Interconnecting Urban Networks: A Novel Approach to Digital Twins Through GlassBox Adaptation

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Abstract: Smart cities are transforming urban living by leveraging technology and data to optimize urban services, to improve resource efficiency, and to promote sustainability. Urban Digital Twins (UDTs) promise to play a central enabling role in this transformation. However, state-of-the-art digital twin models still have to address significant challenging issues, particularly in terms of interoperability and integration with complex and multilayered (often legacy) urban systems. Some emerging approaches rely on specific standards and ontologies, creating "information silos" peculiar to each digital twin solution. After discussing the related and still open technical challenges, this paper proposes a novel extension of the GlassBox urban simulation model to conceptualize a city as a multilayered network, where nodes can be entities at different levels of granularity, such as a single building, a urban energy network, or even an aggregated urban area. Our proposed solution aims to ensure interoperability between these layers by enabling seamless real-time data exchange and optimized resource management. Furthermore, integration between layers such as energy, transportation, and water is essential to ensure data synchronization and provide the basis for more advanced smart city services, e.g., energy consumption/production prediction. To practically exemplify the advantages of the proposed approach, our innovative model is also illustrated when supporting a case study that focuses on urban transportation systems.

1 INTRODUCTION

Smart cities are revolutionizing urban living by leveraging technology and data to optimize services, to enhance resource efficiency, and to promote sustainability. A cornerstone of this transformation is the development of UDTs, i.e., dynamic digital replicas that model real-world urban systems by using simulation models coupled with data-driven models based on machine learning fed by significant flows of real-time data (Thelen et al., 2022). These tools enable simulation, analysis, and prediction, by providing essential insights for planning and decision-making. Various global cities are developing UDTs for specific needs: Singapore uses geospatial data and IoT for urban planning and disaster management; Rotterdam focuses on climate resilience with hydrological models; Cambridge optimizes transportation by analyzing traffic and mobility. In Italy, the Digital Twin of Bologna stands out as a key initiative. Despite their potential, current digital twin models face significant challenges, particularly in achieving seamless interoperability and in integrating complex multilayered urban systems. Most approaches rely on specific standards and descriptors, leading to fragmented "information silos" that obstruct communication and data sharing across systems. Addressing these issues requires a "system of systems" approach to fully capture the interdependencies of urban environments and sub-systems, from individual buildings to city-wide networks (Mihai et al., 2022).

In this context, simulation models emerge as a foundational tool, offering simplified representations of urban dynamics that can be scaled and enriched with real-world data. Looking beyond traditional urban studies, insights can also be drawn from other fields where simulation models have been successfully developed to represent complex systems. A notable example is the GlassBox model, whose development started in 2011 by Maxis for its flagship game

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SimCity, now in its 5th iteration (Maxis, 2012).

Urban simulation models like GlassBox, provide a foundation for modeling urban dynamics through simplified representations of units, resources, networks, and agents. However, GlassBox was designed for simulation environments and struggles with the variability and incompleteness of real-world data collected in real deployment environments of smart cities. To overcome these limitations, we propose an original extension of the GlassBox framework, conceptualizing cities as multilayered networks: nodes within these networks represent various levels of abstraction/granularity, from individual buildings to aggregated regions, and interact dynamically across layers such as energy, transportation, and water. In our design/implementation work, a critical challenge we had to address is enabling seamless communication between these layers, allowing sub-systems with different protocols and standards to exchange data effectively, which is crucial for optimized resource management and informed decision-making. Additionally, we tackled the challenge of multilayer integration, by ensuring that interactions across layers—such as energy demands influencing transportation or water systems—are synchronized to achieve optimized and coordinated responses.

For instance, the transportation network, encompassing both its physical (e.g., streets, traffic lights) and logical (e.g., public transport routes, schedules) components, serves as a foundational layer in UDTs. It integrates key urban services, such as electric vehicles (EV), charging stations, and environmental infrastructures, enabling a holistic digital twin representation. By modeling these interactions, UDTs provide a high-level perspective of urban interdependencies while ensuring the appropriate level of abstraction. This approach highlights the need to address integration challenges across multiple dimensions: horizontal interoperability within the same network, vertical multilayer integration across urban systems, and organizational interoperability between governmental structures.

In short and in summary, the primary contributions of this paper include:

- Analysis of UDTs from an interoperability and multilayer integration perspective, addressing the horizontal challenge of seamless data exchange across diverse subsystems with different protocols and the vertical challenge of synchronizing interactions between urban layers to optimize resource management and reflect system interdependencies.
- Extension of the GlassBox simulation framework for urban environments, adapting it to model cities as multilayered networks with varying levels of abstraction, in order to overcome the limitations of traditional simulation models and better represent the complexity of real-world urban systems.
- Proposal of a multilayered architecture that leverages adaptable data description systems and structured data publishing endpoints. This architecture is designed to handle the complexity of urban data flows, facilitating the integration of both simulation-related and real-time monitoring data within the context of UDTs.

The remainder of the paper is organized as follows. Section 2 introduces the background and key concepts of UDTs, with a rapid overview of the digital twin project of the city of Bologna, to contextualize the challenges of interoperability and multilayer integration. This section also reviews the state of the art, by focusing on how existing solutions approach these issues and outlining the foundational concepts behind the GlassBox model. Section 4 explains how the GlassBox model is originally extended in this paper to address the specific needs of real-world urban systems and demonstrates its application to the use case of transportation in Bologna. In addition, this section proposes an architecture for managing complex urban data, along with an implementation of the extended model, aimed at integrating both simulation-related aspects and real-time monitoring data. Section 5 provides a discussion of the proposed model, by evaluating its advantages and limitations in the context of UDTs. Related work (Section 3) and conclusive remarks and future work (Section 6) end the paper, by outlining a few directions that we are currently investigating as future work.

2 BACKGROUND

This section discusses key aspects of UDTs, interoperability as the basis for seamless communication, multilayered integration as a means of managing interactions between city sub-systems, and the importance of the GlassBox model as the basis for building a smart city framework. Together, these elements highlight the opportunities and obstacles to designing efficient and scalable digital twins for smart cities.

2.1 Urban Digital Twins

An Urban Digital Twin is a virtual representation of the physical assets, processes, and systems of a city or community, powered by real data and constantly updated. However, there is no universal approach or one-size-fits-all model for their implementation: in Italy, for example, the diversity of cities generates as many digital twin models, each adapted to territorial and operational peculiarities. This fragmentation causes a lack of interoperability between systems, amplifying the challenges related to multilayer integration, i.e., managing complex interactions between different layers of urban systems, such as energy, transportation, and waste management. The lack of interoperability and the complexities of multilayer integration highlight the practical challenges faced by cities in implementing UDTs (Ferré-Bigorra et al., 2022).

Globally, several cities worldwide have developed Urban Digital Twins tailored to their specific needs. Singapore's "Virtual Singapore" (Authority, 2014) integrates geospatial data, real-time IoT inputs, and simulations to support urban planning and disaster management. Rotterdam's UDT (for BOLD Cities, 2025) focuses on climate resilience, using hydrological models and environmental data to enhance flood risk management. In Cambridge, a digital twin (Cambridgeshire, 2025) optimizes transportation and mobility by analyzing traffic flow, public transit, and pedestrian movement to inform urban planning decisions.

Following these international examples, Italy is also making strides in the field of UDTs, with the Digital Twin project of Bologna standing out as a significant initiative. This project focuses on developing a comprehensive Data Platform, hosted on CINECA's cloud infrastructure and leveraging FBK's DigitalHub, to harmonize data from diverse systems and ensure seamless interaction between urban layers such as energy, transportation, and healthcare. The platform supports the collection, correlation, integration, visualization, and analysis of city data, empowering stakeholders like the Municipality of Bologna and its subsidiaries to efficiently process and analyze data from various sources, including legacy systems, IT platforms, and IoT solutions. Developing Bologna's UDT involves several significant challenges, particularly during the design and development phases. One major challenge is building an ontology for the UDT, a "semantic model" to optimize data acquisition, storage, and analysis. Urban infrastructure, often operates independently, each following specific rules and technologies.

For instance, in the context of mobility, difficulties arise when attempting to integrate data from various transportation systems, such as public transit schedules, shared mobility services (e.g., bike-sharing, carsharing), and real-time traffic information from IoT sensors. Each of these systems may use different data formats, protocols, and standards, making it complex to create a unified view of the city's mobility network. Moreover, the multilayered nature of urban systems becomes evident when examining how an increase in EV adoption impacts both mobility and energy demand. A rise in EV usage could strain the electrical grid during peak hours, potentially leading to localized shortages in charging availability. This, in turn, influences transportation patterns, as users may adjust their routes or schedules based on the accessibility of charging stations. Adding to the complexity of these interconnected systems, non-electric vehicles contribute to air pollution, which can be monitored through sensors. The resulting data, often generated in diverse formats, requires harmonization to be effectively integrated into the broader dataset representing the city's dynamics.

2.2 Most Open Challenges in Interconnecting Urban Networks

2.2.1 Interoperability

Interoperability refers to the capability of two or more networks, systems, devices, applications, or components to exchange and readily use information securely, effectively, and with little or no inconvenience to the user (Brutti et al., 2018). UDTs and smart cities face significant interoperability challenges across multiple levels. These challenges stem from the heterogeneous nature of urban systems, each with its own technologies and data standards (Quek et al., 2021). Existing interoperability approaches can be categorized into syntactic, semantic, technological, and organizational dimensions (Hatzivasilis et al., 2018), each addressing different layers of integration challenges within complex urban ecosystems.

Syntactic interoperability focuses on establishing common data formats and communication protocols to enable basic data exchange between systems (Aydin and Aydin, 2020). Standardized data models, such as XML or JSON, and widely used communication protocols like Message Queuing Telemetry Transport (MQTT) protocol or REST APIs (Representational State Transfer Application Programming Interface) facilitate this layer of interoperability by ensuring that data from one system can be transmitted and understood by another. However, while syntactic approaches address structural compatibility, they do not resolve deeper issues related to the meaning or context of the data that are exchanged (Veltman, 2001).

Semantic interoperability, on the other hand, aims to ensure that data exchanged between systems are not only structurally compatible but also contextually meaningful (Pliatsios et al., 2023). This involves the use of shared vocabularies, ontologies, and metadata standards to define the meaning of data. For example, semantic frameworks like the Web Ontology Language (OWL) or Next Generation Service Interface - Linked Data (NGSI-LD) [1], which supports linked data and contextual information, allow different systems to align their understanding of key concepts, such as energy consumption or occupancy rate, ensuring that data can be interpreted and utilized consistently across diverse systems. Despite the advantages, (Rahman and Hussain, 2020) underline significant challenges, including managing semantic heterogeneity due to differences in ontologies and terminology adopted by different vendors, as well as the absence of universal standards for data representation.

Technological interoperability focuses on the seamless integration of systems at the infrastructure and protocol levels, ensuring that devices, networks, and applications can communicate and exchange data efficiently. This dimension addresses compatibility in terms of hardware interfaces, network configurations, and data transmission protocols. It often involves adopting common communication technologies such as Bluetooth, Wi-Fi, or LoRaWAN (Long Range Wide Area Network), as well as widely accepted network standards such as Transmission Control Protocol/Internet Protocol (TCP/IP). Technical interoperability is essential to ensure that diverse systems within urban ecosystems, such as those in smart cities or digital twins, can interact without requiring significant customization or modifications.

Organizational interoperability extends beyond technical alignment to address the coordination of processes, policies, and governance structures between different stakeholders and systems (Hardi et al., 2023). This involves establishing agreements on data-sharing policies, access control mechanisms, and privacy standards to enable secure and compliant data exchange. Frameworks like the General Data Protection Regulation (GDPR) in the European Union highlight the importance of organizational alignment, ensuring that interoperability respects ethical and legal boundaries. Collaborative governance models, such as public-private partnerships, can also play a crucial role in aligning the objectives and operations of disparate urban systems.

Hybrid approaches that combine these dimensions, are often necessary to tackle the layered complexity of urban systems. For instance, middleware platforms can act as intermediaries, providing syntactic translation and semantic alignment while enforcing organizational policies. Similarly, emerging technologies like data spaces and digital platforms, such as Gaia-X in Europe (Tardieu, 2022), aim to create ecosystems where interoperability is inherently supported through shared infrastructure and standards.

As a side effect of these factors, the lack of established industry standards and common practices specific to UDT applications highlights the critical nature of interoperability in this field. This challenge is amplified by the need to integrate diverse urban systems, ranging from transportation to energy grids, into a holistic and unified digital representation.

2.2.2 Multilayer Integration

Multilayer integration poses a significant challenge in the creation of UDTs, as it involves managing the complex interactions between various layers of urban networks while preserving the unique dynamics and critical details of each layer (Peldon et al., 2024). Urban systems are inherently multilayered, encompassing sectors such as energy, transportation, water, waste management, and more. Each of these layers operates with distinct physical infrastructures, functional dynamics, and temporal behaviors, yet they are deeply interconnected (Aleta et al., 2017). The challenge lies in capturing these interdependencies in a unified framework without oversimplifying individual layers or losing the granularity necessary for accurate analysis and decision-making.

An approach to multilayer integration is the adoption of hierarchical modeling frameworks (Lu et al., 2020), where each layer is represented with a level of abstraction appropriate to its function, while maintaining links to more detailed submodels. For example, energy systems might be modeled at a high level as grids or hubs, but with the ability to drill down into finer details, such as individual solar panel outputs or battery storage levels, when needed. However, aggregated models at higher levels may overlook important local dynamics, such as fluctuations in solar panel output or energy storage levels, which can lead to inaccuracies in predictions.

Data synchronization and alignment are also critical for multilayer integration (Shih et al., 2015). Different layers often operate on diverse temporal and spatial scales—transportation systems might generate data in seconds, while water management systems might use hourly or daily data. Integrating such data streams requires techniques like temporal resampling, spatial aggregation, and interpolation to harmonize datasets without losing essential information.

[1]NGSI-LD is a specification developed by ETSI (European Telecommunications Standards Institute) for data management and exchange in the context of smart cities and the Internet of Things (IoT).

Additionally, cross-layer optimization algorithms play an important role in achieving effective integration. These algorithms enable the UDT to analyze and manage trade-offs between layers, ensuring that decisions in one domain consider their impact on others (Castelli et al., 2019). For example, optimizing energy usage might involve not only balancing supply and demand but also adjusting transportation schedules to reduce peak loads on the grid. However, cross-layer optimization algorithms have to face still open challenges such as computational complexity and conflicting objectives between different domains.

Finally, the visualization of multilayer interactions is a key aspect of achieving a comprehensive understanding. Advanced visualization tools, such as 3D city models or interactive dashboards, can help stakeholders navigate the complexity of integrated systems. These tools provide intuitive representations of data flows, dependencies, and scenarios, empowering planners and decision-makers to explore the effects of interventions across layers. However, a significant limitation of many current visualization systems is their passive nature—they often display multilayer interactions but do not allow users to directly interact with or manipulate the data. This lack of interactivity restricts the ability to test scenarios, explore dynamic responses, or implement real-time interventions, thereby reducing the practical utility of the insights provided.

Further complexity is given by coordination across neighbor operators that manage complex digital twin infrastructures with specific integration formats. The lack of a de-facto industry standard, as previously noted, makes it very complex to design and implement efficient interactions across digital twins.

2.3 Glassbox

The Glassbox Simulation Engine is an advanced simulation engine developed by Maxis in 2011, for use in SimCity (2013). Presented at GameDeveloperConference 2012 it displayed an innovative and general-purpose approach to the simulation environment. Designed to provide a rich and dynamic simulation experience, Glassbox stands out for its ability to manage large volumes of data and create highly reactive and interconnected virtual systems in a 2013 technological infrastructure. With its flexible architecture, the engine was conceived not only to support the iconic city-building game but also a variety of other simulation titles, making it a versatile tool for creating complex interactive experiences.

The core of Glassbox operations is the detailed management of resources, units, maps, networks, agents, and rules (Figure 1). Resources, such as oil, electricity, wood, and water, are fundamental elements within the game, managed through containers called "bins" that track their quantity and distribution. Each unit, representing entities such as houses or factories, interacts with resources through the rules that describe the needs and conditions specific to each unit in the game as well as its production. These needs and resources move along specific networks. The simulation is further enriched by the presence of maps, which represent environmental variables such as the availability of natural resources, pollution, and land desirability, in general factors that influence the decisions of agents and the evolution of the virtual system.

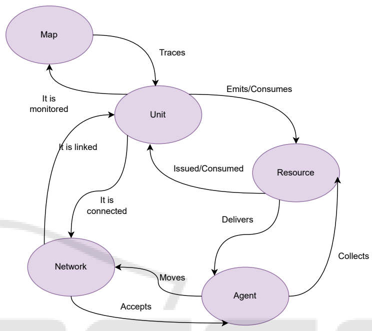

Figure 1: Glassbox Model.

One of the distinctive features of Glassbox is its ability to easily adapt to new game dynamics, thanks to a system that manages behavior rules defined by customizable scripts. These rules allow for accurate simulation of resource transfer and transformation, creating a complex and interconnected ecosystem where every action has a tangible impact on the game environment. This approach, which integrates real-time data management with the simulation of emergent behaviors, enables players to interact with a virtual world that dynamically responds to their choices.

3 RELATED WORK

The growing complexity of urban systems and the increasing reliance on digital twins in smart city frameworks have highlighted interoperability and multilayered integration as critical challenges (Atkinson et al., 2022). Existing solutions often fail to enable seamless integration and communication between different platforms and models, limiting their potential to create interconnected urban ecosystems (Quek et al., 2021). Among the solutions proposed to address this issue is FIWARE (FIWARE Foundation, 2024), an open-source platform that leverages standardized frameworks, such as NGSI-LD, to enable the management and exchange of context data (Bauer, 2022). FIWARE aims to provide a flexible and scalable foundation for developing urban applications, yet its integration with other platforms often uncovers significant limitations. The integration of FIWARE with other platforms, such as robotic operating systems like ROS 2, requires significant development effort, especially in transforming and mapping data between disparate formats and standards. Additionally, while NGSI-LD offers a structured approach to context data management, its reliance on specific standards can result in incompatibility with alternative systems or legacy infrastructures that employ different schemas or data structures (Viola et al., 2019; Abid et al., 2022; Kumar et al., 2022). This dependency can impede seamless data exchange, necessitating additional transformations that add to the complexity and maintenance overhead of these systems. Moreover, maintaining and updating the libraries required for these transformations introduces further challenges, as any evolution in data standards or platforms may demand corresponding updates, thereby increasing the workload for developers and system operators.

UrbanSim (Waddell et al., 2018) and CityZenith (Mukherjee et al., 2014) exemplify the interoperability and multilayered integration challenges faced by urban modeling platforms. UrbanSim excels in simulating urban dynamics by integrating land use, transportation, and economic data, but its reliance on highly detailed, domain-specific datasets complicates integration with other systems and increases computational demands, particularly for large metropolitan areas. Similarly, CityZenith provides advanced 3D visualization and analytical tools for city management but remains limited in scalability and interconnectivity, restricting its effectiveness in enabling inter-city collaboration and integrated urban planning. Ontologies play a crucial role in addressing interoperability challenges by providing a structured framework for representing and integrating diverse data sources. They define a common vocabulary and relationships, enabling different systems to exchange and interpret information effectively. However, semantic interoperability often remains limited due to the fragmented nature of urban systems, where data is organized in domain-specific ways without a shared framework. This creates barriers for cross-sector communication, particularly in smart cities. Additionally, integrating multiple ontologies or aligning them across systems demands significant resources, as each system's unique schemas require complex and time-consuming adaptations(Karabulut et al., 2024). CityGML is a standard for representing three-dimensional urban models that aims to facilitate interoperability and multilayered integration. However, practical implementation of CityGML often encounters difficulties due to variations in the ontologies and data schemas employed by different systems, which can lead to inconsistencies in data exchange(Buyuksalih et al., 2017). Ontological frameworks like RDF (Resource Description Framework) offer a flexible mechanism for representing geospatial data, but they frequently require complex customization to integrate real-time data streams, such as those related to urban mobility or environmental monitoring.g. These adjustments demand significant expertise and computational resources, further complicating efforts to establish interoperable and multilayered networks of UDTs.

4 OUR ORIGINAL PROPOSAL FOR EXTENDING THE GLASSBOX MODEL

Our proposal originates from the Glassbox basic model, but takes into consideration that, while Glassbox was designed to act on a simulation environment where players could never "rewind" and see what a different decision would have brought, a UDT has to cover both simulation-related aspects as well as in-the-field flows of monitoring data, which can not be presumed to be in real time but often aggregated over non homogeneous time periods.

For these reasons our Glassbox-extended model uses the same concepts (resources, units, maps, networks, agent and rules) but adds the "metrics" aspect to them, defining snapshots of the various elements valid for specific timeframes. For example, a unit would not just be an entity associated with a given set of resources and a given set of networks, but also define a metric, a value and a timeframe for which that value is valid. The same happens with the maps: the global situation is defined by temporal and spatial aggregations that represent the current state of the system. Thus, maps are not limited to describing geographic locations or the physical distribution of resources, but incorporate a set of temporal metrics associated with each node in the network. For example, an energy map might include data on generation capacities, consumption flows, and storage levels, each with values valid for specific time intervals, such as hours, days, or weeks.

Similarly, networks are no longer static, but dynamic, updated through real-time data streams or periodic aggregates. Each link in a network is enriched with parameters that define the context of interactions, such as maximum transport capacity, energy losses, or latency times. These parameters are constantly reassessed in light of systemic changes, allowing more realistic simulations and prediction of bottlenecks or inefficiencies.

Building upon this dynamic nature, our model conceptualizes the network as not just a representation of connections and flows, but as a modular framework that can operate at multiple scales. A critical advantage of this approach is its ability to support cross-city interoperability. Using the inherent flexibility of the network model, entire systems, such as energy grids or transportation networks, can be abstracted into a single node capable of emitting and receiving resources. This abstraction enables seamless integration between urban systems of varying complexity or granularity, fostering scalability and collaboration across different cities or regions. At the same time, the model retains the capacity to analyze and optimize interactions within each subsystem, maintaining a balance between global and local perspectives. To support this dual-level functionality, the model incorporates global and local metrics as key elements for capturing and analyzing system states. Global metrics provide a macroscopic view by summarizing the overall state of the system at regular intervals, forming the basis for historical analysis and validation of simulation results. Local metrics, in contrast, detail the specific states of subsystems or individual nodes, such as buildings or electric vehicle charging stations, enabling precise optimization and decision-making at a granular level.

Finally, the concept of “rules” has been expanded to integrate more complex conditional logics that govern interactions among system components. These rules define not only the flow of data between entities but also incorporate temporal constraints and critical thresholds, reflecting both urban realities and simulation requirements. For instance, a rule might specify that during peaks in energy demand, certain urban sectors should be prioritized for energy distribution based on dynamically calculated criticality metrics.

4.1 Architecture

In order to define a flexible architecture that can be helpful in a complex data landscape like the UDT, it is important to leverage both adaptable data description systems as well as structured data publishing endpoints. Figure 2 illustrates this architecture, which is structured into four main layers:

- **Presentation Layer:**This layer is responsible for interfacing with external systems and users, ensuring that data are both ingested and accessed in a standardized and meaningful way. It is divided into two sub-layers:
  - **Semantic Ingestion Layer:** this sub-layer focuses on the semantic description of datasets and data streams entering the platform.
  - **Unified Data Access Layer:** this sub-layer provides standardized access to data for external systems or users. It ensures that data output is consistent, secure, and accessible via well-defined APIs or protocols.

  The Semantic Ingestion Layer enriches incoming data with metadata and semantic descriptions, while the Unified Data Access Layer uses this information to provide consistent and structured access via standard APIs and protocols.
- **Application Layer:** this layer is the core of data processing, where ETL (Extraction, Transformation, and Load) operations are defined and executed. In addition,there are modules for planning and coordinating workflows, making sure that ETL processes are executed at the right time and in the right order;
- **Data Layer:**this layer is responsible for managing, storing, and accessing raw and transformed data. Its main function is to ensure that information is organized in a scalable, secure and efficient manner, supporting analysis, simulation and visualization operations.
- **Integration Layer:** this is a vertical cross-cutting layer that spans across all other layers. It is designed to facilitate advanced data operations, such as simulations, evaluations, and integrations with external systems. More specifically, it is responsible for elaborating the rules to apply in simulations and advanced data operations. The simulation context depends on the descriptions of the rules and semantic metadata from the Semantic Ingestion Layer, on raw and processed data from the Data Layer, and on transformation logic and processing workflows from the Application Layer. Once the simulation context is ready, the Integration Layer communicates with the Unified Data Access Layer to ensure that the processed data and results are made accessible to external systems or users in a standardized and secure way. Moreover, this layer monitors and tracks the flow of data and the operations performed in the various layers.

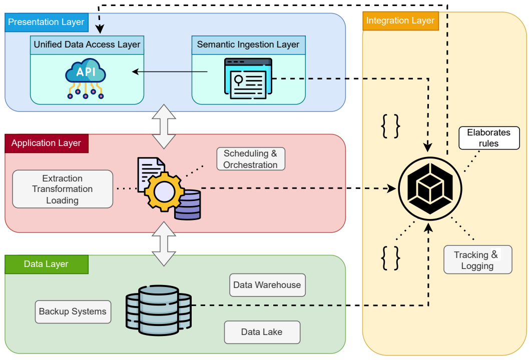

Figure 2: Architecture of the extended Glassbox Model.

4.2 Implementation

Following the structure of the previously defined architecture, the core of the infrastructure is a MediaWiki installation with a semantic module, which enables the use of semantically enhanced templates for creating data descriptors. This forms the foundation of the Semantic Ingestion layer within the Presentation layer, providing tools for non-technical operators to describe datasets in various formats. The templates facilitate the correct definition of the many descriptive aspects of the model, enabling both internal and external descriptor definitions. In addition to the definition of the models, the tool also collects the rules for the simulation itself.

The Unified Data Access layer, also part of the Presentation layer, ensures that data is exposed through standard APIs and formats, making information reusable and integrable into common libraries and tools. Examples include the publication of maps as Web Map Service (WMS) raster layers, allowing navigation of complex datasets as simple visual layers, while maintaining flexibility for reuse in new, complex visualizations. Real-time calculations and updates are made available via MQTT, supporting both 2D and 3D visualizations of simulated items.

The Application layer is where workflows for data ingestion, transformation, and distribution are managed. Tools such as OpenMetadata and CKAN (CKAN, 2025) (Comprehensive Knowledge Archive Network), operating within this layer, enable seamless internal and external descriptor definitions. OpenMetadata supports internal use cases, while CKAN facilitates external data sharing. These tools ensure that data ingestion and management processes are streamlined, supporting a wide range of applications and user needs.

The Data layer is responsible for raw data storage. MinIO, an Amazon S3 replacement, is used in this layer to store temporary datasets. Geographic data is stored for example in the netCDF format, enabling efficient management and retrieval of structured data, while purely tabular data is stored in parquet format. This layer provides the foundational infrastructure required for handling large volumes of data, supporting both simulation and visualization processes.

The Integration layer handles backend calculations and the simulation engine, enabling complex data evaluations. Libraries such as pandas, geopandas, and movingpandas help processing and analyzing data, ensuring that disconnected simulations can be visualized in various formats through the Unified Data Access layer. The simulation itself is based on a custom developed engine, relying on the original concepts of GlassBox but enabling the tracing of the metrics. This is important for the quality analysis of the model as well as of the collected data: a discrepancy of the metrics could have origin in a wrong description of the dataset, but also in an incomplete coverage of the data available in the platform. This approach decouples the simulation engine from the visualization process, enabling flexible visual representation, whether through 3D analysis tools or simpler 2D maps for broader accessibility.

Finally, the infrastructure also supports the dynamic growth of an emerging ontology for the city. As new datasets are integrated and new requirements arise, the ontology evolves to interconnect data over time, progressively enriching the city's description and supporting an adaptable data ecosystem.

4.3 Model Applied to the Use Case

The use case we will analyze is mobility, which is one of the core infrastructures of the city. This use case focuses on how urban mobility systems interact dynamically with other urban layers, such as energy and environmental factors. Using the extended GlassBox model, it is possible to describe its elements with precision. The units are all nodes that interact with the networks. Examples include:

- **Traffic Spire:** Sensors located along roads that monitor the flow of vehicles in real time. Each Traffic Spire is a unit that collects data on vehicles and records them as resources (number of vehicles).
- **Charging Stations:** Units that provide power to EV. The associated resource is the electrical capacity available for charging.

Each of these units interacts with the networks through defined rules, contributing to data collection and analysis. For example, traffic spires measure vehicle flow and serve as input to air quality calculations. Similarly, EV chargers interact with the electric grid to monitor energy consumption and demand patterns.

Resources tracked include:

- **Car (Car.carbon and Car.electric):** Each car is a numeric entity that is tracked through the road network. The entry of a car into a unit, such as a Traffic Spire, is recorded as an incoming resource.
- **Electricity:** The capacity of charging stations and of the electric network is limited.

Maps are visualizations that represent these resources, providing a comprehensive view of the entire urban system.

- **Air Quality Map:** Shows pollution levels in different areas of the city.
- **Noise Map:** Shows noise pollution levels in different areas of the city.

Networks in this context represent the set of connections between units that collect, process, and share information or resources within the city. The networks involved include

- **Road Network:** Representing the infrastructure for vehicles, pedestrians, bicycles, and public transport.
- **Electric Grid:** Supporting electric vehicle (EV) infrastructure, including charging stations and energy distribution.

Municipality open or internal data sets are often structured as CSV files in various formats, which can be normalized according to the Extended GlassBox Model, as described in Table 1.

Table 1: Definition of a Traffic spire csv file - Unit.

Field	Type	Description
ID	String	Identifier for the spire
Position	GeoPoint	Coordinates of the spire
Time	Timestamp	Timestamp of the beginning or end of the collected metric
Vehicles	Integer	# of vehicles sensed by the device in the last valid timeslot
Accuracy	Float	% of validity of the collected metric (Vehicles)

Table 2 represents the csv file structure for the data definition of a static sensor-based Air Quality Map.

In a typical smart city scenario, Traffic Spires along the urban roadways detect an increase in traffic.

Table 2: Definition of an air quality csv file - Map.

Field	Type	Description
Area	GeoPolygon	Area for the data collection
Station	GeoPoint	Location of the station
StationName	String	Name of the station
Pollutant	String	Identifier of the measure
Time	Timestamp	Timestamp of the beginning or end of the collected metric
Value	Float	# measure of the pollutant during the valid timeslot

Listing 1 shows a practical representation of of a rule applied to the Traffic Spire unit. As a car (via) enters the area monitored by a Traffic Spire, it is immediately detected by the sensor (appliesTo). The Traffic Spire records the number of vehicles passing through (log resource: Vehicles and Vehicle.{type}), along with the timestamp for each passage (-timestamp=Time). This means that as the vehicle moves through the monitored area, it is counted as an entering resource (local Car.{type} in 1) and contributes to the overall traffic flow data. Once the vehicle enters the area, it is ”destroyed” in the sense that its data is finalized and recorded as an exiting resource, which helps calculate the impact on the traffic conditions at that moment. A new vehicle is generated and sent as output of the node itself (agent Car.{type} out 1).

Listing 1: Unit Rule Code Example - Spire Trace.

```
unitRule spireTrace
    appliesTo TrafficSpire
    via Car
    using RoadNetwork
    local Car.{type} in 1
    agent Car.{type} out 1
    log -timestamp=Time Vehicles 1
    log -timestamp=Time Vehicles.{type} 1
end
```

At the same time, air quality monitoring stations report a rise in PM2.5 levels, measuring safety limits. Listing 2 represents the rule applied to a single agent during its lifetime defining that every 10 timeslots (repeatAfter 10) if the agent contains a carbon-fueled car (condition resource=Car.carbon), the AirQuality map(-map=AirQualty) will increase its measure of pollutants by a specific amount in a specific area round the position of the agent(area pm10 10 5, area pm5 15 10, area pm25 12 15). This generated air quality map can be compared to the sensor based air quality map coming from institutional providers in order to validate the simulation.

Listing 2: Unit Rule Code Example - Car Pollution.

```
agentRule carPollution
    condition resource=Car.carbon
    repeatAfter 10
    area -timestamp=Time -map=AirQuality pm10 10 5
    area -timestamp=Time -map=AirQuality pm5 15 10
    area -timestamp=Time -map=AirQuality pm25 12 15
    area -timestamp=Time -map=NoiseMap noise 8 10
end
```

Charging stations attract EV, which, in order to refuel, generate increased traffic in their vicinity, often critical during rush hour or in areas with limited road infrastructure. This congestion involves not only electric vehicles, but also internal combustion vehicles, which, stuck in traffic, release pollutants such as PM2.5 and NOx, worsening air quality.

Moreover, during peak traffic periods, charging stations can experience very high energy demand, creating pressure on the remaining capacity of the local electric grid, especially if multiple stations in the same area are overloaded. Pollution data, resulting from road congestion, can inform policies to encourage electric vehicle adoption, such as charging incentives or the introduction of low-emission zones (LZs) in highly polluted areas. An example of a unit rule applicable to charging stations can be seen in Listing 3.

Listing 3: Unit Rule Code Example - Charging Station.

```
unitRule charginStation
    appliesTo ChargingStation
    via Car
    using TrafficNetwork
    using ElectricGrid
    local Car.electric in 1
    local Electricity 1000
    wait 14400
    agent Car.electric out 1
    log -timestamp=Time -event=in Car.electric 1
    log -timestamp=Time -event=out Car.electric 1
end
```

This process allows tracking of the interactions within and across networks over time. Additionally, the collected metrics support the validation of the simulated model. This interconnectedness between networks and data structures facilitates complex decision-making and validation processes.

5 DISCUSSION

The extended model we propose addresses both horizontal and vertical challenges in an integrated manner, focusing on solving interoperability and multi-level integration issues within a complex urban digital context. To tackle the horizontal interoperability challenge, our approach introduces the concept of metrics for each entity (units, networks, maps) within the urban network. The metrics are not only numerical values but also integrate temporal and spatial dimensions, providing dynamic validity to the information. For example, considering the previously discussed mobility example, the flow of vehicles through an intersection is represented not only as a number (e.g., the number of cars per hour) but also with a temporal connotation (e.g., during rush hour) and spatial connotation (e.g., in a specific area). This approach enriches the data with contextual information, making it more meaningful and facilitating the integration of mobility systems using heterogeneous protocols and formats, such as sensor data, traffic management APIs and public transportation systems.

The simple GlassBox model acts as a "*lingua franca*" that facilitates data exchange between technically diverse systems. The temporal and spatial metrics added by our proposed extension help overcome semantic barriers by contextualizing the data and aligning systems with different ontologies or vocabularies. In this way, semantic interoperability is not just about "sharing" data, but about understanding and consistency in interpreting information, improving its usability and the ability to integrate it without losing meaning.

Although metrics do not directly solve organizational challenges, they provide a solid technical foundation for collaboration among different stakeholders, such as public transportation authorities, private operators, and urban infrastructure managers. The standardization, both syntactic and semantic, enabled by metrics reduces ambiguities and conflicts that typically hinder cooperation among different entities, promoting the adoption of interoperable frameworks at the organizational level as well. Additionally, the introduction of data management rules, which include the temporal and spatial validity of information, helps apply clearer management policies, increasing the reliability of shared data and the level of collaboration among various stakeholders.

Regarding the vertical challenge of multilayer integration, our model focuses on managing the interactions among the different components of the urban system without sacrificing the necessary granularity for accurate analysis. In this context, the idea of "networks of networks" fits as a key principle: each network (such as energy, transportation, water) is not just seen as an isolated entity, but as part of a larger network that dynamically interacts with other networks. Local metrics make it possible to analyze the behavior of individual units (e.g., energy flows at an EV charging station), while global metrics provide an overall view of the state of the system, enabling forecasting and resource optimization at the macro level. These metrics, which are constantly updated, allow the dynamics between layers to be synchronized, overcoming the challenges associated with data from systems operating on different temporal and spatial scales. In addition, inter-domain optimization rules, which balance the trade-offs between different domains, allow us to address cross-domain optimization challenges while maintaining a holistic view of urban interdependencies. In this way, our model concretely addresses the difficulties arising from complex multilevel interactions, enhancing the ability to make timely and informed decisions.

6 CONCLUSIVE REMARKS AND FUTURE WORK

In this work, we have proposed an extended digital twin model based on an existing simulation model called GlassBox, in order to address the challenges of interoperability and multilevel integration in complex urban contexts. Our approach relies on introducing the concept of metrics for each entity within the urban network, while integrating temporal and spatial dimensions. This enrichment allows for a more precise and meaningful representation of information from heterogeneous systems, such as public transport or shared mobility systems. The proposed model aims to overcome the traditional limitations of digital twins by offering a holistic view of the city, which facilitates the integration of different urban infrastructures and networks.

The model presents several advantages. First, being simple and based on bottom-up modeling, it generates limited additional work/overhead and allows for scalable adoption in different urban contexts. The ability to model complex informational structures linearly enables addressing urban situations with various needs and characteristics, without compromising the consistency of the system. Finally, one of the most innovative aspects of this model is its ability to promote interoperability between UDTs, as each network can be represented by a single point, simplifying communication between diversified sub-systems.

However, our original model also has some limitations. The integration of data and metrics, while crucial for a comprehensive view, adds complexity to the model itself, making the management and maintenance of simulations more challenging, especially when dealing with constantly evolving environments.

Looking ahead, the next step will be to conduct a wide set of experiments to assess the effectiveness of our original model in real-world contexts. Validating the results obtained from simulations and case studies coming from cities, as well as the application of the model to datasets regarding the past, will provide valuable data to further refine our model.

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