Digital Twinning platforms as an enabler for the ex-ante evaluation of PI-inspired interventions to last-mile logistics networks

Dimitrios Rizopoulos[1], Harris Niavis[2], Maria Kampa[3], Aristea M. Zafeiropoulou[4], Rod Franklin[5], Antonis Mygiakis[6], Anastasios Kakouris[7], Andreas Alexopoulos[7] and Ioanna Fergadiotou[8]

1. Research Engineer, Inlecom Innovation, Athens, Greece
2. Head of Blockchain Research, Inlecom Innovation, Athens, Greece
3. Senior Project Manager, Inlecom Innovation, Athens, Greece
4. Senior Research Scientist, Konnecta Systems, Dublin, Ireland
5. Professor, Kühne Logistics University, Hamburg, Germany
6. Managing Director, Konnecta Systems, Dublin, Ireland
7. Senior Software Engineer, Konnecta Systems, Dublin, Ireland
8. Head of Athens Lab, Inlecom Innovation, Athens, Greece

Corresponding author: dimitris.rizopoulos@inlecomsystems.com, ioanna.fergadiotou@inlecomsystems.com

Abstract: *One of the greatest challenges of the European last mile logistics sector is the requirement to decouple its economic growth from resource use and air pollutants emissions from transport operations. This requirement, alongside the rise of e-commerce and the phenomenon of urbanization, creates an urgent need for European Union's member states to identify and rapidly upscale innovative last-mile solutions that will ensure the green and digital transformation of European urban environments. To achieve such a goal, innovative frameworks such as the Physical Internet (PI) are required, which can lead to low-emission logistics services that remain competitive compared to the latest industry trends such as same- or next-day-delivery, real-time parcel tracking, and omni-channel distribution. The URBANE project introduces an Innovation Transferability Platform with Digital Twinning capabilities, under the Platform-as-a-service (PaaS) paradigm, which enables the project's Living Labs to assess the impact of the PI-inspired interventions before or during their implementation in the real-world context. In that regard, in the current article, a presentation of initial project results is given, including platform micro-services and Use Cases (UCs) that aim at supporting the transition to the PI.*

Keywords: *Digital Twins, PaaS, simulation, blockchain, trusted data sharing.*

Conference Topic(s)*: interconnected freight transport; distributed intelligence last mile & city logistics; PI impacts; PI modelling and simulation; technologies for interconnected logistics (5G, 3D printing, Artificial Intelligence (AI), IoT, Machine Learning (ML), augmented reality, blockchain, cloud computing, digital twins, collaborative decision making).*

Physical Internet Roadmap *(Link): Select the most relevant area for your paper: ☐ PI Nodes, ☒ PI Networks, ☒ System of Logistics Networks, ☒ Access and Adoption, ☒ Governance.*

1 Introduction

The European Green Deal and the EU's objective to separate economic growth from resource use have increased the pressure on stakeholders in last-mile logistics networks and policymakers, to reduce the negative impact of environmental externalities of logistics operations on the urban environment. In the last years, this pressure has only intensified due to the rapid growth of e-commerce, reinforced by the COVID-19 pandemic, resulting in last-mile delivery being one of the most emissions-intensive sectors of the economy (Milewski & Milewska, 2021). Consequently, European cities need to adopt innovative solutions and create a transition path towards effective, safe, and sustainable last-mile logistics. Considering these emerging needs, as well as Logistics Service Providers' (LSPs) competitive pressures, such as same- or next-day delivery, rescheduling missed deliveries, and low prices, an innovative framework of solutions is needed to enhance the operational and environmental efficiency of European logistics. A highly anticipated answer to these requirements is the Physical Internet (PI, π) concept, which aims to bring the operational logic of the digital Internet to logistics networks.

The core idea within PI is to utilise modular and actively connected PI-containers that can be easily interchanged and transferred between different carriers and modern transport modes at PI-nodes of the interconnected logistics super network, based on standardised communication, collaboration, and routing PI-protocols. In this way, collaboration among different actors across the supply chain can be fostered, leading to greater interoperability and interconnectedness among parts of the global logistics network, which previously were disconnected. While PI's benefits have been both analysed (Ballot Eric et al., 2018) and showcased by big players in logistics (Tran-Dang et al., 2020), its adoption is in its infancy. While this is a common phenomenon with emerging technologies (Douthwaite et al., 2001; Wagner & Franklin, 2008), given suitable practices and strategies, the adoption of disruptive innovations can be accelerated in the Transport & Logistics (T&L) sector.

The URBANE project brings together a diverse group of public authorities, industry actors, and research experts to collaboratively create new solutions for last-mile delivery by combining PI-inspired approaches with the latest Internet Communication Technologies (ICT) and last-mile logistics modelling techniques. One of the main digital tools that are being developed is the Digital Twinning Platform, which is designed to function as a Platform-as-a-Service (PaaS) offering for city and logistics stakeholders. The platform utilises Digital Twins (DTs) technology to allow stakeholders to assess the impact of PI-inspired interventions before or during their implementation in urban contexts. As a result, regional authorities and LSPs, can simulate complex operational scenarios to evaluate how different real-world network parameters might affect short-term or long-term future operations (refer to Figure 1). The DT platform offers data-driven decision support capabilities for testing and implementing PI-inspired solutions in last-mile networks.

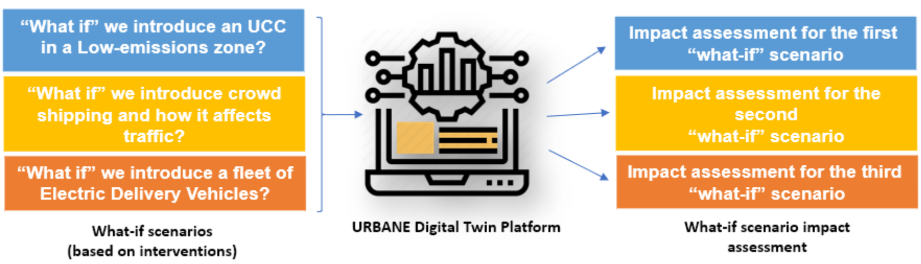

Figure 1: Use case examples for the URBANE Digital Twinning platform

As described in the sections that follow, URBANE will demonstrate prominent UCs of the DT technology, where platform users can utilize a range of digital logistics models and case-specific datasets to assess various "what-if" scenarios. These scenarios are comprised of digitally modelled interventions in the logistics network (based on PI principles), whose impact on the logistics network would require more resources (i.e., case-specific model development, hiring of consultancies, digital infrastructure development, etc.) to be accurately estimated before actual implementation. The DT Platform supports the integration of several types of models, such as descriptive, diagnostic, predictive, or prescriptive analytics models (Cochran, 2018), which can be parametrised through a User Interface (i.e., DT Portal) and executed on a simulation execution engine. The DT platform features are complemented by trusted information sharing mechanisms built on blockchain technology.

This article is focused on two primary themes: *(i)* presenting some of the early results of micro-services of the DT Platform and relevant UCs under the Platform-as-a-Service (PaaS) framework, and *(ii)* introducing blockchain-supported AI-enabled Smart Contracts and Decentralized Identity Management technologies. The article highlights progress in PI-oriented thinking that has resulted from collaboration among industrial partners, public authorities, and researchers. Specifically, Section 2 of this article provides a review of PI-inspired innovative concepts and presents examples of primary PI enablers and expected benefits. Section 3 and Section 4 discuss the core technological aspects of the Digital Transferability Platform. Section 3 provides an overview of the DT micro-services and UCs under the PaaS framework, and Section 4 presents the expected services to be developed based on blockchain technology. Finally, Section 5 includes a discussion of how PaaS offerings and increased data sharing are contributors towards PI adoption, and Section 6 summarises the conclusions and next steps.

2 A review of PI-inspired innovative concepts

The PI represents a ground-breaking approach to logistics and supply chain management, that aims to make logistics systems more efficient, sustainable, and interconnected. At its core, the PI relies on an open network architecture that enables the seamless and interoperable exchange of goods, information, and services, thereby reducing communication barriers between stakeholders and facilitating greater collaboration. To achieve its objectives, the PI relies on a series of innovative concepts such as standardised protocols, container sizes, packaging formats, and modern transportation vehicles to improve LPSs' ability to address customer requirements, minimise environmental impact, and optimise delivery processes. Additionally, the PI leverages communication, collaboration, and routing protocols, as well as interoperability and traceability standards, to ensure seamless and efficient logistics operations among several LSPs. By encouraging new trade configurations and fostering collaboration between various stakeholders, the PI envisions establishing a sustainable, integrated, and effective global logistics super network, where logistics nodes are connected through standardised interfaces and protocols to enable the efficient transfer of goods from the source to the final destination.

The PI is a relatively new concept, and as a result, there is still a developing body of scientific literature on the subject, as well as the PI-inspired innovations, that may assist the transition from traditional segmented logistics networks to collaborative ones. Nonetheless, an increasing amount of research is being conducted on the PI, with numerous studies exploring its potential benefits and challenges (Eric et al., 2018; Montreuil & Nagurney, 2016). One of the most important innovations to achieve the PI is the standardisation of container sizes, shapes, and packaging formats that need to be handled across different countries, transportation modes as well as warehousing and storage facilities. Central to this standardisation of containers is the classification of PI-containers into several types of containers according to size and functionality. On the one hand, the following standardisation according to function has been suggested: transport containers (T-containers), handling containers (H-containers), and packaging containers (P-containers) (Montreuil et al., 2015). Further classification can be achieved based on the size and standard PI-container units (Montreuil, 2011). Given the proper

design of the PI-containers according to size and functionality, one of the end goals is to utilise modular containers, that enable the easier assembling, disassembling, loading, and unloading of goods by encapsulating the goods themselves, or other types of PI-containers. Importantly, PI-containers are envisioned not only to be modular, but also 'smart' and 'active'. Based on the smart PI-containers concept (Sallez et al., 2015), PI-containers can include 'active' tracking elements (i.e., wireless sensors and devices) instead of passive tracking technologies like bar codes. Based on this active connection, several benefits can be expected (Rizopoulos et al., 2022), such as real-time visibility of shipments, including location tracking, container security status (i.e., opening/closing of doors), hygrometry, vibrations, etc. PI-containers of all types should be able to interface with standard "smart" devices as well as PI-handlers and PI-sorters, which enable their efficient handling and manoeuvring in PI-nodes. PI-handlers fall under the umbrella of PI-movers, which are PI-inspired innovations that refer to systems and procedures that are connected to transporting, conveying, handling, lifting, and manipulating goods while they are in the logistic flow (Tran-Dang & Kim, 2018). While PI-movers as a term refers to innovations that are highly automated (i.e., autonomous ground vehicles, drones, robots), human agents can be PI-movers that overall manage and assist automated systems in loading, unloading, and transhipping PI-containers from one PI-mover to another (also assisting with information sharing and management, order management, etc.). An example where PI-movers are showing promising potential can be located within PI-inspired cross-docking facilities (Chargui et al., 2018), where high-speed PI-conveyors can be combined with an automated storage and retrieval system, and PI-sorters to replace a set of traditional forklifts that facilitate the loading, unloading, and transfer process.
When a node of the logistics network is equipped with the necessary PI-inspired infrastructure, protocols, and technologies, then it can serve as an enabler of the seamless consolidation, exchange, and routing of goods within the PI. The aforementioned PI-inspired cross-docking facilities are just one type of a PI-node, which refers to a set of facilities that serve as connecting interfaces between logistics networks. Based on the types of networks that are connected at each PI-node and each node's functionality, PI-nodes are classified into several types, such as PI-transits, PI-switches, PI-bridges, and PI-hubs (Chargui et al., 2022; Tran-Dang & Kim, 2018). When PI-nodes, such as rail-to-road and water-to-road PI-hubs, are designed accurately on a strategic, tactical, and operational level in order to exploit other PI-inspired innovations (Chargui et al., 2019), they can connect and improve logistics networks, but also promote sustainable modes of transport such as railways and waterways (Figures 2 & 3).

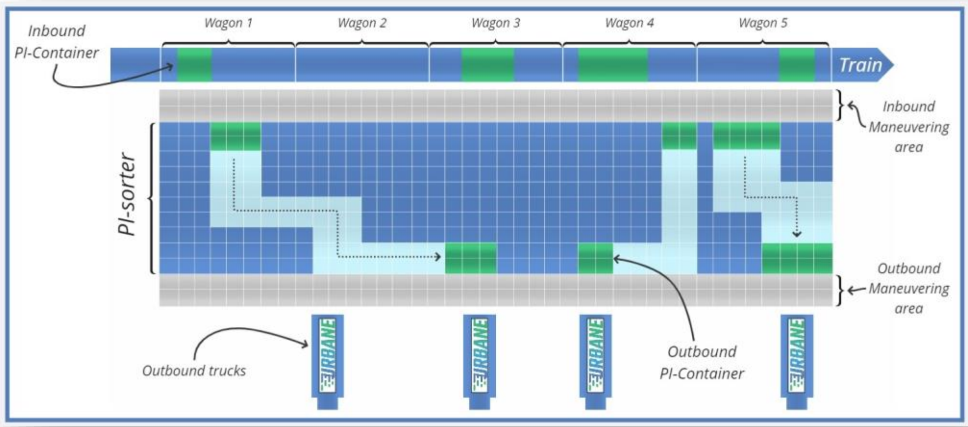

Figure 2: An example of a rail-to-road PI-inspired cross-docking facility (PI-hub), with a PI-sorter and two maneuvering areas.

PI-protocols are also worth mentioning, as they ensure that all PI-inspired innovations (refer to Figure 4) are integrated together by taking the central role of communication, negotiation, and coordination between stakeholders within the PI (Kaup et al., 2021). In contrast to the well-established protocols of the digital Internet, in the PI, some processes, such as packet aggregation and resending lost packages, are much more complex and display different properties as compared to the digital world. For these reasons, although the scientific world has already presented metaphors from the five-layer Internet Protocol model (application, transport, network, link, and physical layers), several PI-protocols and respective technologies may need to be combined to achieve the PI (Briand et al., 2022). An essential research direction in emerging PI-protocols is dynamic routing of PI-containers, as the main object of the flow-to-be-optimised while treating the different logistics sub-networks of the PI as heterogeneous autonomous systems (Gontara et al., 2018).

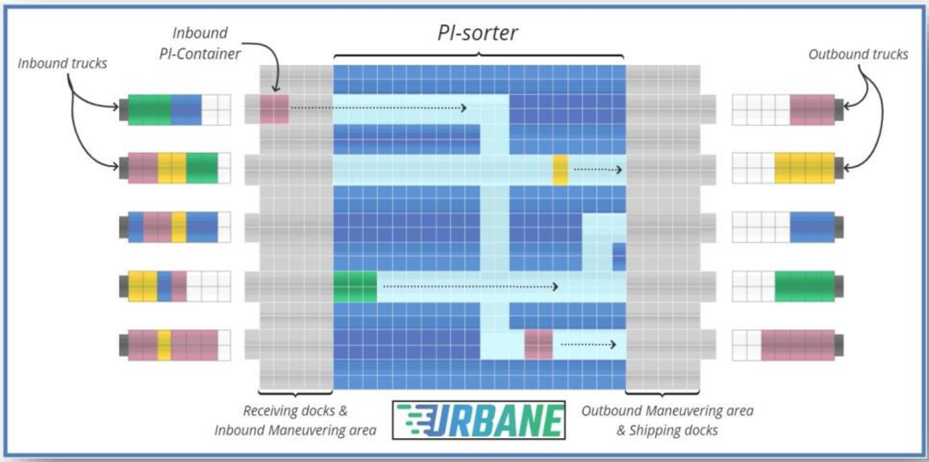

Figure 3: An example of a road-to-road PI-inspired cross-docking facility (PI-hub), including a PI-sorter and two maneuvering areas.

As in the case of the digital Internet, PI-protocols and related innovations have a central role in how communication between LSPs and logistics networks takes place to define how an object-to-be-shipped travels from one node of the PI to another. To achieve this communication, several innovations that have been presented up to now can play an important role. A first fundamental example is GS1's Electronic Product Code Information Services (EPCIS), which is a standardized data exchange format and architecture for real-time capturing and data-sharing related to the status of a shipment and related products, assets and services throughout the supply chain[1]. Potential adoption of EPCIS into practice can bring significant benefits to stakeholders, such as improved inventory management and visibility for LSPs (Soedarno et al., 2020), but can also be a major enabler of the PI since data stored in standardized formats can be exchanged between LSPs that are eager to collaborate and increase delivery efficiency. Supplementary to EPCIS, blockchain and smart contracts technologies can be important for the realization of the PI, which has been proposed as solutions that can bridge cyber and physical systems in multiple sectors (Fotiou et al., 2019). Blockchain and smart contracts solutions have been also proposed for the introduction of a synergetic application framework, which can facilitate the trusted data and value exchange between multiple actors in the PI network (Meyer et al., 2019). In the framework discussed, PI-containers serve as the centre of value exchange

[1] GS1's EPCIS & CBV standards, https://www.gs1.org/standards/epcis

of interest and can be traded and tracked by actors on a decentralized and transparent blockchain network that enables a more optimal routing of parcels between PI nodes.

A final reference within this section is the PI-concept of synchromodality, which can be seen as one of the desired impacts of the application of PI-inspired innovations, advanced analytics applications as well as increased and real-time data sharing across stakeholders. As an extension to intermodal transportation, synchromodality enables dynamic switching between various modes of transportation, such as road, rail, waterways, or air. Based on real-time data, the choice of transportation mode can occur depending on different factors such as cost, time, environmental impact, and other stakeholder requirements (Ambra et al., 2019b) within PI-nodes. Especially in the case of railways and waterways, which are more efficient and sustainable than road transportation for long distances and larger volumes of goods but must deal with the requirement of intermodal transport and transhipments, synchromodality can increase their modal share by enabling the optimization of the entire logistics system and increasing flexibility (Ambra et al., 2019a).

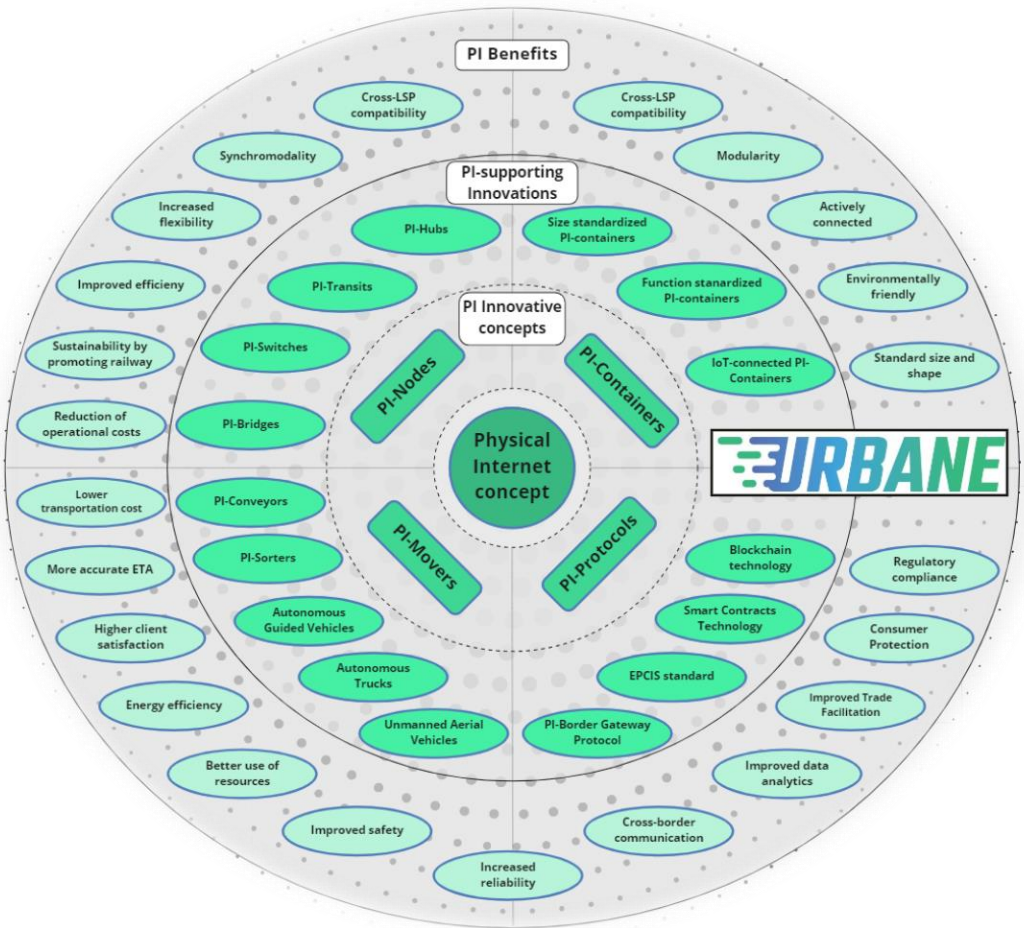

Figure 4: A collection of PI Innovative concepts, PI-supporting innovations, and expected benefits

3 Digital Twinning under the PaaS paradigm

Several definitions of Digital Twins (DTs) have been proposed in recent years (IBM, 2023; Kritzinger et al., 2018; World Wide Web Consortium (W3C), 2023). Despite the lack of a commonly accepted definition, they mostly agree that a DT is a *virtual representation of an object or system*. This is unsurprising, given that their origin lies in smart manufacturing (Kritzinger et al., 2018). Yet, in the domain of smart cities, as well as transport and logistics,

such an interpretation does not seem a good fit since the focus is not only on technology but also on the participation of different communities and stakeholders (Mylonas et al., 2021). In this context, the European Commission defined Local DTs as the "virtual representation of the city's or community's physical assets, processes, and systems that are connected to all the data related to them and the surrounding environment"[2]. Through the use of data analytics, AI, ML, and agent-based modelling they provide answers to case-relevant what-if scenarios. Such a solution was previously designed and developed in the context of the LEAD project[3] and is currently applied and extended in URBANE. In both projects, the DT is offered to the project's Living Labs as a Platform as a Service (PaaS) solution, providing several economic and practical benefits to the pilot cases since there is no need to build and maintain infrastructure, acquire licensing, and so on.
The ambition behind the URBANE DT is to support urban logistics communities with a ready-to-use solution that offers them dynamic data-driven modelling innovations and interventions with the ultimate purpose of empowering their policymaking. Significantly, the DT employs a plethora of different models - from AI models to social simulation, agent-based models developed within the project, but also models developed previously in LEAD – thus, developing a *Model Library* that can be reapplied and extended in several UCs within the project's Living Labs, but also in PI-relevant UCs outside of the realm of the URBANE project.

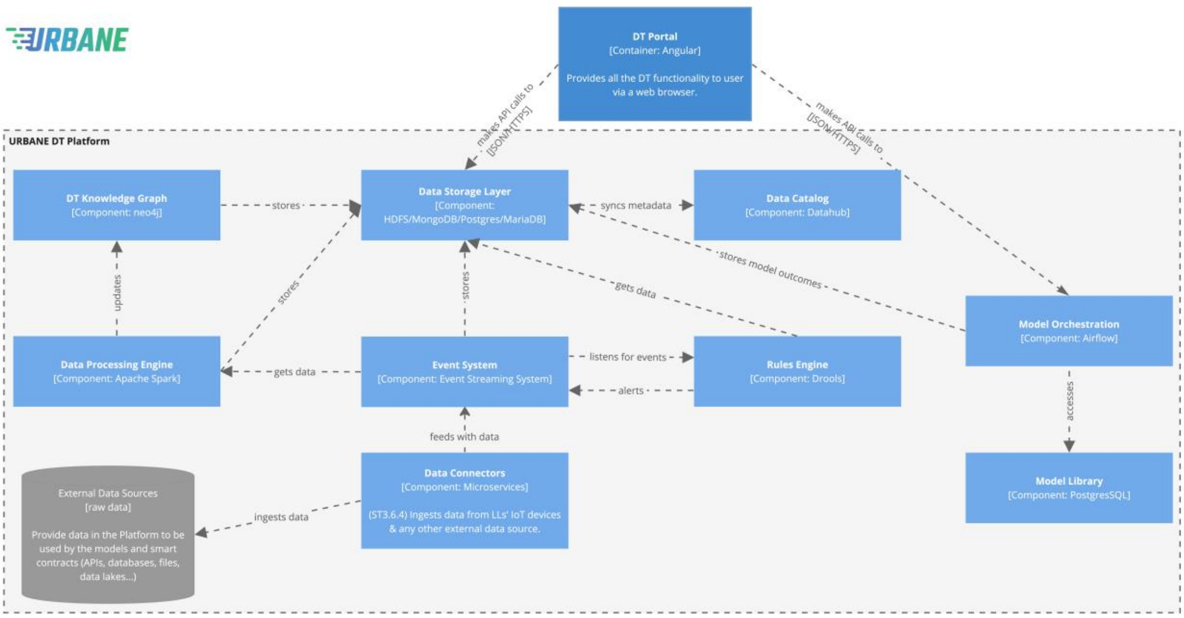

Figure 5: Component Diagram of URBANE Digital Twin

The high-level architecture of the DT consists of several key components as depicted in Figure 5. A feature of critical importance is the ingestion of relevant data from various external sources – either in real-time or in batch – through the dedicated *Data Connectors*. In this manner, the platform ingests raw data and afterward processes – by the *Data Processing* Engine - it and stores it to provide different what-if scenarios with real-life, suitable data. As already indicated, a key component of the DT is the *Model Library*; models are entered into the platform through a meticulous integration process – offered either as open-source components or through API communication – to ensure reusability and even extendibility of the models. On top of this, the

[2] "Workshop - Local Digital Twins Technology", European Commission, https://digital-strategy.ec.europa.eu/en/events/workshop-local-digital-twins-technology
[3] Low-Emission Adaptive last mile logistics supporting 'on Demand economy' through digital twins (LEAD), https://www.leadproject.eu/

Model Orchestration component enables the dynamic creation of model workflows by the DT users. This functionality, enabled by Apache Airflow, empowers users to create their own what-if scenarios comprised of chains of different models – often one model output is used as input to another model – serving their own UCs. These functionalities are offered through a dedicated DT Portal that can be accessed through a web browser.

The following sections present a real-world application of Digital Twinning and last-mile logistics modelling, in which a model performs an estimation of Electric Delivery Vehicles (EDVs) fleet size to cover real-world parcel delivery demand. In more detail, the DT and the respective model have been used in two UCs:

- <u>Historical data analysis, based on monthly demand data:</u> Models are used to estimate EDV fleet size to assess the establishment of LSP's logistics services that focus either on missed and rescheduled deliveries or 'small' deliveries (i.e., lower volume orders), and,
- <u>Real-time DT:</u> Based on the available fleet size and specification, the DT and underlying model estimate the number of EDVs needed to cover demand on shorter time frames (i.e., daily horizon and dispatch windows within a day).

Based on these UCs, the LSPs can develop a techno-economic analysis of prospective services and/or calculate EDVs to be purchased/leased within different time horizons (i.e., months, days, and dispatch windows). The estimator model that has been developed and used in these UCs is based on a Capacitated Vehicle Routing Problem with Time-Windows (C-VRP-TW), LSP's parcel delivery data and routing based on the OpenTripPlanner engine and OpenStreetMap data. Through the developed DT solution, LSPs are empowered to move towards the 'electrification' of their fleet by acquiring quantified evidence of what is the number of electric delivery vehicles (specified by the maximum delivery range and capacity) required to cover a specific delivery demand over a timeframe (i.e., as indicated by input data to the DT). Not only that but the quantified evidence can be produced/re-produced by the LSPs themselves by utilizing the DT and underlying models under the PaaS framework, when needed. In URBANE, extensions of these UCs are under development, including the use of other innovative delivery vehicles, as well as the examination of as-is and to-be scenarios for their use.

During the last few years, research on DTs related to supply chain management, T&L, and the PI has increased (Barykin et al., 2020; Leung et al., 2022), though it is still in its infancy (Deepu & Ravi, 2021; Nguyen et al., 2022; Pan et al., 2021). Our work focuses on the development of a DT that focuses on last-mile logistics in urban areas and aims at improving the operation of parcel delivery, reducing costs but also emissions in a sustainable manner through PI-inspired forecasting and simulations applied to different scenarios within the project's Living Labs.

4 Blockchain-supported AI-enabled Smart Contracts and Decentralized Identity

Blockchain technology has the potential to play a significant role in the materialization of the PI paradigm by enabling secure and transparent data sharing across the entire logistics network while also supporting identity management towards a more user-centric approach. To this end, the URBANE Platform uses smart contracts to increase the transparency of interactions between T&L stakeholders and automate processes such as the movement of goods, payments, inspections, quality control, and last-mile infrastructure/resource sharing. The employment of AI-enabled smart contracts brings us a step closer to PI since it makes them even more intelligent and automated by analysing historical or live IoT data from sensors to trigger pre-defined actions, which were otherwise triggered by paper-based contracts.

The URBANE project integrates a blockchain-based service that employs AI to predict future demand in shared last-mile delivery lockers and automatically generate contracts between T&L stakeholders for a more fine-grained management of physical resources. The AI analytics of the service predicts trends and incoming loads of shipments in the lockers that help LSPs adjust their operations, secure better pricing policies with their partners, and open up their privately owned infrastructure to competitors in a trusted way.

Another key functionality that is supported by blockchain technology in URBANE is the identity management of the platform's users, namely actors in the supply chain (e.g., carriers, shippers), but also administrators, and data analysts who wish to experiment with or develop data-driven services. Devices and systems are also using the same decentralized identity management mechanism to interact with the platform, since it follows legacy standards (i.e., OAuth 2.0 (Hardt., 2012), that make the integration straightforward. URBANE's identity management approach follows the SSI paradigm (Preukschat & Reed, 2021) that gives full control of the data to the user and enables GDPR[4] to the greater extent possible, by allowing the right of data erasure (to be forgotten) and the right of data portability.

Overall, the blockchain-based functionalities of the URBANE Platform enable the interoperability of stakeholders in the last-mile delivery, as it offers i) the ability for automated smart contracts between different organisations to eliminate ambiguities in case of disputes ii) increased transparency in the entire supply chain by allowing a trusted shared registry for data exchange and iii) secure and globally unique identities that follow the latest emerging standards i.e., DIDs[5] and VCs[6].

5 PaaS offerings and increased data sharing as contributors towards PI adoption

The PaaS model originated with the advent of cloud computing. According to the United States' National Institute of Standards and Technology (NIST) Definition of Cloud Computing (NIST SP 800-145), a cloud PaaS service is the capability provided to a consumer of the service to deploy consumer created or acquired applications using programming languages, libraries, tools, and services provided by the PaaS service provider. This definition provides a general overview of the PaaS service being developed in the URBANE project that has been described previously in this document.

Such platform services, facilitate migration to PI logistics operations in urban settings by providing LSPs the tools needed to develop and deploy scalable Logistics as a Service applications without having to worry about integration and dynamic management of sensor-enabled urban infrastructures that comprises the infrastructure as a Service layer of an urban cloud model. For example, a cargobike service provider performing last-mile delivery services within a city would be able to use the PaaS services to monitor the delivery performance of its workforce, predict failure to deliver situations due to congestion, accidents, or other delaying situations and design rerouting options to eliminate the delays. The service provider could also integrate with the PaaS blockchain and smart contracting services to create a smart contract model that, when the platform is notified of a successful delivery, the delivery person's account is credited, and a payment is executed.

With respect to the PI, a functional PaaS coupled with a true urban Infrastructure as a Service capability allows logistics operations to be managed in a manner mirroring how the digital Internet operates through cloud infrastructure. Shipments can be tracked in a distributed manner, infrastructures allocated and "scaled" based on flow demand, and pricing for usage can be allocated efficiently. The blockchain non-repudiation layer of the PaaS ensures that deliveries and other contracted events are documented and, if smart contracts are enabled, then automated bonus/malus, payments, and other operational actions can be executed in an automated manner. While the existence of a PaaS and IaaS structure are not required for

[4] Regulation (EU) 2016/679, European Parliament, Council of 27 April 2016, http://data.europa.eu/eli/reg/2016/679/oj
[5] Decentralized Identifiers (DIDs) v1.0, World Wide Web Consortium (W3C), thttps://www.w3.org/TR/did-core/
[6] Verifiable Credentials Data Model v1.1, W3C, https://www.w3.org/TR/vc-data-model/

implementing either the PI or the digital Internet, as has been seen with the implementation of cloud services for the digital Internet, their availability eases the setup of innovative operational approaches and facilitates payment for only those services used.

6 Concluding remarks

The development of the DT and blockchain technologies has opened new opportunities for cities' transition to PI-inspired last mile logistics. To address the barriers to PI adoption, a comprehensive approach is necessary for PI projects on a Pan-European level. This approach should address the various challenges posed by technical complexity, lack of standardisation, upfront investment costs, regulatory, legal and cultural barriers. URBANE project's PaaS envisions to lift the PI adoption barriers by combining DT and blockchain technologies. In the current article, a presentation of the first results is given, including the main development directions for two of the core technological tools: *i)* DT platform as well as *ii)* the Blockchain-supported AI-enabled Smart Contracts and Decentralized Identity Management technologies. Numerous challenges remain ahead for the URBANE project to accelerate the adoption of the PI vision and bring emerging innovative logistics solutions to real-world application, including data sharing governance mechanisms, the introduction of automated vehicles and transforming logistics hubs to smart PI-nodes. However, we believe that these challenges can be overcome and that the results of the effort to overcome them will lead to positive outcomes for cities, citizens, LSPs, and the environment.

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