An Urban Intelligence Framework for Cognitive Digital Twins: The Catania Case Study

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***Abstract*—We present an Urban Intelligence framework for the development of Urban Digital Twins in Catania (Italy). Integrating geospatial data, IoT sensing, predictive modelling, and decision-support tools, the platform enables real-time monitoring and data-driven governance for the sustainable and resilient management of urban systems.**

***Index Terms*—Urban Intelligence, Smart Cities, Urban Digital Twin, Microservices Architecture**

I. Introduction

The increasing complexity of urban systems, together with the challenges posed by climate change, digital transformation, and the need for more efficient and sustainable governance, requires the development of new paradigms for territorial management. In this context, the Urban Intelligence Science Hub for City Network (UISH) project is an integrated ecosystem of digital infrastructures, data, and advanced models aimed at building dynamic and predictive representations of cities. This contribution presents an innovative architecture developed for the pilot city of Catania (Italy), based on the implementation of Urban Digital Twins (UDTs), as advanced and continuously updated digital models of urban physical systems and their subsystems (mobility, environment, and built environment) [1]. These models enable the integration of heterogeneous data from multiple sources and support real-time analyses and predictive simulations, thereby fostering new approaches to urban planning and management.

II. Architecture

The proposed architecture is built upon a microservices-based infrastructure, easily deployable both on-premises and in cloud environments, ensuring scalability and interoperability. Geospatial data are managed, integrated, and maintained within intelligent Geographic Information Systems (GIS), capable of providing data access, visualization, and advanced analytics. Accessibility for non-technical users is ensured through the integration of WebGIS platforms that publish maps, data, analyses, and reports online. The user profiling functionalities allow for the assignment of specific roles and permissions. Within this framework, UDTs are not merely simulation tools, but genuine cognitive platforms capable of learning from data and supporting complex decision-making processes. The UDT ecosystem consists of several thematic Digital Twins designed to describe and address urban complexity, such as the Mobility Digital Twin (*DTMOB*), the Built Environment Digital Twin (*DTBUILT*), and the Environmental Digital Twin (*DTENVIRONMENT* or *DTAIR*), as shown in Figure 1.

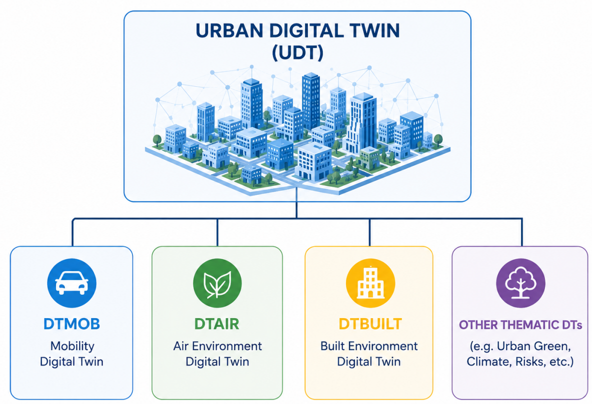

Fig. 1. Thematic Urban Digital Twins.

The data infrastructure represents the enabling core of the system and is based on the integration of environmental sensor networks and distributed Internet of Things (IoT) technologies. In particular, the system monitors parameters related to the built environment, mobility, air quality, urban greenery, climatic conditions, and exposure to environmental risk factors, including electromagnetic and radiological hazards. The integration of DTMOB functionalities with heterogeneous datasets is crucial to provide a robust Decision Support System (DSS) layer for strategic assessments. The developed system integrates field-collected data, forecasts, and simulations, making them uniformly available either on an area basis or through road-network graphs. In this context, road sensor data are used to calibrate Origin-Destination (OD) matrices [2]. Subsequently, traffic volumes and associated road emissions

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can be calculated for each road segment through macroscopic traffic macro-simulation. These emissions are then related to population presence estimates derived from mobile phone data and assigned to individual road links.

To enhance environmental representativeness and territorial monitoring capabilities, the CNR research team developed a deployment and management protocol for the air-quality sensor network, and implemented it with the support of the local transport company, whose vehicles and staff made it possible to deploy the sensors across the territory, enabling greater spatial coverage and an extended number of data collection sites. An advanced air-quality characterization system has been developed based on satellite observations and forecasting models, with the objective of building an integrated platform for acquiring, processing, analysing, and visualizing atmospheric pollutant data at high spatial and temporal resolution. The datasets include hourly concentrations of gaseous pollutants and particulate matter (NO_2, O_3, SO_2, PM_{10}, and $PM_{2.5}$) for the years 2024 and 2025, provided in netCDF format through the AIR-Portal-DDAC system. This platform applies downscaling techniques to regional forecasts produced by the European CAMS programme, adapting them to the urban scale through the integration of static information (land use) and dynamic information (meteorological data and in situ observations). Daily, monthly, and annual statistics (means and maxima) are generated. The representation of pollutant distributions through vector isolines and raster datasets enables intuitive interpretation within a WebGIS environment (https://uish.ifac.cnr.it). By querying grid cells within the study area, users can investigate relationships among pollutants, particularly the photochemical anti-correlation between NO_2 and O_3. The results are displayed through innovative visualizations, including three-dimensional radar charts and toroidal surfaces, highlighting both daily and seasonal variability.

The acquired data are integrated into an ecosystem of interoperable databases designed to manage multidimensional geospatial big data, historical time series, and real-time data streams. Different technologies are adopted according to the characteristics and requirements of the data, including relational and non-relational databases, file systems, asynchronous notification protocols, and dedicated data-ingestion systems [3]. A unified and standardized interface is provided through custom REST APIs. In this case, the main challenges addressed concern data quality, semantic standardization, security, performance requirements, and information governance.

From a methodological perspective, the project adopts a multidisciplinary approach that integrates numerical modelling, urban simulation, AI, and machine learning [4]. These methodologies support the development of predictive models for analysing complex phenomena such as pollutant dispersion, traffic dynamics, and the evolution of the built environment. The integration of multi-source and multi-fidelity data further improves simulation accuracy and enables large-scale optimization processes. Quantitative data are complemented by qualitative data derived from participatory approaches, implemented through Public Participation Geographic Information Systems (PPGIS) methodology and emotional mapping. Both enable the collection of georeferenced and interoperable information and allow direct input from those who experience the city and their perceptions, supporting an adaptive governance that is genuinely responsive to citizens' needs. A key component of the system is the Decision Support System (DSS), which transforms data and simulations into operational tools for decision-making. Through the DSS, alternative scenarios can be simulated, the impacts of urban policies and infrastructure interventions can be assessed, and emergency situations can be managed more effectively. The system also provides dashboards, synthetic indicators, and real-time analytical tools, acting as a strategic support instrument for public administrators and urban planners. From this perspective, Urban Digital Twins can be interpreted as true cognitive infrastructures for Public Administration, capable of transforming data into knowledge and knowledge into action. They enable a new form of data-driven governance based on predictive capabilities, continuous learning, and integration across different decision-making levels (strategic, operational, and emergency management). This evolution contributes to strengthening urban resilience and improving the quality of public services.

Moreover, the development of UDTs takes place within a complex and fragmented European regulatory framework, including rules on data protection, AI, and cybersecurity (such as the GDPR, Data Governance Act, and AI Act). This fragmentation can limit interoperability and scalability, highlighting the need for greater harmonization. Additionally, UDT adoption raises important legal and ethical issues related to privacy, algorithmic transparency, non-discrimination, and accountability in automated decisions. Therefore, it is essential to implement ethics-by-design and privacy-by-design approaches, along with governance mechanisms that ensure fair, secure, and responsible use of technology.

In conclusion, the work supports a shift towards Urban Digital Twins as evolving intelligence infrastructures, where semantic integration, meta-learning, and decision intelligence jointly enable scalable and adaptive urban governance and sustainable management of territorial systems.

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