A Multi-Dimensional Framework for Urban Digital Twins: The AVANT Approach

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Abstract—**This paper introduces a modular, multi-dimensional framework for Urban Digital Twins (UDTs) developed in the AVANT (IPCEI-CIS) project. It centers on three interconnected components: Citizen Twin (personalized services and behavior analysis), Government Twin (administration and asset management), and Territorial Twin (spatial-temporal urban data). The framework enables applications like land use monitoring, environmental tracking, traffic forecasting, and personalized eco-tourism, highlighting how their synergy improves user experience and policy-making.**

Keywords—Urban Digital Twin, Citizen, Government, Territory

I. Introduction

Urban Digital Twins (UDTs) [1] are key tools for evidence-based [2] and data-driven governance, improving public services, and supporting sustainable urban development. In the AVANT (dAta and infrastructural serVices for the digitAl coNTinuum) project (IPCEI-CIS) [3], we propose a flexible, modular framework leveraging digital twin technologies to help local governments and citizens understand, simulate, and manage urban complexity.

II. Objectives and Methodology

The AVANT Urban Digital Twin (UDT) framework aims to deliver interoperable, complementary tools, models, and methods for building digital representations of cities from multiple viewpoints. It is structured around three interconnected dimensions:

- **Citizen Twin** models the urban user, analyzing behaviors, needs, and interactions with city resources. It supports personalized services [4] for citizens and helps public authorities observe behavioral patterns to inform policy decisions—while preserving privacy [5].
- **Government Twin**: focuses on administrative processes, public services, governance policies, and the use of urban assets. Its goal is to improve transparency and efficiency at both strategic and operational level [6].
- **Territorial Twin**: geospatial core, offering a digital replica of the city. It integrates environmental, infrastructural, socio-economic, and mobility data over time and space. The Territorial Twin enables spatial-temporal analysis and supports predictive modeling and simulations, allowing stakeholders to anticipate future scenarios—such as mobility changes, environmental impact, or infrastructure stress—and test policies or planning strategies virtually before implementation [7][8].

The AVANT framework will be validated through a multi-layered approach combining technical testing, scenario-based simulations, and stakeholder engagement. Component testing will verify reliability and interoperability, while real-world scenarios will evaluate decision-support capabilities. User feedback and cross-validation with external datasets will guide refinements, ensuring both technical soundness and practical relevance for governance.

III. System Architecture and Data Governance in AVANT framework

From an implementation perspective, the AVANT framework adopts a **microservices-based architecture**, using **containerized services orchestrated via Kubernetes**. To ensure high availability, the deployment includes replication strategies for critical pods, allowing automatic failover and load balancing.

The **data ingestion layer** relies on the **Data Mashup Editor** tool from the **Digital Enabler suite** [9], which enables integration of heterogeneous data sources through a configurable interface. It supports various connectivity protocols, such as RESTful APIs and MQTT, for both structured and real-time streaming data.

Data harmonization and interoperability across the Citizen, Government, and Territorial Twin components are ensured through semantic alignment and shared data schemas, supported by a centralized metadata registry compliant with the DCAT-AP standard. Asynchronous communication between microservices is managed via message brokers (e.g., Apache Kafka), ensuring scalability and fault tolerance.

Due to the Citizen Twin's behavioral profiling features, the AVANT framework incorporates a **privacy-by-design approach** aligned with GDPR. User data—such as preferences, mobility patterns, and interaction history—is subject to pseudonymization, aggregation, and purpose limitation to reduce privacy risks. A key component is a **customized Citizen Data Vault (CDV)**, a secure, user-centric data store that gives individuals control over their

personal data. Through the CDV interface, citizens can grant or deny consent for specific data uses. Third-party services must explicitly request user authorization via the CDV before accessing data. This mechanism ensures **transparency, accountability**, and **granular consent management**, allowing users to see what data is accessed, by whom, and for what purpose. Role-based access control, auditing, and consent revocation are built into the data governance model to ensure ethical and legal compliance.

IV. Use Case Focus: Territorial TWIN

A key capability of the Territorial Twin is advanced **geospatial analysis**, integrating different data sources such as satellite imagery (e.g., Copernicus), historical orthophotos, thematic GIS layers, and in-situ measurements. This supports multiple urban use cases:

Change Detection: identifies land use changes, including unauthorized developments, loss of green spaces, new quarries, deforestation, and water-to-soil transitions.

Water Quality Monitoring: assesses large water bodies by measuring TSM, Chlorophyll, and CDOM to assess water health.

Soil Moisture Monitoring: detects drought effects, dryness levels, and desertification.

Flood Mapping: maps flooded areas, affected municipalities, and inundation boundaries.

Urban Traffic Analysis and Forecasting: combines real-time and historical data for short-term congestion prediction, scenario-based simulations, and pollution impact assessment.

These capabilities enable authorities to conduct multi-temporal and what-if analyses, validate results via interactive dashboards, and integrate insights into urban planning and governance.

V. Integrated Use Case: Personalized Eco-Tourism through Digital Twin Synergy

A representative integrated use case demonstrates how the three types of digital twins can work together to enhance user-centered access to local resources and promote sustainable tourism. The service enables citizens and visitors to discover cultural, natural, and recreational assets—including lesser-known destinations—by combining behavioral profiling, infrastructure data, and territorial analysis. The **Citizen Twin** is activated via a mobile app where users complete a preferences questionnaire (e.g., cultural interests, nature, accessibility, mobility habits). This input fuels tailored suggestions and personalized routes based on individual needs. The **Government Twin** supplies verified, up-to-date data on public and private assets—such as monuments, parks, transport infrastructure, and mobility services—acting as a structured knowledge base for itinerary creation. It also models services and governance aspects to design accessible, integrated travel paths and inform strategic decisions on soft mobility and cultural initiatives. It further processes user feedback and spatial data to generate insights on service usage, tourism patterns, and asset performance, supporting data-driven policy and investment. The **Territorial Twin** provides geospatial intelligence, enabling dynamic route planning optimized for soft mobility options like pedestrian areas, bike paths, and electric shuttles, while prioritizing proximity to green and cultural spaces.

The adopted approach relies on Information Fusion (IF) paradigms to extract predictive models from highly heterogeneous data sources—including behavioral, infrastructural, environmental, and administrative variables—thus enabling a holistic and forward-looking understanding of tourism flows and territorial dynamics.

VI. Conclusions and Outlook

The AVANT framework adopts a multi-dimensional approach to Urban Digital Twins by integrating citizen, government, and territorial perspectives into a unified architecture. This enables a holistic view of urban systems and supports data-driven governance. The synergy among the three Twins goes beyond visualization, enabling informed decision-making, personalized services, and systemic analysis. Advanced spatial-temporal features—such as change detection, environmental monitoring, and traffic simulation—highlight the Territorial Twin's role in delivering policy-relevant insights. A personalized eco-tourism use case illustrates how multi-twin coordination enhances citizen engagement, promotes sustainability, and guides investment in underused assets.

Future developments will extend the framework to diverse contexts, integrate real-time analytics and AI reasoning, and evaluate long-term impacts on governance, resilience, and sustainability.

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