources include operational data from Vanapedal, RFID-tagged parcel movements, and sensor-based data.
- **Visualisation & User Interface:** CitIQore provides a user-friendly interface enabling non-technical users to interact with the DT. Users select geographical areas, define operational parameters (fleet type, delivery method, parcel volume), and launch simulations that visualise KPIs such as energy consumption, CO_2 emissions, travel times, and delivery efficiency.

Within the Barcelona LL, the DT was used in two ways. First, it supported the First Mile simulation, evaluating different delivery scenarios through the CitIQore platform, where user-defined parameters triggered a sequence of integrated models. Results from both applications were visualized through CitIQore's dashboards, allowing comparisons and providing measurable insights into emission reduction and delivery time, as detailed in chapter 6. Second, it was applied in the planning of pilot operations using Vehicle Routing Problem optimization, guiding efficient routing and scheduling.

Through this implementation, the Barcelona LL demonstrates the applicability of the URBANE Digital Twin as a decision-support tool for public authorities and logistics operators. By combining simulation capabilities with real-world data, the DT facilitates the testing of innovative logistics solutions, such as micro-consolidation centres and electric cargo-bike fleets, before physical deployment. It supports a more sustainable and resilient urban logistics network in alignment with Barcelona's mobility and environmental goals.

4.3.2. Impact Assessment Radar

The Impact Assessment Radar (IAR) is a data-driven decision-support tool developed within URBANE to support the evaluation, planning, and comparison of innovative urban logistics solutions across different cities and Living Labs. It enables the assessment of readiness, operational efficiency, and sustainability impacts in a harmonised way, combining qualitative and quantitative perspectives. The IAR has already been applied in Lighthouse Living Labs to evaluate city readiness and compare logistics configurations, providing a fully transferable methodological framework. Barcelona now uses the same assessment structure to examine strategic readiness, explore operational scenarios, and later integrate real-world data.

The IAR is structured around three interlinked analytical levels:

- **Level 1 – Strategic Planning**.
- **Level 2 – Tactical Planning**.
- **Level 3 – Operational Evaluation**.

Through these three levels, the tool provides a continuous analytical pathway from policy and strategic alignment to operational performance evaluation, enabling cities to plan, assess, and replicate sustainable logistics innovations.

At Level 1, the Impact Assessment Radar allows cities to evaluate their readiness and maturity to adopt innovative, green, and digitally enabled logistics solutions. The assessment is based on a structured framework composed of six key pillars: governance, infrastructure, economy and market, environment and safety, innovation ecosystem, and digitalisation. Each pillar contains measurable sub-indicators designed to capture the institutional, regulatory, and technological conditions that influence the successful implementation of sustainable city logistics models. The outcome is a radar-style visualisation that highlights strengths, weaknesses, and areas for improvement.

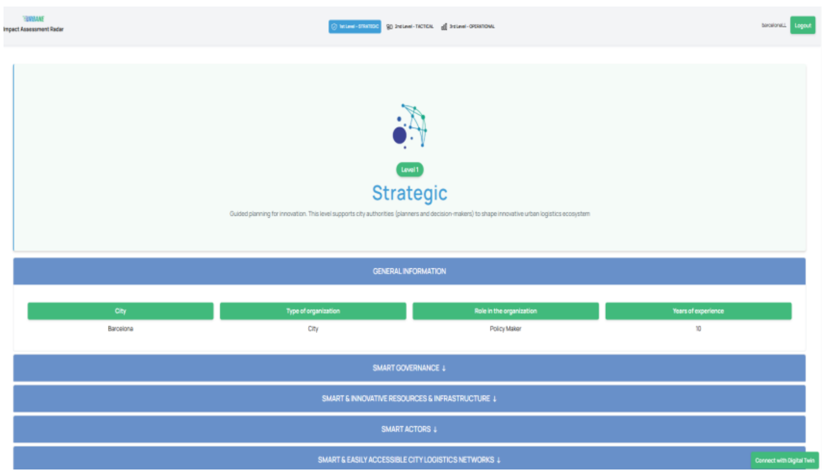

Figure 8. Impact Assessment Radar First Level

The second level of the Impact Assessment Radar provides analytical models for tactical decision-making, focusing on the design and optimisation of logistics infrastructure and operations. These include:

- a micro-hub delivery simulation module,
- a fleet composition optimisation tool, and
- a locker network design module.

In the Barcelona Living Lab, all three Level-2 modules were applied. These simulations were used to explore alternative configurations tailored to the Ciutat Vella district, leveraging operational data from the characteristics of the local logistics environment. The detailed application and results of these three modules are presented later in the report in section 8.1 – Impact Assessment Radar, where each module is executed independently as part of the scenario-based analysis.

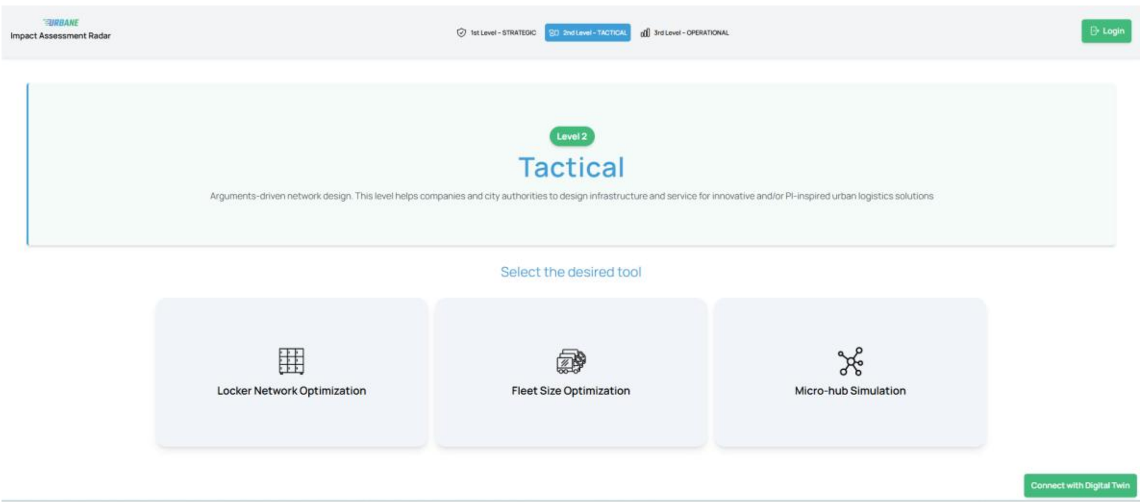

Figure 9. Impact Assessment Radar Second Level

The application of the Impact Assessment Radar in the Barcelona Living Lab provided a structured methodological framework to assess the city's readiness and to simulate alternative logistics configurations.

4.3.3. Blockchain Technology

The Blockchain tool implemented within the Barcelona Living Lab forms an integral part of the URBANE Innovation & Transferability Platform. Developed under Task 3.3 – Distributed Ledger & Smart Contracts, it provides a secure and transparent framework for data exchange, validation, and event recording in last-mile logistics operations. The

Blockchain Service implemented in Barcelona follows the architecture built within URBANE's Innovation & Transferability Platform and demonstrated in the Lighthouse Living Labs, where its core components were designed to be fully transferable across cities.

Blockchain is a distributed ledger technology that enables the immutable recording of transactions in a decentralised and auditable manner. Within URBANE, it serves to guarantee trust, data integrity, and accountability among multiple logistics stakeholders, such as last-mile operators, data providers, and city authorities, who interact within the Living Lab ecosystem. In more detail, the Blockchain component provides:

- Smart contract execution, allowing pre-defined business rules (e.g., delivery confirmations, service-level checks) to be automatically enforced.
- Event transparency, so that every action, parcel handover, delivery attempt, or return, is chronologically and verifiably logged.
- Decentralised data storage, ensuring that operational information cannot be tampered with or deleted once recorded.

In the Barcelona Living Lab, the Blockchain system was linked with the RFID data capture tool to ensure the traceability and integrity of parcel handling information across all operational stages. Although the Blockchain Service was not originally linked to RFID in the Lighthouse Living Labs, its modular architecture allowed Barcelona to integrate real-time parcel events without modifying the underlying system design. This demonstrates how the Lighthouse-level Blockchain architecture can be extended to new operational tools in city-specific contexts.

In Barcelona, smart contracts were configured to register parcel movements captured by RFID readers, confirm delivery milestones, and verify the execution of Service Level Agreements (SLAs). These contracts automatically produced delivery records, eliminating manual validation steps and providing a trusted data source for later impact assessment.

The adoption of Blockchain technology within the Barcelona Living Lab operations establishes a reliable and transparent framework that plays a key role in fostering trust among logistics service providers (LSPs). By securely recording and validating transactions, Blockchain minimises the risk of disputes and enables smoother cooperation across different LSPs, reinforcing confidence in the integrity of the overall system.

5. Living Lab Set Up

5.1. Stakeholders and their role

Barcelona Living Lab consist of a diverse range of stakeholders, including public authorities, last-mile delivery providers, technical experts, and research institutions, aiming to ensure efficient delivery of e-commerce parcels while promoting sustainability and efficiency.

Table 3. Stakeholders and their role

Stakeholder	Role	Internal /External	Objective
URBANE partners			
Metropolitan Area of Barcelona (AMB)	Coordinator and transparent policy-maker in the metropolitan area of Barcelona	Internal	Improve transport in the city, reducing externalities
Universitat Oberta de Catalunya	Technical assessment and deployment of the RFID system	Internal	Optimize logistics operations in the last mile through RFID technology and digital tools
Vanapedal	Users of loading and unloading parking areas	Internal	Achieve optimization of operations to be more sustainable and efficient
Last mile delivery providers			
Vanapedal	Logistic operator	Internal	Implement RFID technology in Vanapedal's micro-consolidation centre
Technical Providers			
KLU and INLECOM	IT solutions developer	Internal	Smart Contract and Blockchain development
Konnecta and INLECOM	IT solutions developer	Internal	Digital Twin development
Konnecta and VLTN	IT solutions developer	Internal	Development of VRP model and integration in DT
CERTH	Transport expert and IT developer	Internal	Development of Impact Radar Assessment model
UOC	IT solutions developer	Internal	Development of dedicated software for RFID

5.2. Stakeholders' involvement in UFD in Barcelona

One of the initial outputs underpinning the Barcelona Living Lab is the study by Castillo et al. (2024a), which provides the conceptual and institutional baseline for the LL design.

Based on 16 in-depth semi-structured interviews with public authorities, logistics operators, carriers, and retail stakeholders in the Barcelona Metropolitan Region, the study identifies structural barriers affecting urban freight distribution. These include fragmented and non-harmonised municipal regulations, limited coordination and trust between public and private actors, heterogeneous operating criteria, and the absence of unified representation mechanisms for logistics stakeholders.

The analysis highlighted operational and coordination gaps, such as inefficiencies in loading and unloading processes, lack of traceability, and misalignment between regulatory expectations and operational practices, that the LL addresses through organisational innovation and the deployment of digital solutions, including RFID-enabled workflows.

The article offers actionable policy recommendations that directly informed the design of several LL activities, including the approach to stakeholder engagement, the mapping of relevant actors, and the identification of challenges that RFID-based workflow automation could help address. In this regard, the article served as the analytical baseline that justified the need for technological, organisational, and governance innovations tested in the Barcelona Living Lab.

5.3. Models and tools developed: The RFID system

The Radio Frequency Identification (RFID) system implemented in the Barcelona Living Lab constitutes one of the core technological innovations developed and validated within the URBANE project to enhance the efficiency, transparency, and traceability of last-mile operations. Designed specifically for the micro-consolidation centre and cargo-bike delivery environment of Vanapedal, a zero-emission operator located in the historical district of Ciutat Vella, the system addresses the operational bottlenecks identified in the AS-IS scenario, particularly those related to manual parcel handling, lack of automated confirmation processes, and limited real-time information. Its purpose is to automate parcel registration, support real-time tracking, and generate high-quality operational data that can be used to evaluate and optimise performance.

The RFID system, as shown in Figure 10, functions through the interaction of electromagnetic tags and readers, enabling parcels to be identified automatically without requiring manual intervention. Every parcel processed at the micro-consolidation centre is equipped with an RFID tag containing a unique identification code linked to its digital record. A RFID reader, located in the cargo bike, is responsible for detecting these tags during delivery operations. Unlike traditional barcode systems, which require deliberate positioning and manual scanning, the RFID reader captures the tag's information automatically as the parcel is removed from the bike. This automation accelerates handling, reduces the risk of human error, and increases the reliability of delivery confirmation.

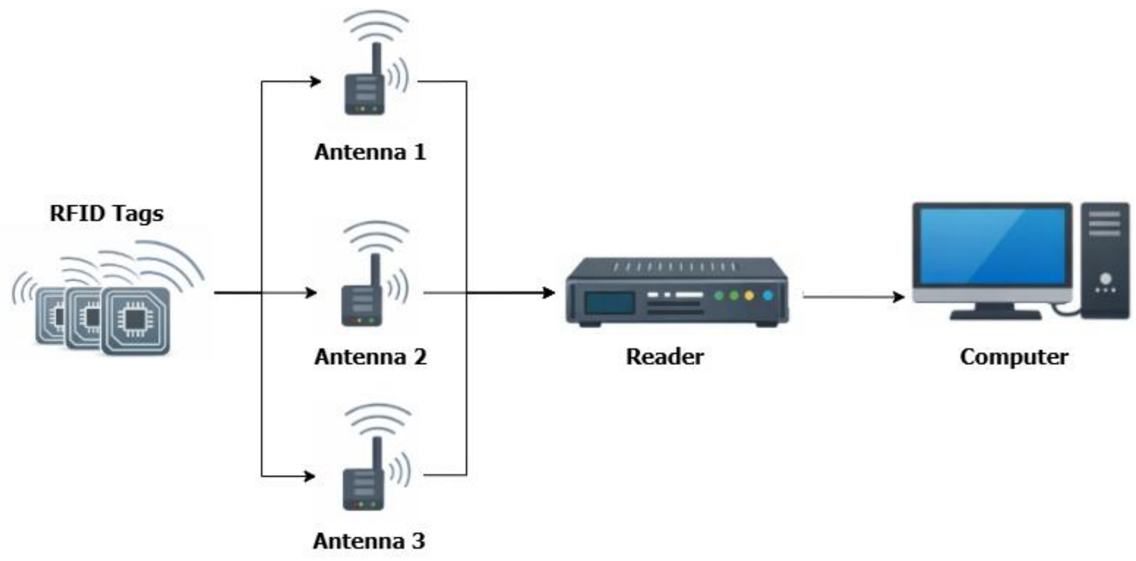

Figure 10. Mechanism of the RFID System

A central component of the system is the linkage between detected RFID tags and a cloud-based digital inventory database that records the parcel assignments for each cargo bike's route. When the cargo bike begins its delivery round, the on-board reader continuously scans its environment for tags, but only registers those matching the authorised list stored in the database. Any tag not included in the route inventory is automatically disregarded, filtering out noise from surrounding RFID sources on the street and ensuring high-quality, route-specific data capture.

During operations, each time a parcel is delivered, the RFID reader automatically detects the absence of the tag and generates an event containing the parcel ID, timestamp, and contextual delivery information. This data is transmitted in real time to the cloud, where it is securely stored and synchronised with the Blockchain system. The resulting dataset provides continuous visibility over the status and progress of deliveries, enabling precise monitoring, improved traceability, and streamlined performance evaluation.

Figure 11 provides a technical overview of how RFID-generated events are processed within the IT system during the TO-BE workflow, illustrating the interaction between the cargo-bike reader, the cloud server, the database, and the supporting digital services (e.g., blockchain and route validation).

The technical implementation of the project involved multiple URBANE partners. UOC led the integration of the RFID hardware and software and developed the IT architecture to read, transmit, process, and store operational data. Vanapedal provided the cargo bikes, ensured the correct functioning of mechanical and operational elements, and incorporated the RFID-supported workflow into daily operations. KLU and INLECOM contributed to Smart Contract and blockchain development for traceability, while Konnecta and INLECOM developed the Digital Twin, and Konnecta and VLTN integrated the VRP model. CERTH developed the Impact Radar Assessment model, and the Metropolitan Area of Barcelona (AMB) coordinated the project and ensured alignment with city transport policies. Together, these stakeholders enabled the deployment of RFID technology to optimize last-mile logistics and support sustainable urban mobility.

The implementation of RFID technology addresses key needs identified for last-mile logistics in Barcelona, including the reduction of handling times, improvement of process transparency, and automation of operational tasks prone to delays or human error. By eliminating manual logging of deliveries, the system supports more fluid operations within the micro-consolidation centre and enables the measurement of the pilot's Key Performance Indicators (KPIs), such as reduced unloading and reconsolidation times, improved delivery accuracy, and overall productivity gains. Overall, the RFID system developed within the Barcelona Living Lab represents a significant advancement in the digitalisation of last-mile logistics.

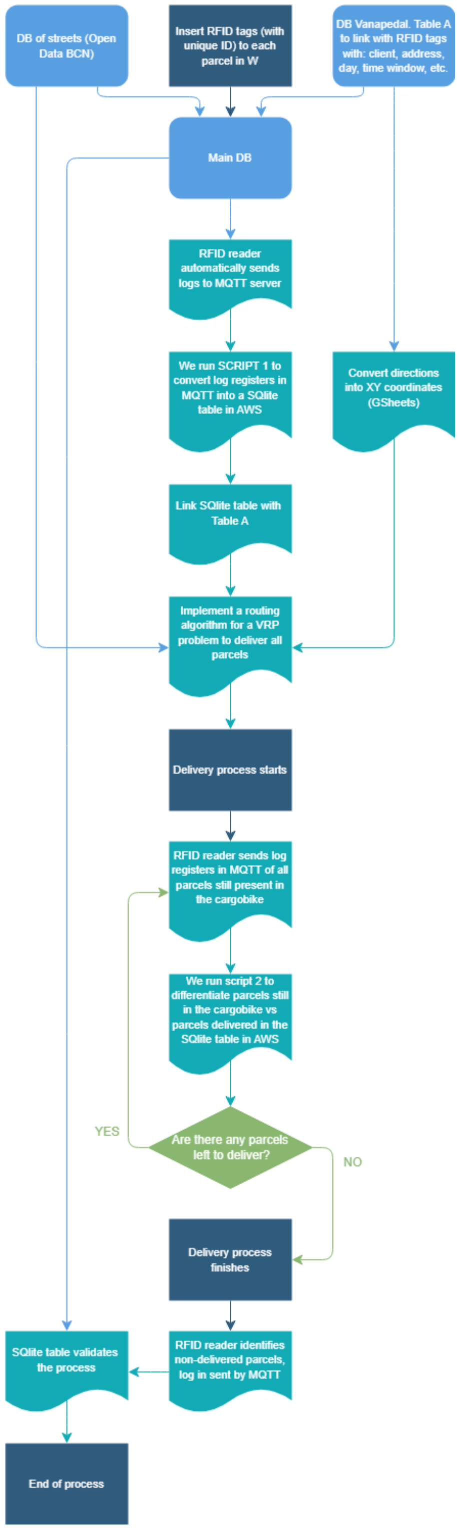

Figure 11. IT Diagram of the RFID System

5.3.1. Technology related to the RFID System

The deployment of the RFID-enabled workflow in the Barcelona Living Lab required a robust combination of customised hardware, digital infrastructure, and data management tools. This section provides an overview of the physical components and equipment acquired to enable real-world implementation of the prototype on cargo bikes. It also outlines the technological ecosystem that supports the RFID system, including ICT solutions, web-server environments, datasets, and software scripts used to collect, process, publish, and analyse operational data. As well as the integration of smart contracts and Blockchain technology, which ensures secure and traceable event recording.

5.3.1.1. Hardware specifications

To enable the deployment of the prototype, some equipment had to be acquired and adapted. The KEONN AdvanReader-160, a high-performance UHF RFID reader with an onboard Linux microcomputer, forms the core of the hardware system. It is paired with three KEONN Advantenna-SP11 antennas, installed on the cargobike to maximize reading coverage and reliability. A stock of PolyPro RFID tags ensures that every package can be uniquely identified. A mobile router with a dedicated SIM card enables constant cloud communication, even during movement, supporting real-time updates. Additionally, an ECOFLOW battery was acquired to provide power to all components during the delivery process. The full list of components used in the implementation is provided in Table 4 below.

Table 4. The RFID system: hardware specifications

Component	Description
RFID reader	KEONN AdvanReader-160: 4 port RFID UHF high performance reader with on-board Linux-microcomputer.
RFID antennas	KEONN Advantenna-SP11: RFID UHF high gain antenna ETSI frequency band with IP67 enclosure.
RFID tags	1.000 PolyPro 3000T RFID tags. 76x25 mm.
Router	Conventional router with a SIM card slot.

Disposable SIM card	SIM card with access to data (no calls) from a regular telecom operator.
Portable battery	256Wh portable battery developed by ECOFLOW, especifically the EFR600 model.

5.3.1.2. Software, scripts, and servers

Third-Party commercial tools or widely available solutions were used that support the RFID prototype and operational workflows:

- **MQTT web server:** Coordinates communication between the web interface, RFID reader logic, and backend components using a lightweight publish–subscribe protocol. It ensures synchronized operations and real-time event streaming, even over mobile data on moving cargo bikes.
- **Amazon web server:** Hosts backend services, including the web interface, Flask application, and APIs for data exchange. Cloud hosting ensures scalability, secure access, and high availability. AWS also executes scripts that process RFID events and communicate with external systems, such as the Blockchain API.
- **Python environment:** Hosts the core system logic, including RFID event processing, MQTT communication, and API interactions. Python enables modular development and flexible integration of hardware, software, and algorithms.

In addition, Custom scripts and tools developed within URBANE. These components were created specifically for the project to enable RFID data processing, analysis, and operational management:

- **RFID Data Acquisition Scripts:** Manage communication with the RFID reader's microcomputer, filter readings, and associate each event with timestamps and antenna identifiers for reliable package tracking.
- **Data Publishing Scripts:** Processed RFID events are published via MQTT and transmitted to backend servers, ensuring real-time updates for route monitoring and blockchain logging.

- **Data Processing Scripts:** Update package status, detect delivery events, and link tag reads with corresponding delivery routes. These scripts remove duplicates, validate event logic, and prepare structured event records.
- **Data Analysis Scripts:** Support post-operational evaluation by aggregating delivery times, calculating route performance indicators, and identifying RFID detection patterns to optimize operations.

In addition, a web Interface for Vanapedal Operator and Living Lab partner was developed. In more detail, a custom web interface allowed Vanapedal operators to input delivery data at the start of each round and monitor operations in real time. The interface provides status updates and operational visibility, enabling staff to interact efficiently with the RFID system. The interface is shown in figure 12.

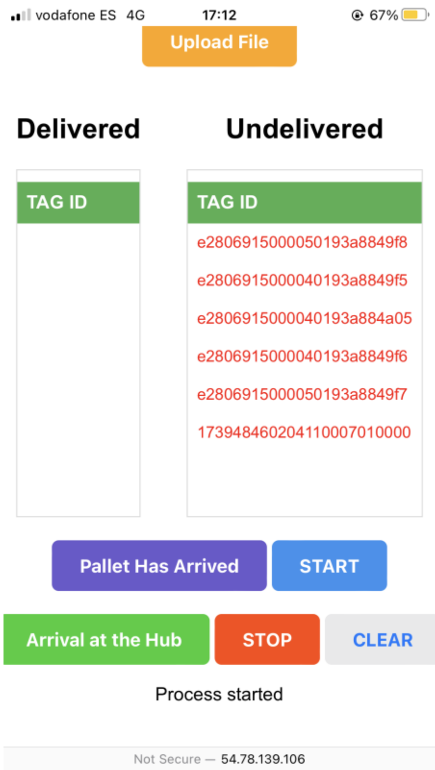

Figure 12. Web interface for Vanapedal operators

Finally, URBANE's Blockchain and smart contracts were integrated in the Living Lab and tested in its operations. The RFID system integrates with URBANE's blockchain infrastructure for secure, immutable storage of delivery events. Smart contracts ensure tamper-proof records and automated verification of deliveries, strengthening data reliability and traceability for all stakeholders.

Table 5. The RFID system: software, scripts, and servers

Component	Description
MQTT Server	Broker enabling lightweight real-time communication between system components.
AWS Backend	Cloud server hosting the web interface, backend logic, and API communication.
Python Environment	Core environment running RFID logic, web server code, and data processing scripts.
Operational Tools	Supporting software for monitoring, routing, diagnostics, and daily operations.
Data Gathering Scripts	Scripts interfacing with the RFID reader to collect tag detections.
Data Processing & Publishing Scripts	Scripts that process RFID events, update package status, and publish data via MQTT and backend APIs.
Data Analysis Script	Scripts performing post-operational evaluation, analyzing delivery performance, RFID detection patterns, and operational efficiency.
Web Interface	Custom web application for Vanapedal operators to input delivery data and monitor operations in real time.
Blockchain Integration	URBANE's Blockchain API used for secure event logging.

5.3.1.3. Datasets

The system uses several pre-existing datasets that provide essential operational context. A database of delivery addresses and ensures that every scanned tag is linked to its correct delivery point and constraints. A complementary street database supports route planning, matching RFID tags to spatial contexts such as specific delivery. These datasets enable meaningful interpretation of tag readings and support automated detection of delivery events.

Table 6. The RFID system: datasets

Component	Description
Operational Datasets	Address database and street database used to contextualize RFID events.

5.3.2. RFID Patenting Process

Importantly, the RFID system developed for the Barcelona LL represents not only an applied pilot but also a technological innovation with long-term transferability potential. The system architecture, interaction logic, and data-processing model have advanced sufficiently to initiate the patenting process, reflecting both the novelty of the solution and its relevance for wider deployment in European cities. The patent process underscores the system's originality and strengthens its prospects for commercial exploitation after the project's completion.

5.4. LL trial set up and preparation

Especially focusing on the IT-related processes, the LL trial set up and preparation was characterized by the following activities:

- **Assessment of Vanapedal's operations:** A comprehensive understanding and documentation of the processes employed by last-mile delivery companies is achieved; after, an analysis and identification of critical points in Vanapedal's logistics operations is conducted.
- **Delivery preparation:** Vanapedal receives pallets in the micro-consolidation centre containing all the parcels to be delivered along with a database of the addresses where to deliver them that is uploaded into the web server. The parcels, then, arrive with their unique RFID tag already in place. All the parcels contained in the cargobike's box are automatically detected by the RFID reader and the reader is sent to a MQTT server. A script combines the database of addresses with the information contained in the RFID tag in a single table and is stored in the cloud. With that information, an algorithm estimates the most suitable route to sort all the deliveries.
- **Last-mile delivery operation:** Once the rider is ready to start the delivery process, it is manually indicated in the web server. Each time the rider removes a parcel from the cargo-bike, the RFID reader loses one of its elements, identifying the delivery. This

process is repeated iteratively. All parcels that cannot be delivered and returned to the micro-consolidation centre are also automatically detected.

5.4.1. Timeline

Figure 13 below outlines the overall timeline of the project. The conceptualization phase began in 2023, covering both the Living Lab definition and the first negotiations with stakeholders, and continued until mid-2024. In parallel, development activities were launched in early 2024, including RFID technology deployment, infrastructure acquisition, and lab setup, all completed by October 2024.

The testing phase followed shortly after, with laboratory tests taking place from mid-October to mid-December 2024, and on-site tests running from November 2024 to January 2025. Based on these results, the project moved into the pilots phase, starting with the pilot setup in January 2025, followed by three consecutive pilots carried out between February and April 2025.

Simultaneously, the operational data analysis extended from late 2024 through mid-2025, progressing from data gathering to data analysis and eventually long-term reporting activities that continue toward 2026. In addition, the patent process began in November 2025 and is planned to run until early 2026.

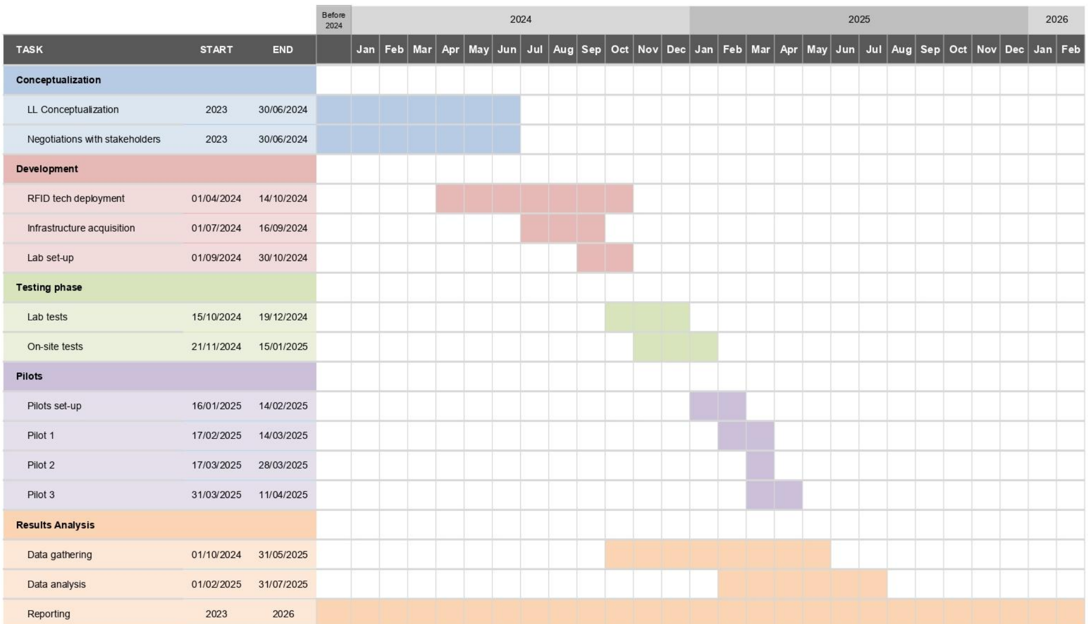

Figure 13. GANTT Diagram of the Barcelona LL's timeline

6. URBANE Use cases in Barcelona Living Lab

The Barcelona Living Lab Use Case focuses on demonstrating how digitalisation, micro-consolidation, and zero-emission mobility can be combined to enhance the sustainability and efficiency of urban logistics in dense historic environments. Within the framework of URBANE, the Use Case is structured around two complementary components that together form a holistic assessment of environmental impact, operational feasibility, and technological innovation. These two components are: (i) a first-mile simulation using the project's Digital Twin tool, and (ii) a series of three last-mile pilots testing the integration of RFID technology and digital tools in real delivery operations. Together, they provide a comprehensive and multi-layered approach to evaluating both strategic and operational interventions in the urban freight ecosystem.

The first component consists of a first-mile simulation conducted through the URBANE Digital Twin tool. This simulation evaluates the potential CO_2 emission reductions achieved by replacing conventional internal-combustion vans with electric vehicles for the upstream transport of consolidated pallets from Zona Franca's logistics area to the micro-consolidation centre serving the old town. This modelling exercise enables the Living Lab to quantify system-level environmental benefits and supports evidence-based decision-making on the electrification of urban freight transport.

The second component focuses on last-mile operations, where the Living Lab tests the integration of digital tools and RFID technology into the delivery processes of Vanapedal, a cargo-bike logistics operator active in the historic centre of Barcelona.

Figure 14. Distinction of the First-Mile and the Last-Mile in the Barcelona LL

Together, the first-mile simulation and the last-mile pilots offer an integrated assessment of how technological innovation and sustainable mobility solutions can reshape urban logistics. By linking environmental concerns with real-world operational testing, the Barcelona Use Case contributes to the broader URBANE objective of enabling cities and logistics operators to transition towards more efficient, decarbonised, and intelligent urban freight systems.

6.1. Use Case 1: First-Mile Simulation

The first-mile simulation was executed as a core component of the Barcelona Living Lab's environmental impact assessment, leveraging the capabilities of the Digital Twin tool to model and evaluate sustainable logistics interventions. The primary objective was to quantify the CO_2 emission reduction potential achievable by transitioning the critical first-mile operation from conventional internal combustion engine vehicles to an electric engine alternative.

The simulation employed a comparative scenario analysis for the first-mile supply leg, based on a standardised approximate of 24 - 25 km delivery trip (from Zona Franca to Ciutat Vella):

- **Baseline Scenario (Conventional):** Utilisation of a standard conventional (ICE) van.
- **Intervention Scenario (Sustainable):** Utilisation of an electric vehicle (EV) van.

The analysis demonstrated a significant and quantifiable improvement in operational sustainability under the Intervention Scenario:

- The use of an electric van resulted in an estimated 59% reduction in CO_2 emissions per trip compared to the conventional van.
- The conventional van was modelled to generate approximately 4,500 grams of CO_2 per trip, whereas the electric van generated approximately 1,850 grams of CO_2 for the identical route.
- The findings indicate significant potential for achieving daily environmental gains, projecting a saving of up to 10,800 grams of CO_2 per day when the electric vehicle is fully integrated into the first-mile logistics chain.

This simulation validates the environmental benefits of electrifying the fleet of logistics operators, providing evidence for the scalability and impact of zero-emission solutions within the urban logistics framework.

The results, shown below, are derived from the simulations that were carried out using the Digital Twin. The tool was used to generate quantitative outputs under controlled and comparable conditions, serving as the analytical basis for the assessment of the first-mile scenarios. The following figures present the visual outputs of these simulations, summarising the modelled performance of the analysed configurations.

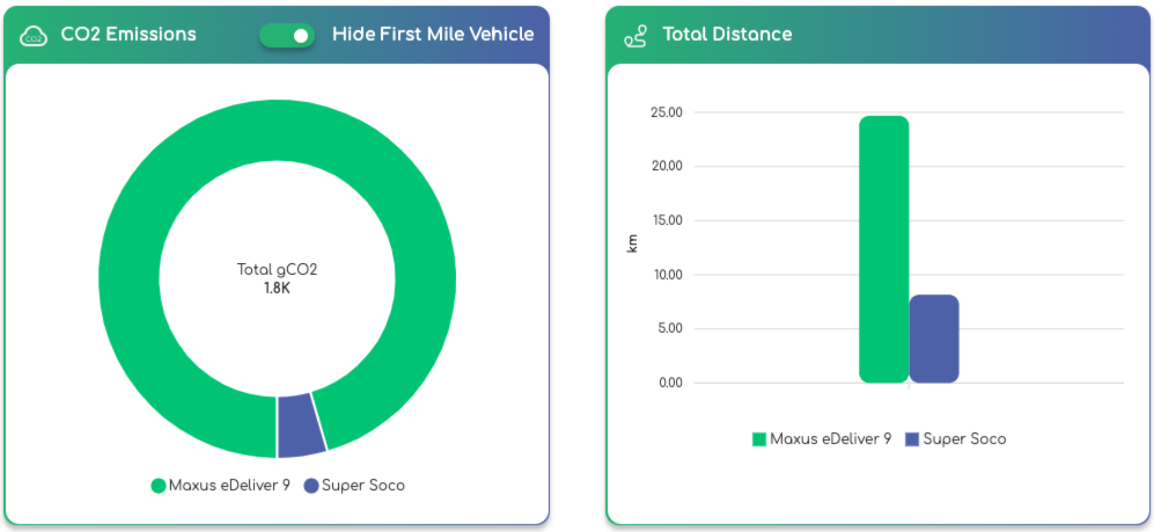

Figure 15. First-Mile simulation results 1

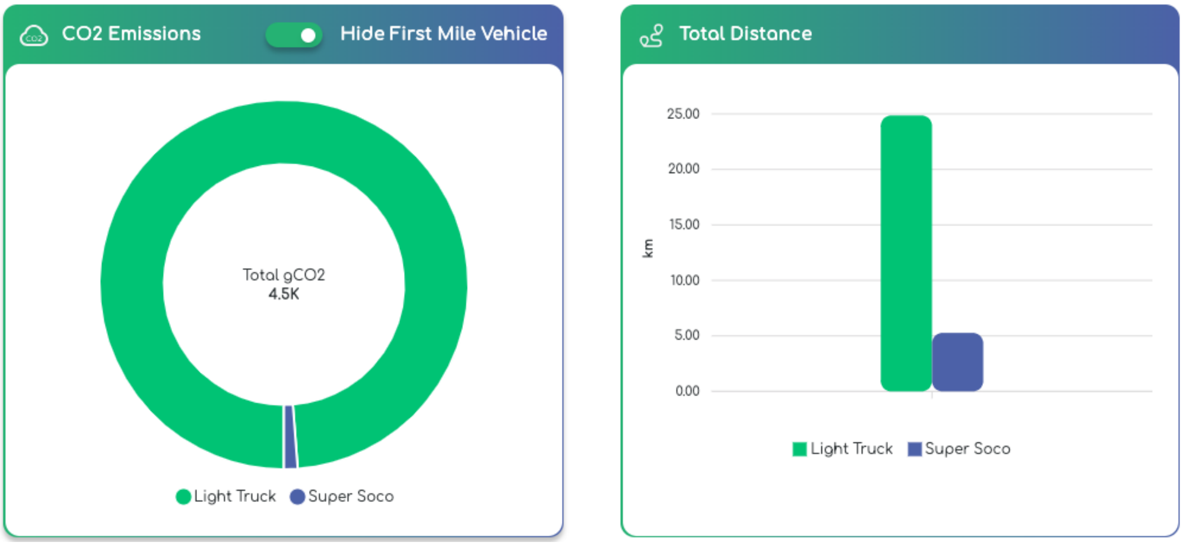

Figure 16. First-Mile simulation results 2

6.2. Use Case 2: Last-Mile Pilots

The second component of the Barcelona Use Case focuses on the digitalisation and optimisation of last-mile delivery operations through the implementation of digital tools and RFID technology. The Living Lab carried out a sequence of pilot trials to validate system performance in real operating conditions, assess robustness, and identify areas for refinement.

These pilots constitute the operational core of the last-mile Use Case and enable a detailed evaluation of the system's impact on parcel handling times, route efficiency, delivery speed, and traceability. The lessons learned directly inform the definition of the TO-BE operational scenario and set the foundation for long-term optimisation of zero-emission last-mile delivery in Barcelona.


Figure 17. RFID technology


Figure 18. Cargo bike where RFID technology was implemented

6.2.1. Operator and Operational Context: Vanapedal

The successful implementation of the last-mile pilots in the Barcelona Living Lab required a detailed understanding of the operational realities faced by Vanapedal, the cargo-bike logistics operator participating in the Use Case. Vanapedal operates in the dense and historically protected district of Ciutat Vella, where physical, logistical, and economic constraints significantly influence daily performance and highlight the need for innovative, data-driven solutions such as those introduced through the URBANE project.

Vanapedal is a specialised last-mile operator that manages an average of several hundred parcels per day, reaching peaks of up to 1000 parcels during high-demand periods. It acts as a subcontractor for some of the major international logistics companies. Vanapedal is responsible for final delivery within the urban core, where van access is often restricted and cargo bikes offer a more agile and low-impact alternative. Despite these advantages, the company operates under conditions that limit its capacity to scale and compete on equal terms with conventional van-based couriers.

6.2.1.1. Operational Constraints

The execution of the Use Case was conducted in an environment defined by significant physical, logistical, and economic constraints inherent to last-mile operations in a dense urban centre like Ciutat Vella. These challenges highlight the necessity for the innovative micro-consolidation centre and zero-emission delivery models being tested.

Physical and Spatial Constraints (Micro-Consolidation Centre and Delivery)

These challenges relate to the physical necessities of the operation:

- **Necessity of delivery loading/unloading areas:** There is a need for designated parking and transfer zones not only at the micro-consolidation centre but also at final delivery locations. In narrow peatonalized streets, where there is little or no space for vehicles, this further complicates last-meter parcel movement and impacts delivery speed.

- **Policy on use of driving vehicles in high-affluence areas:** Regulatory restrictions regarding the usage of vehicles, including bikes, in dense or highly-trafficked pedestrian zones impact route flexibility and delivery times.

Supply Chain and Logistical Control Constraints

These points highlight the lack of end-to-end control Vanapedal experiences:

- **Subcontractor status and reactive operations:** As a subcontractor for larger logistics companies, Vanapedal lacks control over the overall value chain and upstream supply. This forces them to operate reactively to the needs and schedules of partner companies, limiting proactive optimization.

- **Late arrivals of pallets:** The frequent late arrival of consolidated pallets from external upstream companies directly disrupts the micro-consolidation centre's operational schedule, increasing the risk of delayed last-mile deliveries.

- **Lack of full traceability:** The existing process suffers from a lack of complete, consistent parcel traceability, which complicates operations management, accountability, and the ability to provide clients with real-time status updates.

Equipment and Technical Constraints

These are issues related to the tools and assets required for delivery:

- **Vehicle downtime (Bikes requiring repair):** Cargo bikes are subject to wear and tear and require frequent maintenance and repair. Bike downtime directly reduces daily delivery capacity and requires rapid, cost-effective maintenance processes to mitigate.

Economic and Client-Related Constraints

These challenges impact the financial viability and customer relationship:

- **High exigency for first-try deliveries:** Partner companies impose high level service requirements, demanding a high percentage of successful first-attempt deliveries and often imposing penalties for failure, which increases pressure on riders and routing efficiency.
- **Disparity in payment structure:** Despite the lower capital investment and operational cost (lower amortization and depreciation) of bike deliveries compared to van deliveries, cargo-bike operators are compensated at a lower rate than traditional van couriers. This economic disparity creates a barrier to the wider adoption of sustainable, zero-emission logistics.

6.2.2. Baseline Workflow (AS-IS Scenario)

The operational process carried out by Vanapedal serves as the Baseline (AS-IS) Scenario for the Living Lab analysis. This workflow is highly reliant on manual procedures and local knowledge, reflecting the current state of last-mile delivery in the historic city centre. The entire process is visually detailed in the BPMN Diagram of the AS-IS situation (Figure 19).

The process is initiated when users make purchases and their orders are processed and sent to a warehouse (W), in this case, in Zona Franca. From W, consolidated pallets of packages are prepared and transported to the Micro-Consolidation Centre (M), using conventional vehicles (Vehicle A1, normally vans) from partner couriers. Once the pallets are received at micro-consolidation centre (M), the parcels are manually processed: they are unloaded, sorted, and reconsolidated from the incoming pallets. The key step of de-consolidation and reconsolidation then takes place, where parcels are grouped by cargo bike, area, customer, and delivery sequence. This consolidation phase, along with the manual route planning based on staff experience and local knowledge, is labour-intensive and represents a significant portion of the total handling time.

Following consolidation, packages are loaded onto the electric cargo bikes (Vehicle A2). Couriers then distribute the parcels across their designated zones. This process typically follows a two-cycle daily structure with one delivery round in the morning and another in the afternoon. Once the vehicle returns to M, the packages are unloaded and sorted into new pallets depending on their destination. These pallets are then shipped back to W for further processing.

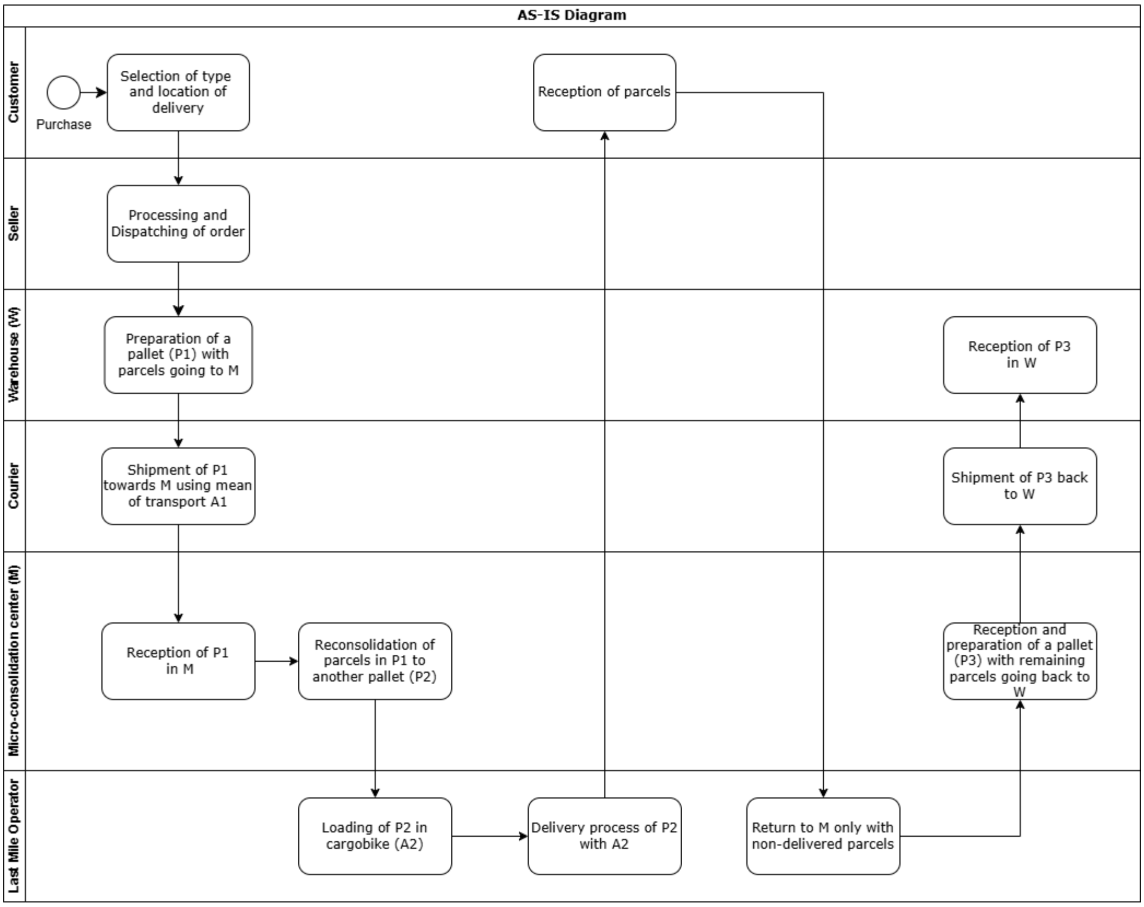

Figure 19. Diagram of the AS-IS situation for Vanapedal

The detailed assessment of Vanapedal's AS-IS operations conducted at the start of the Use Case revealed these several bottlenecks:

- **Manual parcel sorting and reconsolidation**, which require significant handling time and are vulnerable to errors.
- **Manual route planning**, reliant on local knowledge rather than digital optimisation.
- **Limited real-time traceability**, reducing inventory control and the ability to manage returns efficiently.
- **Lack of automated delivery confirmation**, relying instead on paper logs and manual reporting.

These bottlenecks explain the need for technological support and provide the rationale for the implementation of digital tools and the deployment of RFID technology within the Living Lab. By addressing the structural challenges faced by Vanapedal, the Use Case aims not only to enhance operational performance but also to strengthen the competitiveness and long-term viability of zero-emission last-mile delivery in Barcelona.

6.2.3. RFID-Enabled Workflow (TO-BE Scenario)

The introduction of the digital tools and the RFID technology within the Barcelona Living Lab fundamentally transforms Vanapedal's operational workflow, shifting from a manual, experience-based process to a digitally supported and partially automated system. The TO-BE scenario leverages the Digital Twin (with integrated VRP), RFID tags, readers, and Smart Contract and Blockchain-based data processing to improve accuracy, reduce handling time, and enhance traceability across all stages of last-mile delivery. This new workflow is reflected in the TO-BE operational diagram below (Figure 20) and represents the state of operations once the RFID system is fully deployed.

In the TO-BE process, each parcel is labelled at the warehouse with an RFID tag containing a unique identifier and routing information. Tagged parcels are then loaded onto pallets and transported from the warehouse to the micro-consolidation centre using a conventional or electric A1 vehicle. Once the pallets arrive at the micro-consolidation centre, the parcels are sorted and classified according to the delivery areas they belong to, following an improved and more reliable classification process supported by digital tools. A list of every parcel and its destination is generated and sent to Vanapedal. The Digital Twin uses the list to calculate the optimal routes, therefore ensuring maximum efficiency in the delivery route of the courier.

When the classified parcels are loaded onto the cargo bikes (A2 vehicles), the RFID reader installed inside each bike container automatically detects the tags. This automatic reading process confirms the set of parcels assigned to the delivery round against the list and uploads the information to the cloud, where it is processed and stored. This eliminates the need for manual checking, significantly reducing preparation time and minimising errors associated with manual consolidation.

As the courier proceeds along the delivery route, each time a parcel is removed from the cargo bike, the RFID reader registers the event. This triggers an automatic message to the cloud indicating that a delivery attempt has taken place. These real-time delivery events can be used to update parcel status, notify partner couriers, or create immutable records when integrated with blockchain-based systems developed within URBANE.

Once the courier completes the route and returns to the micro-consolidation centre, any undelivered parcels are unloaded, sorted, and prepared for reintegration into the upstream logistics chain. These items are then reconsolidated into new pallets and transported back to the warehouse.

Overall, the TO-BE workflow represents a significant step toward a more efficient, transparent, and data-driven last-mile system. By automating parcel identification, implementing digital tools, improving traceability, and enabling real-time operational monitoring, RFID technology addresses the key bottlenecks in the AS-IS scenario.

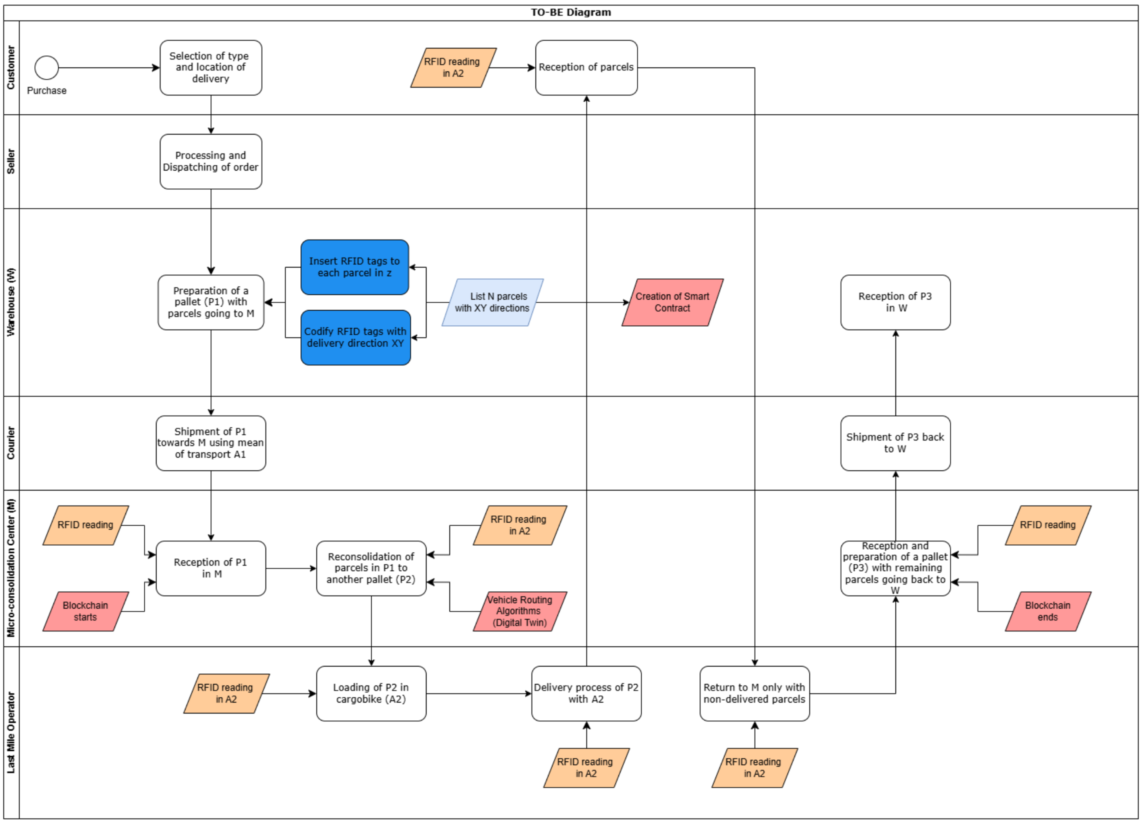

Figure 20. Diagram of the TO-BE situation for Vanapedal

6.2.4. Last-Mile Pilot Implementations

The performance of the Barcelona Living Lab was validated through a structured sequence of three pilot trials, each designed to test, refine, and evaluate the implementation of the digital tools and the deployment of RFID-based technology in real operational conditions. Together, these pilots enabled the assessment of the technical reliability of the system, the quantification of the operational impacts, and the identification of the barriers and enablers influencing adoption by a cargo-bike logistics operator.

Across all pilots, the technological set-up included the Keonn RFID readers and antennas installed in the cargo-bike box, RFID tags applied to simulated parcels, a router with SIM card for data transmission, a portable battery, and an interactive IT interface enabling couriers to initiate and close operational cycles. Data was captured through Keonn's platform using MQTT, exported to web servers for processing, and, in the more advanced pilots, integrated with the Digital Twin (VRP model) and blockchain-based smart contracts. This common technical framework ensured comparability across pilot stages and progressive validation of increasingly complex functions.

Each pilot was conducted over several weeks, however, the data collected corresponds to a two-week period for each pilot, following a standardised methodology to simulate similar deliveries to ensure comparability. The first week replicated the AS-IS workflow, relying exclusively on manual processes, traditional reconsolidation, and courier-dependent route planning. The second week implemented the TO-BE workflow, integrating RFID-assisted parcel identification, automated reconsolidation, and technology-supported delivery execution. This mirrored structure enabled direct comparison between manual and digitalised operations and provided a robust basis for evaluating performance improvements attributable to the use of digital tools and the RFID system.

6.2.4.1. Pilot 1: 1 antenna vs 3 antennas

Pilot 1 conceived as a technical validation phase, aimed at establishing the operational feasibility of using RFID equipment inside a cargo-bike in the dense urban environment of Ciutat Vella. Rather than testing the technology in full delivery operations, this initial pilot sought to identify the basic functional limitations of the hardware and communication systems. It examined several variables that could potentially affect scanning quality, including the number of antennas inside the cargo box and its position, the number of tags, the effect of movement on detections, and the influence of areas with weak mobile reception.

The tests revealed clear performance differences across configuration types. The use of a single antenna proved insufficient for achieving reliable tag detection, resulting in inconsistent and incomplete readings. The spatial characteristics of the cargo-bike box created blind spots in which tagged parcels were not consistently captured. Three antennas were, then, installed at the top and on the sides of the cargo box. The detection quality increased substantially when moving them to the laterals, enabling simultaneous scanning of multiple tagged parcels and largely eliminating blind zones. This three-antenna configuration was therefore adopted as the standard for all subsequent pilots. Even with the optimal antenna arrangement, Pilot 1 detected sporadic misreadings linked to specific tag types or parcel orientations, as well as brief interruptions in data transmission in narrow streets where mobile connectivity was weaker. As shown in Figure 21, the reading error percentage for a single antenna increased sharply with the number of parcels, reaching nearly 95% at the highest load. In contrast, when three antennas were used, the reading error remained low and did not exceed 4%.

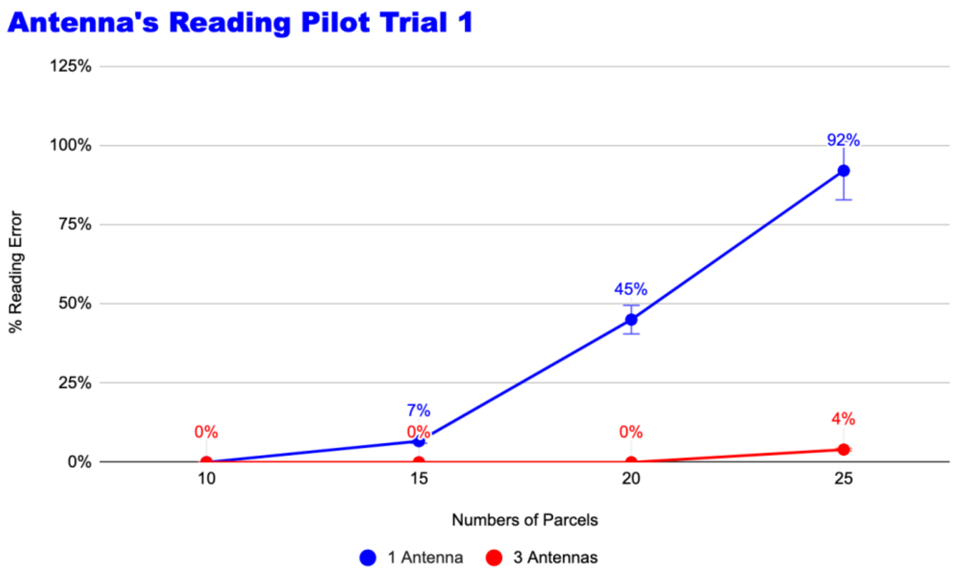

Figure 21. Pilot 1 results

A preliminary attempt to integrate blockchain-based validation was also carried out. Although the system technically allowed parcel-related events to be forwarded to smart contracts, token-related issues prevented stable and seamless event registration. These integration challenges made clear that additional refinement was required before blockchain could be reliably deployed in real operations. Nonetheless, Pilot 1 successfully served its intended purpose by exposing configuration issues, highlighting environmental constraints, and establishing a stable baseline for the next stage of testing.

6.2.4.2. Pilot 2: RFID and Digital Twin deployment

Pilot 2 represented the first full operational deployment of the RFID system. In this pilot, the system was tested in real delivery conditions, combining traditional courier work with the new digitalisation tools developed in the project. The pilot introduced several new layers of complexity, including blockchain-enabled smart contracts and the integration of the Digital Twin's routing optimisation capabilities. Two delivery approaches were compared: the traditional manual workflow based on courier experience and handwritten logs, and a technology-assisted workflow supported by RFID-based event logging, the Digital Twin's VRP-generated routes, and the blockchain system.

During the AS-IS week, logistics operations were entirely manual: couriers classified and reconsolidated parcels at the micro-consolidation centre based on visual inspection and personal experience, planned routes using their knowledge of the urban environment, and recorded delivery events on paper. In contrast, the TO-BE workflow implemented a fully automated process: RFID-tagged parcels were automatically detected during loading and delivery by a three-antenna system, reconsolidation and route planning were supported by the Digital Twin's VRP model, and delivery events were digitally recorded through blockchain-based smart contracts.

Pilot 2, however, faced external factors that influenced system behaviour. Heavy rainfall occurred on several testing days, which required suspending the pilot to avoid potential damage or interference with the technological components. Despite these challenges, the three-antenna configuration continued to produce reliable detection results and the RFID system and the Digital Twin allowed for more efficient operations. The outcomes were notable: time reductions were observed. When dealing with volumes of 15 to 20 parcels, the VRP-generated routes tended to be more efficient than those planned manually by couriers. Distance results, however, were mixed. In some cases, experienced couriers produced shorter routes thanks to their knowledge of shortcuts and local street dynamics. Yet in scenarios with larger parcel volumes or more complex delivery distributions, the VRP-generated routes outperformed manual planning by improving route coherence and reducing backtracking. In figure 22, the time saved per delivery route can be observed, exemplifying the improvement in operational efficiency.

Pilot 2 therefore demonstrated that while manual expertise remains valuable in simple routing scenarios, the combination of RFID-enabled automation and VRP-assisted route optimisation can introduce greater structure, consistency, and reliability into the delivery workflow. It also confirmed that the system can function effectively under real operational conditions, while providing meaningful performance improvements over the traditional workflow.

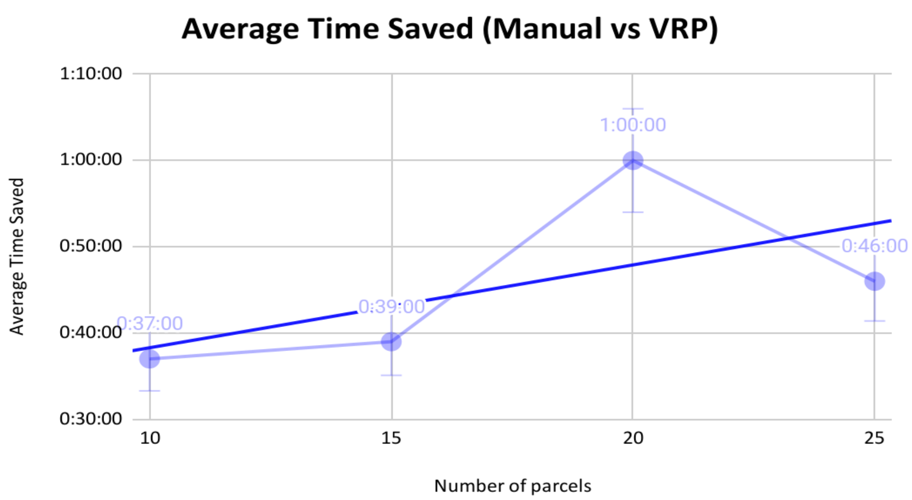

Figure 22. Pilot 2 results

6.2.4.3. Pilot 3: Full deployment of the system

Pilot 3 represented the most advanced and comprehensive test conducted within the Barcelona Living Lab, integrating RFID-supported micro-consolidation centre activities with technology-assisted last-mile delivery into a single, end-to-end operational workflow. This pilot reproduced the complete TO-BE process as designed in the Living Lab architecture and compared it directly with the traditional AS-IS workflow. Unlike the previous pilots, which focused either on technical validation or on operational deployment limited primarily to the delivery phase, Pilot 3 encompassed the entire operational chain, from parcel arrival and reconsolidation at the micro-consolidation centre to the execution of the delivery route. The pilot was also carried out across four distinct parcel volumes (10, 15, 20, and 25 parcels) which made it possible to evaluate system performance under different operational loads and assess how benefits scale as complexity increases.

In the AS-IS scenario, all activities were performed manually. Couriers classified and reconsolidated parcels at the micro-consolidation centre based on their experience and visual inspection, grouping parcels into delivery rounds without digital support. Route planning relied entirely on courier knowledge of the urban environment, and delivery events were recorded using paper-based methods. This traditional workflow, although functional, was highly dependent on the skill and familiarity of individual couriers, and it generated limited traceability information. The manual nature of the process further introduced inefficiencies, particularly when handling larger volumes or when couriers were less familiar with specific zones.

In contrast, the TO-BE workflow implemented in Pilot 3 deployed all digital tools developed within the project. Each parcel was equipped with an RFID tag, enabling automatic identification throughout the reconsolidation process. When parcels were placed inside the cargo-bike, the three-antenna RFID system detected them automatically, generating digital records without requiring manual input from the courier. Reconsolidation at the micro-consolidation centre was supported by these automated detections, which provided immediate insight into the parcels loaded in each batch. The Digital Twin's VRP model used these updated parcel datasets to generate optimised routes for each delivery round, eliminating reliance on manual planning and ensuring consistency across different parcel volumes. During the delivery phase, RFID scans captured each delivery event, while the blockchain layer provided an immutable trace of the process. This full digital workflow not only increased accuracy but also ensured continuous synchronisation between the micro-consolidation centre, the cargo-bike, and the potential stakeholders.

The results of Pilot 3 confirmed substantial efficiency gains, even though the total distance travelled changed only minimally. The near-constant distance reflects the structural constraints of navigating Barcelona's historic centre, where narrow streets and limited routing alternatives restrict major changes in travel geometry. However, while distance remained essentially stable across scenarios, operational time demonstrated a striking improvement. The KPIs show that both consolidation and delivery phases experienced drastic reductions in processing time when using the digitalised workflow. The average time per parcel fell from nearly 11 minutes in the AS-IS scenario to approximately 5.5 minutes in the TO-BE scenario. These results were consistent across all tested parcel volumes, with the digital workflow performing particularly well as the number of parcels increased. In figure 23, the average time saved per delivery route can be observed, exemplifying the improvement with the increase in number of parcels.

Pilot 3 therefore provides strong validation of the added value generated by integrating digital tools and RFID technology both upstream in micro-consolidation centre processes and downstream in last-mile delivery operations. Automated identification significantly reduces handling times, eliminates errors in parcel allocation, and supports more efficient and coherent route design. The combination of automated reconsolidation, VRP-based optimisation, and real-time traceability produces the most substantial operational impact observed across the three pilots. This final pilot thus demonstrates the transformative potential of a fully digitalised last-mile ecosystem and highlights the scalability and robustness of the Living Lab's TO-BE architecture.

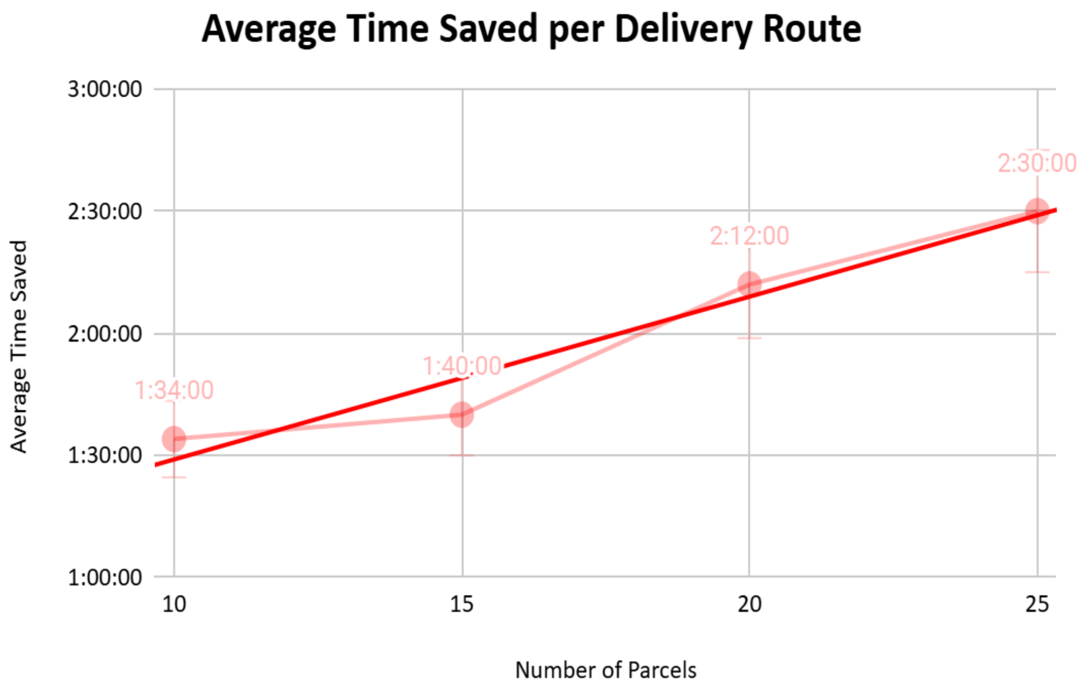

Figure 23. Pilot 3 results

6.2.4.4. Errors / Issues Detected

The pilot operations exposed several vulnerabilities in the data collection and processing infrastructure, primarily related to the RFID/Blockchain setup and user interaction. These challenges impact the roboustness of the KPIs and must be addressed for future scalability.

- **RFID System Accuracy:** The RFID system's performance was found to be highly sensitive to real-route conditions. Issues with signal strength, antenna placement, and environmental interference led to instances of failed or delayed scans. Specifically, it was identified that the setup required three antennas especifically located and real-time validation checks to ensure continuous, accurate tracking of parcels as they moved through the micro-consolidation centre and during transfer to the last-mile fleet. In one instance, system performance was also affected by a portable battery failure. Furthermore, it was necessary to limit tag detection to the active delivery list, as unrestricted reading caused interference from external RFID tags present in the surrounding environment.

- **Blockchain Checkpoint Automation:** While the Blockchain provided an immutable ledger, the validation checkpoints, designed to confirm the transfer of custody, were not fully automated. This led to potential data loss or discrepancies, particularly when required validation steps before and after each route were missed or executed out of sequence.

- **Human Error and Training:** The greatest source of preventable error stemmed from operators. Insufficient training and the lack of in-app validation steps led to human errors during scanning, mis-scanned, duplicate, or out-of-sequence tags, ultimately affecting the cleanliness and consistency of the delivery data used to calculate the time and cost KPIs.

- **External Factors:** Data quality control needed to be fully integrated into the real-time monitoring process. External factors, such as adverse weather, occasionally led to route deviations or delays that were not adequately planned for in the system's contingency scenarios, complicating the analysis of optimal routes and delivery times.

These challenges highlight the need for robust hardware configuration (notably the adoption of three antennas per cargo-bike), more reliable tag standardisation, strengthened data validation processes, and simplified blockchain integration mechanisms. The pilots also demonstrate the importance of clear operational protocols and training to minimise human error.

7. Evaluation/Impact assessment

7.1. KPIs

The data presented in this section are derived from the work carried out in the impact assessment methodology of Task 3.2, where Fit Consulting provided the URBANE Living Labs with a holistic and comprehensive framework, a defined set of Key Performance Indicators (KPIs), and dedicated tools and methodologies to support their impact assessment.

The KPIs for the Barcelona LL, defined in Table 7 and analysed in Table 8, have been meticulously selected to evaluate the performance and sustainability of the innovative last-mile logistics operations, which are centred on cargo-bike-based delivery solutions. These indicators are designed to capture key dimensions such as operational efficiency, environmental impact, and operational reliability.

All KPIs are intrinsically linked to the main Use Case implemented in the Barcelona LL. They are calculated for both the AS-IS (baseline) and TO-BE (LL results) scenarios, enabling a comprehensive cross-comparison of results and a robust assessment of the proposed innovative logistics model. The LL's evaluation is structured across two distinct project components: First Mile Logistics and Last Mile Logistics.

The primary goal of the First Mile Logistics evaluation was the comparative analysis of the environmental impact of different vehicle types, specifically a combustion van versus an electric van, on the first mile route. This route refers to the fixed trip from the warehouse to the micro-consolidation centre and back, using a constant distance of approximately 24-25 km. This evaluation was performed through a simulation utilizing the CitlQore Digital Twin tool across four different parcel volume scenarios: 10, 15, 20, and 25 parcels.

The key objective for the Last Mile Logistics simulation was the evaluation and comparison of two distinct last-mile delivery scenarios (AS-IS vs. TO-BE). Real-life pilot tests were conducted using simulated parcels, with RFID tags and Blockchain-based tracking technology across the three different pilots:

- **Pilot 1** involved the use of cargobikes, a manual route planned by the courier, and a comparison of two technology configurations (one antenna vs. three antennas).
- **Pilot 2** adopted a VRP-based route design to enhance delivery efficiency, utilizing the RFID system with three antennas.
- **Pilot 3** combined the VRP-based route design with parcel reconsolidation in the micro-consolidation centre, also using the RFID system with three antennas

The distance for the last-mile routes varied depending on the customers' addresses.

7.1.1. Defined KPIs for the Barcelona LL

Table 7 below presents the complete list of Key Performance Indicators selected for the Barcelona Living Lab. These indicators were defined according to the methodology established in Task 3.2 and are categorised by the specific logistics component they address (First Mile or Last Mile, and Pilots 1 to 3), along with their relevant description and comments regarding the Use Case.

Table 7. Defined KPIs for the Barcelona LL

Category	KPI	Description	Comments
Vehicle operations in first mile	CO2 emissions	CO_2 emissions generated per trip by van from the consolidation center to the micro-consolidation center.	Baseline and estimates, comparing combustion and electric vans, simulated using the CitlQore Digital Twin tool.
	Average number of km per trip	Average distance traveled by van from the consolidation center to the micro-consolidation center.	
	Total distance travelled in urban area	Sum of the total distance traveled by van daily from the consolidation center to the micro-consolidation center.	
Operations in last mile in Pilot 1	Total distance travelled in urban area	Average of the total distance traveled by cargo-bike daily in delivery.	Baseline and measurements, comparing AS-IS and TO-BE scenarios of Pilot 1, testing different configurations of the RFID system.
	Delivery completion	Percentage of successful deliveries on the first attempt divided by the total number of deliveries made.	

	Errors	Average reading error percentage of the RFID system	
Operations in last mile in Pilot 2	Total distance travelled in urban area	Average of the total distance traveled by cargo-bike daily in delivery.	Baseline and measurements, comparing AS-IS and TO-BE scenarios of Pilot 2, using a VRP tool embedded in the CitlQore Digital Twin to optimize last mile deliveries.
	Average time to complete a delivery route	Average daily total operational time from the start to end of the process.	
	Average time to complete a delivery route per parcel	Average total time divided by the number of deliveries made.	
	Delivery completion	Percentage of successful deliveries on the first attempt divided by the total number of deliveries made.	
	Packages with full traceability	Percentage of parcels traced with RFID and registered in Blockchain	
Operations in last mile in Pilot 3	Total distance travelled in urban area	Average of the total distance traveled by cargo-bike daily in delivery.	Baseline and measurements, comparing AS-IS and TO-BE scenarios of Pilot 3, using a VRP tool embedded in the CitlQore Digital Twin to optimize micro-consolidation center reconsolidation and last mile deliveries.
	Average time to complete a delivery route	Average daily total operational time from the start to end of the process.	
	Average time to complete a delivery route per parcel	Average total time divided by the number of deliveries made.	
	Delivery completion	Percentage of successful deliveries on the first attempt divided by the total	

		number of deliveries made.	
	Packages with full traceability	Percentage of parcels traced with RFID and registered in Blockchain	

7.1.2. Evaluation Results and Cross-comparison (AS-IS vs. TO-BE)

The results of the impact assessment for the Barcelona LL are detailed in Table 8 below. This table provides a comprehensive cross-comparison of the performance metrics, contrasting the baseline (AS-IS) scenario with the results achieved by implementing the innovative logistics model (TO-BE). The data are segregated by the two components: First Mile Logistics and Last Mile Logistics, which at the same time is divided into its 3 Pilots.

Table 8. KPIs and evaluation results and cross-comparison

KPI	Measurement unit	Baseline value	Simulated value	Measured value	Change
First Mile					
CO2 emissions	g of CO2	18,000	7,200	N/A	-10,800 (-60%)
Average number of km per trip	Km	24.7	24.7	N/A	0
Total distance travelled in urban area	Km	98.8	98.8	N/A	0
Last Mile: Pilot 1					
Total distance travelled in urban area	Km	7.5	N/A	7.5	0
Delivery completion	%	99	N/A	100	1

Errors	%	36	N/A	1	-35
Last Mile: Pilot 2					
Total distance travelled in urban area	Km	7.5	N/A	6.7	-0.8 (-11%)
Average time to complete a delivery route	hh:mm:ss	02:36:15	N/A	01:50:45	-00:45:30
Average time to complete a delivery route per parcel	hh:mm:ss	00:07:51	N/A	00:05:41	-00:02:10
Delivery completion	%	100	N/A	100	0
Packages with full traceability	%	0	N/A	100	100
Last Mile: Pilot 3					
Total distance travelled in urban area	Km	7.3	N/A	7.2	-0.1
Average time to complete a delivery route	hh:mm:ss	03:44:30	N/A	01:45:30	-01:59:00
Average time to complete a delivery route per parcel	hh:mm:ss	00:10:55	N/A	00:05:26	-00:05:29
Delivery completion	%	100	N/A	100	0

Packages with full traceability	%	0	N/A	100	100

The evaluation of the Key Performance Indicators in the Barcelona LL demonstrates the potential of the micro-consolidation centre and green fleet strategy. The results confirm the environmental and operational benefits of the Barcelona LL model, particularly demonstrating CO_2 reductions in the first mile and time savings in the last mile.

These underline the combined importance of technological robustness and operational optimisation. In Pilot 1, the comparison of RFID configurations confirms that the use of three antennas is required to ensure reliable system performance. The three-antenna setup drastically reduced reading errors and enabled full delivery completion, demonstrating that a multi-antenna configuration is necessary to minimise detection failures in real operating conditions.

In Pilot 2, the introduction of VRP-based route planning led to a clear improvement in operational efficiency. The average total route time was reduced by approximately 45 minutes, while the average time per parcel decreased by nearly two minutes compared to the baseline scenario. These results highlight the effectiveness of route optimisation in reducing delivery times without affecting service reliability.

Pilot 3 achieved the strongest performance gains, the integrated approach reduced the average time per parcel by approximately five minutes and almost halved the total route duration. The results demonstrate the cumulative benefits of aligning digital routing tools with improved consolidation strategies in last-mile operations.

8. Tactical Assessment of the Barcelona LL

This section presents the two subsections on the tactical-level evaluations conducted for the Barcelona Living Lab using. First, it presents the simulations done using Level 2 of the Impact Assessment Radar. The second subsection presents the results of one of the outcomes of the LL in the form of an academic article.

8.1. Impact Assessment Radar

The purpose of the evaluations done using the Impact Assessment Radar is to support evidence-based decision-making regarding micro-hub design, fleet composition, and locker network configurations under the specific conditions of Ciutat Vella.

8.1.1. Context and Scope

Ciutat Vella represents one of the densest and most operationally constrained areas of Barcelona, with narrow streets, limited access for motorised vehicles, and high volumes of daily commercial and residential activity. As of 2025, the district hosts approximately 115,311 inhabitants. According to the survey by the Consorci de Comerç, Artesania i Moda de Catalunya (2020), the volume of online purchases in Catalonia has grown to about 79 million per year, representing a 44.6% increase since 2018. Based on our estimates, in Ciutat Vella this translates to roughly 40–50 e-commerce purchases per person per year, or about 15,800 parcels entering the district daily, handled by nine major logistics operators: Correus, SEUR, MRW, DHL, GLS, Nacex, CTT Express, UPS and InPost (as commonly listed among Spain's main courier and parcel service providers according to the CNMC's sector analysis (2021)).

The combination of high parcel density, fragmented operations, and tight urban constraints makes Ciutat Vella a suitable environment for tactical simulations aimed at evaluating greener, more efficient last-mile configurations. Level 2 of the IAR allows exploring alternative operational setups before intervention, ensuring that any proposed redesign of the micro-hub network, delivery fleet, or last-mile infrastructure is grounded on a robust analytical framework.

8.1.2. Methodological Approach

The tactical analysis followed the workflow embedded in the IAR Level 2 interface. After defining the contextual characteristics of Ciutat Vella, daily parcel demand, residential density, operator landscape and typical routing conditions, the three Level-2 modules were run independently.

Each module requires a set of input parameters derived from district conditions (parcel flows, service area size, vehicle characteristics, locker capacity, cost factors) and returns a structured set of quantitative outputs describing expected costs, operational performance, and environmental implications. The models do not simulate detailed routing or street-level behaviour; instead, they rely on validated continuous-approximation formulations, as described in the report D3.5. Data-driven Impact Assessment Radar (URBANE, 2025), to compute optimal system configurations. This makes them suitable for early-stage planning and rapid comparison among alternative design options.

8.1.3. Results of the simulations

The following subsections summarise the analytical scope of each of the three modules and the detailed results.

8.1.3.1. Combined Micro-hub Delivery Simulation Module

The micro-hub delivery simulation module was used to assess the feasibility and performance of the delivery system in Ciutat Vella, in which incoming parcels are first transported by vans to micro-hubs and lockers, and subsequently distributed to final customers via cargo bikes or on-foot delivery. This model enables the evaluation of cost, fleet needs, and hub requirements under dense urban conditions, using continuous-approximation formulations configured with district-specific parameters.

The simulation considered nine logistics operators active in Ciutat Vella, each with its own estimated parcel demand. The total daily parcel volume of 15,800 parcels was allocated proportionally across companies as follows:

- Correos (31%): 4,898
- SEUR (12%): 1,896
- MRW (9%): 1,422

- DHL (8%): 1,264
- GLS (8%): 1,264
- NACEX (8%): 1,264
- CTT Express (8%): 1,264
- UPS (8%): 1,264
- InPost (8%): 1,264

The model accounted for the presence of nine operators, an area of interest of 4.37 km², and known depot distributions (Each: 2 depots; SEUR: 3; and Correos: 4). Two types of vehicles were parameterised for the two-echelon system:

- **Vans**, operating between depots and micro-hubs;
- **Cargo bikes**, serving final delivery segments from hubs to customers.

Advanced operational inputs included:

- **Van parameters:** 150-parcel capacity, β-route factor 2.5, speed 25 km/h, delivery time 0.07 h/stop, labour cost €12/h, and transport cost €0.12/km.
- **Micro-hub parameters:** fixed cost €10,000, opportunity cost rate 1.3, operating lifetime 5 years, working days 250/year, and micro-hub handling capacity 120 parcels/day (adjusted by capacity factors).
- **Bike parameters:** capacity 60 parcels, β-route factor 2, speed 15 km/h, delivery time 0.05 h/stop, labour cost €12/h, and transport cost €0.02/km.

Additionally, two capacity factors modulated handling at the hubs:

- **Self-pickup capacity factor:** 1.25
- **Home-delivery capacity factor:** 2.0

These parameters replicate the operational realities of Ciutat Vella, where delivery densities are high and micro-hub throughput is limited by spatial and staffing constraints. The model outputs indicate that a dense micro-hub network is required to efficiently manage parcel flows under the assumed conditions. The optimal configuration identified by the module consists of:

- 94 micro-hubs (lockers) across the 4.37 km² district,
- 4,873 parcels/day served through home delivery (cargo bikes),
- 10,927 parcels/day served through on-foot or walking-distance pickup,

- resulting in an average cost per parcel of approximately €1/day.

The aggregated system-wide cost amounts to €1.1 per parcel per day, reflecting the combined costs of first- and second-echelon transport, micro-hub operation, and labor. This cost structure highlights the trade-off between high hub density and reduced second-echelon travel distances.

These results suggest that, under the assumed operational parameters, Ciutat Vella would require a highly decentralised micro-hub network to support a cargo-bike-based two-echelon delivery system. The high number of hubs is a consequence of the district's compact yet highly fragmented urban fabric and the relatively low handling capacity per micro-hub. Despite this, the resulting cost per parcel remains competitive with conventional delivery operations, particularly when considering the potential reductions in congestion, emissions, and curbside pressure that micro-hub strategies can deliver in dense urban areas. These results can also inform policy recommendations for the municipality and contribute to discussions on urban logistics planning.

8.1.3.2. Fleet Composition Optimisation Tool

The fleet composition optimization module was applied to Ciutat Vella by running eight scenarios in which the minimum CO_2-reduction requirement was progressively increased from 10% to 80%. All other operational parameters were kept constant across scenarios, including the daily demand of 15,800 parcels, 21 depots, identical vehicle capacities, and the cost, routing and operational parameters described earlier. Diesel and electric vans were both enabled as candidate fleet options. The model determines the least-cost mixed fleet capable of meeting demand while satisfying the specified emissions constraint. Across all scenarios, the baseline system, defined as a 100% diesel van fleet, emits 1,971 kg CO_2/day and requires 161 diesel vehicles.

The results show a consistent pattern. As the CO_2 reduction requirement increases, the model gradually shifts deliveries from diesel to electric vans. This transition occurs smoothly, without producing sharp increases in cost. This indicates that, under the assumed parameters, significant emission reductions can be achieved in Ciutat Vella. The scenario results are the following:

- **10% reduction requirement:** The model achieves 11% CO_2 reduction, lowering total emissions to 1,755 kg/day. The optimal fleet is composed of approximately 87% diesel (140 vehicles) and 13% electric (21 vehicles).
- **20% reduction requirement**: The target is met exactly (20% reduction), reducing emissions to 1,571 kg/day. The fleet shifts to 75% diesel (121 vehicles) and 25% electric (39 vehicles).
- **30% reduction requirement:** The model delivers a 30% reduction, with emissions at 1,371 kg/day. The fleet mix becomes 63% diesel (102 vehicles) and 37% electric (59 vehicles).
- **40% reduction requirement:** The achieved reduction is 41%, bringing emissions down to 1,155 kg/day. The fleet becomes perfectly balanced: 50% diesel (80 vehicles) and 50% electric (80 vehicles).
- **50% reduction requirement:** The model obtains a 51% reduction, reducing emissions to 971 kg/day. The optimised fleet consists of 38% diesel (62 vehicles) and 62% electric (99 vehicles).
- **60% reduction requirement**: The resulting reduction is 61%, with emissions at 771 kg/day. The fleet shifts further to 26% diesel (42 vehicles) and 74% electric (118 vehicles).
- **70% reduction requirement:** The model reaches 70% emissions reduction, reducing CO_2 to 586 kg/day. The fleet mix becomes 15% diesel (24 vehicles) and 85% electric (137 vehicles).
- **80% reduction requirement**: The model exceeds the target, achieving 82% reduction, with emissions at 355 kg/day. Diesel van use nearly disappears: only 1% diesel (2 vehicles) remain, complemented by 99% electric (159 vehicles).

Across all scenarios, electrification demonstrates strong potential as a cost-competitive means of reducing last-mile emissions in Ciutat Vella. Even stringent CO_2-reduction requirements lead to fleet configurations whose operating costs differ only marginally, often slightly favorably, from the reference diesel-only system. This reflects the district's compact area, balanced depot distribution, and relatively low energy cost factor for electric vans under the assumed parameters.

8.1.3.3. Locker Network Design Module

The locker network design module was used to examine the feasibility and performance of parcel locker deployment in Ciutat Vella under both single-operator and multi-operator configurations. The model assesses how many lockers would be required to efficiently serve daily parcel demand, as well as the associated operational costs, walking times for customers, and potential CO_2 savings. The simulation framework applies continuous-approximation methods to identify the cost-minimising number of lockers and their expected utilisation under different organisational arrangements.

The analysis considered the same nine logistics operators active in Ciutat Vella, each allocated share of the district's total daily demand, which was identified previously as a daily parcel volume of 15,800 parcels. The spatial extent of the analysis was again defined by an area of 4.37 km^2, with depot distributions matching known operator presence (two depots for all operators except Correus with four and SEUR with three). The typical locker capacity was set to 120 parcels. The transport parameters used in the model were:

- fleet mix: 80% diesel vans and 20% electric vans
- vehicle capacity: 150 parcels
- vehicle speed: 30 km/h
- fuel price: €1.5 per litre
- diesel fuel consumption: 8 L/100 km
- delivery time per parcel: 0.0667 hours
- labour cost: €12/hour
- routing β-factor: 2.5

Locker-related parameters included:

- acquisition cost: €10,000 per locker
- annual opportunity cost rate: 1.3
- operational cost per locker: €10/day

The model runs for both independent operator solutions (each operator deploying its own locker network) and a multi-operator alliance (all operators sharing a common locker infrastructure). For the alliance scenario, the model identifies an optimal requirement of 272 lockers, with a total system cost of €9,165 per day. This shared network significantly reduces the number of lockers required per operator while providing district-wide coverage and very short customer access distances.

When evaluated independently, each operator would require a substantially smaller number of lockers, but the total across all companies would be considerably higher. For example, Correus would require 106 lockers on its own, SEUR 39, MRW 29, and the remaining operators 25 each. The alliance thus avoids duplicated infrastructure by consolidating locker capacity into a single shared system.

Under the alliance, the optimal number of lockers per operator is always 272 due to the joint optimisation, but individualised costs differ according to demand levels:

- Correos: total cost €2,841/day
- SEUR: €1,100/day
- MRW: €825/day
- DHL, GLS, NACEX, CTT Express, UPS and InPost: each €733/day

Across all companies, the average customer walking time remains extremely low at 1 minute, illustrating the high accessibility achieved through dense locker placement.

A comparison between independent and alliance configurations shows that 52 lockers are avoided through shared deployment, and that average walking time is reduced to one minute. Additionally, the alliance achieves substantial environmental benefits: total emissions savings amount to 16,197 kg CO_2 per day. Based on these savings, the model identifies that only 190 lockers would be required to achieve the same CO_2-reduction effect when coordinated across companies, representing a 24% reduction in lockers compared with the independent case.

The simulation results demonstrate that a coordinated, multi-operator locker network offers clear operational and environmental advantages in Ciutat Vella. These findings highlight the strong suitability of locker-based, out-of-home delivery strategies for dense historic districts, particularly when operators collaborate rather than implementing isolated parallel systems.

8.2. Tactical assessment of the optimal number of micro-consolidation centres

As part of the tactical assessment of the Barcelona Living Lab, we developed a modelling and simulation output that evaluates the potential performance of micro-consolidation-based logistics at city scale. This work, published by Castillo et al. (2024b), constitutes a direct analytical output of the project and complements the Living Lab's operational pilots by providing a system-level assessment of alternative last-mile configurations.

Using actual geographic, infrastructural, and operational data from the city of Barcelona, the model analyses the design of a micro-consolidation-centre-based distribution network supported by agile routing algorithms. The simulation framework enables the identification of optimal micro-consolidation centre locations and the generation of multi-objective routing plans, and the estimation of operational and environmental impacts under different demand scenarios.

The results show that a limited network of 61 micro-consolidation centres, representing 5.8% of the initially analysed locations, would be sufficient to satisfy parcel demand in a high-intensity scenario. Compared to conventional van-based distribution, the simulated configurations achieve clear reductions in travelled kilometres, delivery times, and CO_2 emissions. These improvements are driven by an intermodal structure combining micro-consolidation, cycle logistics, and electric vehicles, supported by dynamic routing optimisation. Within the tactical assessment of the Barcelona Living Lab, these results provide quantitative evidence supporting the micro-consolidation strategy tested with Vanapedal.

9. Conclusions

The Barcelona Living Lab provided a real-world framework to test, validate, and refine innovative solutions for sustainable and digitally enabled last-mile logistics. By combining micro-consolidation centres, cargo-bike deliveries, RFID-based traceability, Blockchain integration, and Digital Twin modelling, the project generated valuable insights into both the opportunities and constraints of such systems in the context of dense urban environments. The conclusions below consolidate the key lessons derived from the pilots and translate them into actionable recommendations for future projects and replication.

9.1. Lessons Learned

The implementation and evaluation of the Barcelona Living Lab highlighted several key lessons across technological, operational, modelling, and environmental dimensions.

The integration of the digital tools combined with the deployment of RFID technology demonstrated strong potential for digitalising parcel flows and increasing transparency in last-mile logistics. However, the pilots also exposed the need for a more resilient and carefully engineered physical and digital setup:

- **Hardware configuration:** A key insight was the requirement for a multi-antenna configuration. Relying on a single antenna proved insufficient for complete and consistent tag detection, especially inside the cargo-bike container. The final setup determined that three antennas, one on the ceiling and two at the bottom of the laterals, are needed to guarantee accurate and continuous parcel scanning.

- **System reliability:** Early tests revealed issues such as missed readings, partial detection of tags, and occasional synchronisation errors across the software stack. These interruptions highlighted the importance of robust calibration and iterative fine-tuning of the system.

- **Stress testing under real conditions:** Operational complexity in dense historic areas, narrow streets, obstacles, variable weather, reinforced the need for extensive real-world stress testing. Physical shielding and stable power supply (portable batteries, secured wiring) proved critical to ensure data integrity.

In terms of operational efficiency and improvements, the implementation of digital tools and RFID-supported workflows generated measurable efficiency gains when compared with manual or semi-manual processes:

- **Handling time reduction:** Considerable time savings were observed in parcel manipulation at the micro-consolidation centre. When combining the usage of digital tools for consolidation and delivery, average savings reached up to 5.5 minutes per parcel, highlighting the impact of automating operations and verification tasks.
- **Faster delivery routes:** Delivery routes benefited from faster loading and manual checks, such as prior route planning, leading to average time savings of over 2 minutes per parcel during last-mile operations.
- **End-to-end traceability:** The system successfully enabled full visibility of parcel movements, providing real-time traceability from loading to final delivery. This capability is central to improving reliability, enabling automated confirmation, and supporting more advanced optimisation models in later stages.

In addition, the Living Lab experience also underlined the importance of accurate, high-quality data and the influence of uncontrollable factors:

- **Digital Twin data quality:** For the Digital Twin and the Vehicle Routing Problem solver to produce meaningful recommendations, real-world operational data must be provided consistently into the models. Inaccurate or incomplete data, particularly regarding rider behaviour, route inefficiencies, or parcel variability, can significantly distort the outcomes.

Finally, the tools deployed in the Barcelona Living Lab, especially the Digital Twin, also helped quantify the broader sustainability benefits of greener logistics operations:

- **Environmental benefits:** Digital Twin simulations demonstrated that the electrification of the first-mile segment can deliver substantial environmental benefits.
- **Zero-emission logistics:** The combination of electric vehicles for first-mile transport and cargo-bike-based last-mile delivery reinforced the relevance of multimodal, zero-emission logistics strategies in dense urban areas.

9.2. Recommendations

Based on the lessons learned from the Barcelona Living Lab, the following recommendations are proposed to guide future projects, strengthen system robustness, and support wider replication of sustainable and digitally enabled last-mile logistics solutions.

Technical and operational recommendations

- **Improve the set-up of RFID systems configuration.**
  The pilots demonstrated that reliable parcel detection requires multiple antennas in specific positions within the cargo-bike container. Future implementations should adopt a standardised setup, typically three antennas, to ensure full coverage, minimise blind spots, and guarantee continuous data capture during loading and delivery.

- **Increase the robustness and resilience of technological components**
  RFID readers, antennas, wiring, batteries, and communication equipment should be housed in weather-resistant, shock-absorbing, and shielded enclosures to withstand real urban operating conditions.

- **Reinforce data synchronisation and communication protocols.**
  Stronger mechanisms should be implemented between edge devices, cloud servers, and Blockchain system, including buffering, retry logic, timestamp verification, and automated anomaly detection, to prevent data loss and ensure consistency.

- **Model Refinement Through Continuous Integration of Operational Data**
  Digital Twins and routing optimisation models should be fed with detailed real-world data (e.g. unloading times, route inefficiencies, courier behaviour, parcel variability) to improve predictive accuracy and support dynamic routing in future deployments.

Finally, drawing on the Living Lab activities, results, and experiences, the following strategic, policy, and scalability recommendations can be proposed:

- Public authorities should incentivise the adoption of electric or low-emission vehicles for first-mile urban freight. The Living Lab results show that even partial electrification can deliver significant CO_2 reductions. Existing regulatory instruments such as the Low Emission Zones could be leveraged to accelerate fleet renewal in goods distribution, using access restrictions or differentiated requirements to favour cleaner vehicles.

- Cities should prioritise the development of distributed micro-consolidation centres and integrate small-scale logistics spaces into urban planning frameworks. Public authorities could also facilitate deployment by reserving or temporarily allocating publicly owned or underused spaces to zero-emission and sustainable logistics operators (i.e. using cargo-bikes), lowering barriers to adoption and scaling.
- The successful use of RFID and Blockchain highlights the value of interoperable traceability tools. Cities should encourage shared digital standards to support transparency, performance monitoring, regulatory compliance, and data-driven urban logistics planning.

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[27] Institut d'Estudis Regionals i Metropolitans de Barcelona. (2019). Urban Mobility Metropolitan Plan (PMMU) 2019–2024. Àrea Metropolitana de Barcelona.

Annexes

Annex I. Conceptual Framework: Key concepts in Urban Logistics

A shared understanding of core logistics concepts is necessary to interpret the objectives, methodology, and outcomes of the Barcelona Living Lab. This section defines the essential terminology related to supply chain management and last-mile logistics used throughout the report.

Core definitions

- **Supply Chain Management:** It encompasses the planning and management of all activities involved in sourcing and procurement, conversion, and logistics management. It also includes coordination and collaboration with key channel partners, such as suppliers, intermediaries, third-party service providers, and customers, and integrates supply and demand management within and across organizations.

- **Logistics:** Logistics is a component of supply chain management that focuses on the detailed coordination of complex operations involving the movement and storage of goods. In commercial terms, it encompasses the planning, implementation, and control of the efficient and effective forward and reverse flow and storage of goods, services, and related information between the point of origin and the point of consumption in order to meet customer requirements (Council of Supply Chain Management Professionals, n.d.).

Delivery Stages

The physical distribution of goods from the producer to the consumer is traditionally broken down into two stages, with the Last Mile being the most challenging in urban environments:

- **First Mile:** The movement of goods between major logistical hubs, such as from regional distribution centres to smaller city warehouses. This stage focuses on consolidation and efficiency across long distances.

- **Last Mile:** The final leg of the delivery journey, moving goods from a transportation hub (e.g., a sortation centre or consolidation centre) to the final destination (the customer's home or business). This stage is characterized by high costs, low speeds, traffic congestion, and fragmented deliveries, making it the primary focus of urban logistics innovation (DHL Freight Connections, 2025).

Consolidation Centres

These concepts relate to strategic points within the urban fabric designed to improve the efficiency of the Last Mile:

- **Urban Consolidation Centre (UCC):** A facility, typically located on the outskirts of an urban area, where freight from multiple logistics operators is collected, sorted, and consolidated onto shared, smaller, or cleaner vehicles for the final delivery into the city centre.
- **Micro-Consolidation Centre (MCC):** A smaller-scale consolidation centre situated within the city core, closer to the final delivery points. Their primary function is to serve as a transfer point where goods arriving via first-mile transport (often vans or small trucks) are transferred to zero-emission vehicles like cargo bikes or foot couriers for the highly restrictive last-mile delivery zone (e.g., Ciutat Vella).

Annex III. Dissemination and Publications

The Barcelona LL has delivered a diverse set of outputs encompassing scientific articles, workshops and events, and forthcoming communication activities, all contributing to knowledge dissemination, stakeholder engagement, and long-term impact.

- **Articles and publications:** Two main articles, both present in the report, have been produced as part of the LL's dissemination activities and together they document both the strategic and technical contributions of the project:
  - "Tackling Urban Freight Distribution: A Public-Private Perspective", released on the 1st of March of 2024, which explores governance and collaboration models for urban freight systems.
  - "Towards Greener City Logistics: An Application of Agile Routing Algorithms to Optimize the Distribution of Micro-Hubs in Barcelona", which was published on the 23rd of August 2024, presenting applied research derived from the project's technological development and data analysis phases.
- **Workshops and events:** The project's results have been disseminated through several workshops and major sector events. Early outreach included Lleida Tech, held on 26–27 October 2023, which provided a platform to present exploratory research conducted during the first stages of the project. Barcelona LL was subsequently showcased at the Transport Research Arena from 15 to 18 April 2024, reaching a broad international research and policy audience. Further dissemination took place at Terrassa Tech on 14–15 May 2025, presenting the most relevant results reached within our pilot tests. An Advisory Board Presentation, held on 18 June 2025, allowed for expert feedback and strategic guidance. Stakeholder-focused engagement continued with the Workshop: BiciHub El Clot, held the 30th of October 2025, enabling direct dialogue with local actors and practitioners. The dissemination activities will conclude with a Final Workshop on February 2025, dedicated to presenting final results and lessons learned.
- **Communication activities.** To complement these outputs, a dissemination article is scheduled at UOC's Faculty of Economics and Business' Blog for release in February 2026. This blog post will provide an accessible overview of the project's objectives, progress, and key results, targeting a wider audience beyond the project's core stakeholders.

Annex III. Photos

A.3.1. Cargobikes

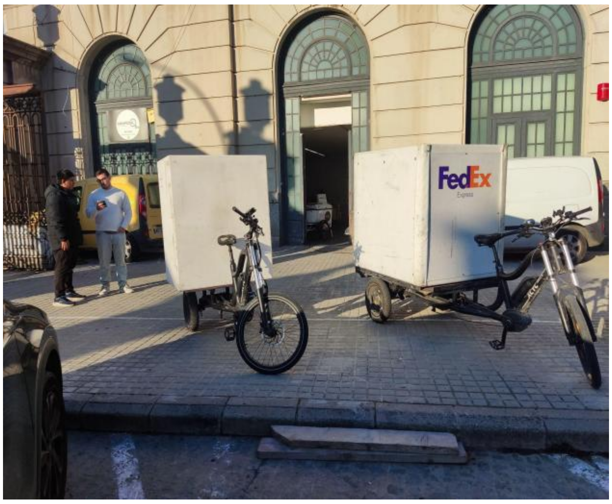

Figure 24. Cargobikes 1

Figure 25. Cargobikes 2

A.3.2. RFID System Set-Up

Figure 26. RFID System Set-Up 2

Figure 27. RFID System Set-Up 3

A.3.3. Cloud-based Server Deployment

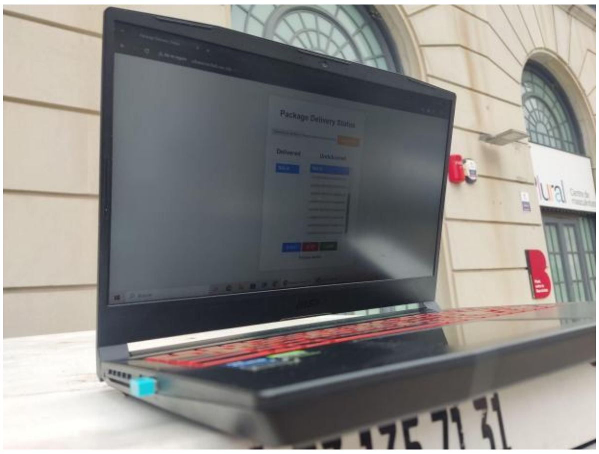

Figure 28. Cloud-Based Server Deployment

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