METACITIES Excellence Hub in South-Eastern Europe

D3.3 Instantiation of smart cities digital twins and transition to Metaverse

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Lead Beneficiary	CYENS		
Responsible Author	Vasos Vassiliou (CYENS)		
Contributions from	Tanya Politi (UPAT), Spyros Denazis (UPAT), Ioannis Tsampras (UPAT), Daniela Aleksieva (ISBUR), Dian Raykov (ISBUR), Kremena Chilikova (ISBUR), Marios Nicolaou (PNET), P. Kalozoumis (HAEC), Christiana Ioannou (CYENS), Natalie Temene (CYENS), Savvas Antoniou (CYENS), Marios Pafitis (CYENS), Evi Faliagka (UoP), Eleni Christopoulou (UoP)		

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				Popunkyov (BUR), M. Nicolaou (PNET), Daniela Aleksieva (ISBUR), Dian Raikov (ISBUR), Kremena Chilikova (ISBUR), UoP Team
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Glossary of terms and abbreviations

Abbreviation / Term	Description
ABM	Agent-based Modelling
AF	Application Function
AI	Artificial Intelligence
AR	Augmented Reality
BIM	Building Information Modelling
BIMS	Building Information Management System
DT	Digital Twin
eMBB	enhanced mobile broadband
ESBs	Enterprise Service Buses
GA	Grand Agreement
GDPR	General Data Protection Regulation
GST	Generic Slice Template
ICT	Information and Communication Technologies
LOD	Level of Detail
M2M	machine-to-machine
mMTC	massive machine-type communications
MEC	Mobile Edge Cloud
MR	mixed reality
MSF	Metaverse Standards Forum
N3IWF	Non-3GPP InterWorking Function
NEF	Network Exposure Function
NFV	Network Function Virtualisation
OARC	Open AR Clour
ODTF	Open Digital Twin Framework
OGC	Open Geospacial Consortium
PCF	Policy Control Function
PoP	point of presence
QH	Quadruple Helix
RBAC/ABAC	role- or attribute-based access control
SDN	Software-Defined Networking
SLA	Service Level Agreement
UHI	Urban Heat Island
UI	User Interface
URLLC	ultra-reliable low-latency communication
UX	User Experience
VPS	Visual Positioning Systems
VR	virtual reality
XR	Extended Reality

Executive Summary

The main goal of METACITIES is to develop a common Open Digital Twin framework (ODTF) for three (3) different domains of smart cities that will take advantage of the functionalities of Digital Twins (DT) and Metaverse. The main objective of Deliverable D3.3 is to demonstrate how smart city DT can be instantiated and progressively integrated into Metaverse environments, in alignment with the ODTF developed in D3.2. The work is structured to address both the domain-specific needs of pilot cities and the technological requirements for a future-proof, interoperable transition to the Metaverse. This document captures the DT instantiations and planning, and presents the mature implementations and the roadmap towards their integration into Metaverse infrastructures.

This deliverable provides a comprehensive overview of the initial and final stages of the DT life-cycle, from localised instantiation to immersive, interconnected representations within the Metaverse paradigm.

The work reported herein is the outcome of Task 3.3 and partially Task 3.4, within the context of the overarching methodology defined in Task 3.2. Task 3.3 focuses on the practical instantiation of smart city and smart region DTs for selected pilot cities, grouped in three domain clusters: smart mobility (Greece), green city (Bulgaria), and urban planning (Cyprus). Implementation guidelines and three specific roadmaps (one for each domain cluster) are provided, taking into account the DT characteristics, reference architectures, and identified technical and societal challenges.

Building on the outputs of Task 3.3, Task 3.4 addresses the transition of the instantiated DTs to Metaverse environments, identifying the required ICT architectures and infrastructure enablers. The integration leverages emerging technologies such as 5G and 6G, aiming to ensure high scalability, interoperability, and real-time data integration within extended digital ecosystems.

The work presented in this deliverable was carried out in three main steps. First, the design of guidelines and definition of roadmaps for the implementation of the DTs for each of the cities. Then, reference ICT architectures and infrastructures suitable to support the transition of DTs to Metaverse environments were outlined. The third step was to specify implementation challenges and solutions for each use case.

1 Introduction

1.1 Mapping METACITIES outputs

This section presents the METACITIES Grand Agreement (GA) commitments, as extracted from the formal deliverable and task description, with respect to their outputs and work to be performed. The purpose is to aid the reviewer in finding the specific sections of the document where the respective tasks' requirements are addressed, but also to guide the author through and serve as a checklist to address everything that needs to be addressed.

TABLE 1: ADHERENCE TO METACITIES GA DELIVERABLE & TASKS DESCRIPTIONS.

METACITIES GA Component Title	METACITIES GA Component Outline	Respective Document Chapter(s)	Justification
TASKS			
Task 3.3 Instantiations of specific smart city digital twins	Using the ODTF provided by Task 3.2, this task will instantiate specific smart city and smart region DTs as proposed by the different clusters. These DTs will reflect the three domains accommodated by each cluster; smart mobility (GR), green city (BG) and urban planning (CY). Specifically, the design of guidelines and definition of roadmaps for the implementation of the DTs for each of the cities will be provided here. It will also summarize the specifics for each pilot city with their use cases to leverage the QH impact of the project. In the process of the roadmap preparation, the DT characteristics, reference architectures and implementation challenges for each use case will considered.	Chapter 2	Chapter 2 presents the Open Digital Twin Framework and Implementation diagrams for all use cases
		Chapter 3	Chapter 3 presents the instantiation of the Smart City Digital Twin
		Chapter 5	Chapter 5 presents Implementation Challenges and Solutions
Task 3.4 Transition of the digital twins to Metaverse environments	Using the ODTF provided by Task 3.2, this task will provide the transition of the DTs produced in Task 3.3, to Metaverse environments. Reference ICT architectures and infrastructures suitable to support DTs to Metaverse environment will also be identified and proposed. These will be based on cutting-edge network technologies such as 5G and 6G, which are expected to be building blocks of the digital communication infrastructure of cities by offering a pool of computing, networking and storage resources.	Chapter 4	Chapter 4 presents the transition to the Metaverse environment
DELIVERABLE			

D3.3 Instantiation of smart cities digital twins and transition to Metaverse Environments: The instantiation and transition of digital twins, as proposed by the different clusters, to Metaverse environments

1.2 Deliverable Overview and Report Structure

This deliverable is organised to follow the logical progression from conceptual frameworks to implementation and transition of smart city DTs into Metaverse environments. Chapter 1 introduces the objectives of the deliverable and its alignment with the METACITIES project tasks and outputs. Chapter 2 presents the ODTF, which defines a common architectural foundation for cross-border collaboration among smart cities. It also presents implementation templates and detailed technical documentation for each of the domain clusters. Chapter 3 outlines practical guidelines and roadmaps for the instantiation of DTs across the three pilot clusters. Chapter 4 addresses the transition of these DTs into Metaverse environments, detailing the required extensions to ICT architecture, the integration of immersive technologies, and strategies for ensuring scalability and interoperability. Chapter 5 discusses the main implementation challenges encountered during the project and provides targeted solutions in areas such as interoperability, infrastructure, security, and real-time performance. Chapter 6 concludes the report by summarising key findings and highlighting next steps.

2 Open Digital Twin Framework (ODTF)

2.1 Enabling Cross-Border Smart City Collaboration through the Open Digital Twin Framework in METECITIES

As smart cities evolve, the need for interoperable, scalable, and intelligent digital infrastructure becomes essential. The ODTF emerges as an enabler in this transformation by offering a reference software architecture that models the digital counterpart and the virtual representation of physical urban environments. ODTF supports collaboration across different national ecosystems by defining a common structure for smart city development. In METACITIES, ODTF facilitates cross-border collaboration between the smart city ecosystems of Greece, Bulgaria, and Cyprus, fostering regional innovation, data-driven policy-making, and sustainable urban development.

In METACITIES, the specification of the ODTF entails:

- capturing functional requirements and end-user needs for the smart city use cases of interest to the involved ecosystems
- analysis and translation of said requirements into technical specifications, considering not only the technical aspects but also the user-centric social and economic dimensions
- definition of the actors responsible for the data collection, including the definition of data collection tools and online data repositories
- description of a reference software architecture for smart city operations that can be used to build city-wide common digital layers, coupled with existing city ICT infrastructure, to enable multiple domain-specific DTs
- highlighting of the common functions that a smart city digital infrastructure should implement, giving emphasis on the functionality and interfaces.

The framework that is described in D3.2 is designed to:

- Categorise core DT functions, such as simulation, actuation, or storage.
- Provide an object-oriented development environment, where DT Backbone Building components are defined so that they can be reused and connect different smart city verticals.

ODTF aligns with academic and industry trends while remaining flexible for local adaptation, enabling it to serve as a unifying framework across heterogeneous national and municipal infrastructures. It facilitates the centralised co-development of complementary smart city domains along with their equivalent DT, thus creating an agile and efficient nexus of collaborative links.

This work enables the interoperability of smart city solutions in the three participating ecosystems. All three ecosystems benefit from participation, allowing their municipalities and ICT providers to exchange tools, procedures, algorithms, and data while ensuring the semantic and syntactic interoperability of services. The technical teams are using a shared interface offering the possibility to connect different Metacity Instances, including their IoT systems, edge computing platforms, and first-party applications, under a unified architecture, as defined in D3.2.

This harmonised approach significantly reduces development duplication and ensures consistency in data governance and integration practices, hence the technical teams can reuse tools and enablers that are being developed for the specific use case. Each ecosystem has identified a specific priority and developed or integrated tools, respectively.

2.2 Collaborative Urban Innovation

The ODTF enables cross-border collaboration among smart cities in Greece, Bulgaria, and Cyprus through its modular, intelligent, and interoperable architecture. This framework accelerates joint initiatives by allowing each ecosystem to contribute complementary expertise: Greece provides a strong academic R&D community in IoT and ML solutions, Bulgaria offers proficiency in urban resilience and DT analytics, and Cyprus brings agile frameworks and testbeds for urban planning DTs, 3D representation capabilities and innovative applications. These synergies, fostered by shared tools and federated data strategies, lead to co-created solutions that build a more connected, sustainable, and intelligent region while simplifying the adoption and onboarding path for new partners.

The ODTF serves as a collaborative enabler, offering a modular, intelligent, and interoperable architecture that facilitates cross-border smart city cooperation. By promoting shared tools, joint development, and federated data strategies, ODTF strengthens collaboration, simplifies onboarding for new participants, and drives innovation toward a more connected, inclusive, safe, and sustainable regional ecosystem.

2.3 Cross-Border Collaboration Levels through Open Digital Twin Framework

The METACITIES Common foundation layer supports four progressive levels of collaboration, enabling flexible integration and innovation across the DT backbones of regional clusters. Each level reflects a deeper alignment in how the innovation ecosystem can adopt, adapt, or share architectural and technical components of the ODTF. The detailed guidelines for the cross-border instantiation of DT will be part of the next section.

2.3.1 Level 1 – Shared Architecture (Baseline Commonality)

At its core, the ODTF provides a unified architecture that any ecosystem can adopt. This architectural layer defines the structural and conceptual foundation for DT implementations, while allowing flexibility in software choices and deployment strategies. For example, as the ODTF may dictate, a time-series database is required for the storage layer of specific implementations; however, each City may use different time-series storage implementation systems—such as InfluxDB[1] or CrateDB[2]—depending on their preferences, licensing limitations, expected use case KPIs or legacyinfrastructure.

2.3.2 Level 2 – Shared Architecture and Interfaces

This level enhances interoperability by defining common communication interfaces across the instances. By aligning how components interact—such as through standardised data formats and service protocols — DT instantiation may ensure greater compatibility even when using different implementations of the same architectural element. This approach encourages a federation of independently evolving but interoperable systems. In METACITIES, where cross-border collaboration relies on co-development of tools, this level of interoperability allows common sharing of specific tools while the instantiation of City DTs relates to each city's implementation options. The minimum required shared interface is the Metacity-to-Metacity interface, where interoperability between instances can be achieved.

2.3.3 Level 3 – Shared Deployment Practices

The deepest collaboration can occur at the deployment level. By adopting shared practices for containerisation, orchestration, and infrastructure provisioning, innovation ecosystems that envisage and plan their common DT implementation and instantiations can streamline the rollout of both common and custom components. This not only fosters interoperability but also simplifies cross-cluster testing and operational alignment, regardless of differences in the application or

[1] https://www.influxdata.com

[2] https://cratedb.com

implementation layers. The METACITIES Excellence Hub is developing guidelines that enable cross-regional and cross-border collaboration and the sharing of DT assets, such as IoT data streams, 3D assets, applications, edge processing modules, and supporting services.

2.3.4 Level 4 – Shared Implementations

While such a level of integration may seem ideal for a specific City or Region, full alignment on software implementations across all innovation ecosystems and DT implementations in METACITIES and beyond is largely impractical due to the diverse tools and platforms already in use. However, some components, like mapping tools (e.g., Google Maps, Leaflet) or storage solutions, have a higher potential for shared implementations. This level might be selectively feasible where tools are ubiquitous or easily containerised, allowing for partial convergence on specific subsystems. Furthermore, as the integration of new DTs within a city or region may follow the METACITIES paradigm, this level of collaboration could become an option.

2.4 METACITIES ODTF overarching architecture

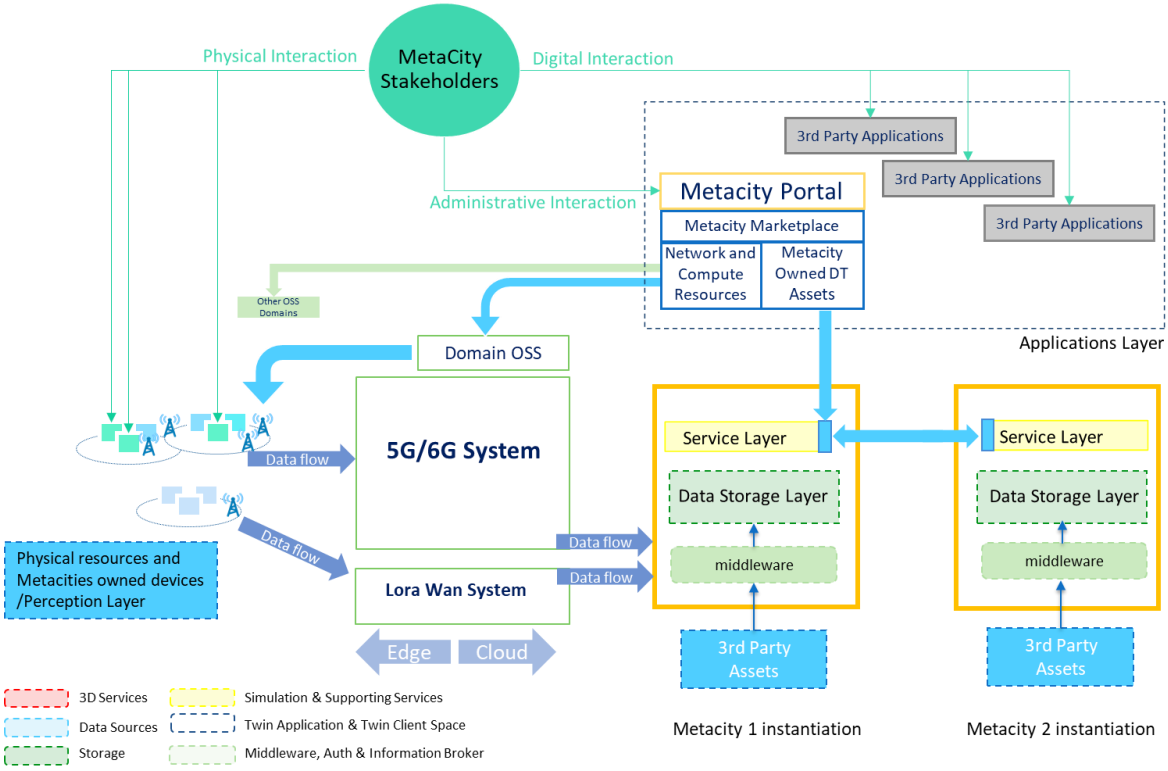

FIGURE 1: METACITIES VISION FOR OVERARCHING ARCHITECTURE ENABLING STAKEHOLDERS' INTERACTIONS.

The METACITIES Excellence Hub acts as a unified digital ecosystem that bridges QH city stakeholders (governments, businesses, citizens, researchers), a dynamic marketplace (for city-owned assets, services, data, and smart solutions), and DT instances (virtual replicas of urban infrastructure, utilities, and services). This interconnected framework enables seamless collaboration, real-time decision-making, and innovation in urban development and assumes the existence of various city instantiations according to the ODTF architecture described in D3.2. Here we discuss the overarching architecture envisaged as a collaboration enabler for multiple METACITIES instantiations.

Error! Reference source not found. illustrates how the METACITIES Excellence Hub is supported by a digital infrastructure and portal that may serve as a multi-layered urban intelligence platform, enabling stakeholders to engage through:

- Digital Interactions (Portal, Marketplace sharing, METACITIES Applications, Data Visualisation)
- Administrative Interactions (Governance & Policy Management)
- Physical Interactions (Sensor Networks & IoT Integration)

Each mode of interaction ensures streamlined collaboration between humans, machines, and urban infrastructure. The METACITIES Excellence Hub portal will be the interface of the DT instantiation with stakeholders for all digital interactions and an interface between the stakeholders and the METACITIES Marketplace, and/or even third-party applications.

2.4.1 Digital Interactions (METACITIES Applications)

Stakeholders may interact with a METACITIES Excellence Hub's digital portal via web dashboards, mobile apps, and in the future, immersive interfaces (AR/VR). The interaction concerns both production and consumption of digital content and services that may rely on functions, e.g. Real-Time City Monitoring. Applications may be designed for the broad public (e.g., parking apps, crowd-reporting issue tracking) or city authorities, specific agencies, local companies and academics.

2.4.2 Administrative Interactions (Metacity Administration)

Access control and requests, marketplace management, and a myriad of other administrative actions and monitoring should be accessible through the Metacity portal. From here, both interested citizens, academics and corporations may submit requests to on-board applications, access interfaces or connect equipment and at the same time, administrative users may accept the requests and monitor usage. Additionally, from here, the administrative user may control the marketplace and its contents as well as the life cycle of other Metacity services and modules.

2.4.3 Physical Interactions (Sensors, IoT & Real-World Actuation)

Stakeholders engage with the physical city infrastructure via the Hub's IoT integration and possible edge computing. The interconnection, data flow, discovery and actuation of the devices is part of these interactions. The addition of sensors or the discovery of assets into the physical world may take place through some key functions like direct sensor control & maintenance and even Citizen-Reported Data, where citizens with their smartphones may act as sensors in the city. At the same time, actuation (e.g., control of physical devices like traffic lights or digital signs) is used to take "Actions" in the city infrastructure.

By orchestrating these three types of interactions through one reference point, METACITIES Excellence Hub ensures that every stakeholder—from citizens to city leaders—can interact with the smart city in the most effective way possible. Currently, the availability of such a portal is only provisioned on a city basis, and it only provides Seamless Stakeholder Experience for specific ecosystem stakeholders.

- Digital → Dashboard insights, simulations, and collaboration.
- Administrative → Managing the Metacity Instance itself.
- Physical → Physical Sensor or Device Interactions, Maintenance, and real-time urban adjustments.

2.4.4 METACITIES Application Layers: METACITIES portal, METACITIES applications and Market Place

The METACITIES interface to the stakeholders through the Application Layer that may comprise the METACITIES Portal, METACITIES Applications, and a Marketplace. Together, these elements enable streamlined integration, scalability, and user-centric smart city development. The METACITIES Portal serves as the central access point, offering a unified interface for users to engage with digital services, urban data, and governance tools. METACITIES Applications is the exact part of the ODTF architecture that consists of specialised software solutions designed for smart city functionalities. As shown in the

legend, at the core lies the DT instantiation as architected in D3.2. A preliminary implementation design of the envisaged architecture is shown in the figure below. Here we have identified in the METACITIES portal the DT application space, which integrates real-time data from the context broker with the results from the analytics and simulation components.

Although not provisioned in the METACITIES description of work, we support the requirement for a Marketplace that may offer smart city solutions and access to open datasets for research or app development. The common METACITIES marketplace may list available city-owned assets such as application-level METACITIES components, various services as containers or virtual machines and various data endpoints. The marketplace may also list Metaverse assets (3D Representation exchange assets) and serve as a registry for third-party applications shown in the Figure 1. In Section 4.1.3 the interface of the METACITIES to the digital infrastructure and network resources will be discussed in detail. Finally, the Marketplace acts as a dynamic platform where developers, businesses, and governments can exchange digital services, APIs, and IoT solutions, fostering innovation and collaboration within the urban ecosystem.

2.4.5 Digital Twin Components

In order to design and implement the ODTF as an installation of a Metacity Twin, the mapping of the generic data/control paths and overall components and architecture are shown with emphasis on the architectural components. Data (physical) sources that are scouted via the platform are interconnected and collected from municipality sensors via LoRa and or third-party sensors via other IoT communication systems or 5G network operators. These can be supplemented by simulated devices that serve as test inputs and enriched with information from the data acquisition layer interacting with various public APIs, ranging from bus arrival times and traffic data to maps and GIS services from third parties, as shown in the diagram and will be analysed later in this deliverable. The exact role of the infrastructure will be analysed in Section 2.5, while the technological selections of each innovation ecosystem will be delivered in Section 3.

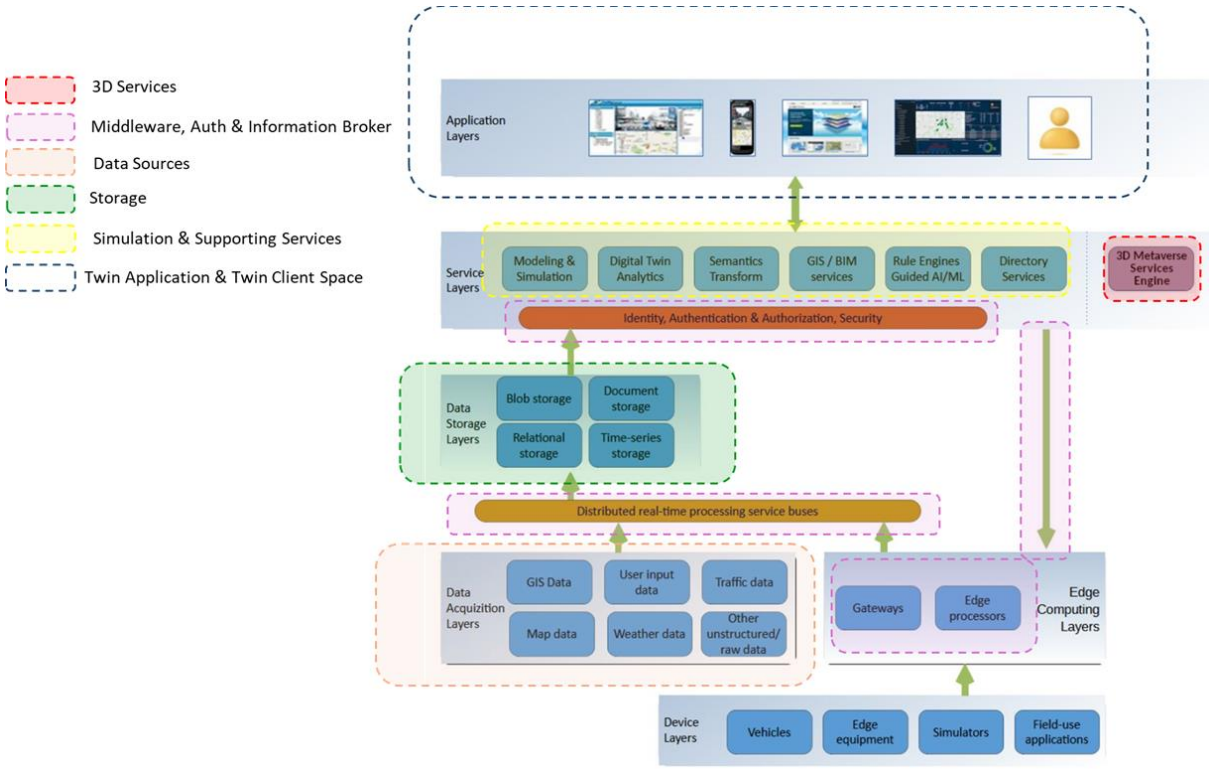

FIGURE 2: ODTF ARCHITECTURAL COMPONENT CATEGORISATION

2.5 ODTF architecture - towards Implementation

As discussed in more detail in Section 3, the DT instantiation varies depending on the pilot, context, use cases, deployed technologies and implementation choices.

While the ODTF architecture demonstrates the components and their interactions, the implementation design is a more complicated perspective where different architectural components may be served from one software implementation or vice versa. Therefore, we introduce the implementation template, which is used by the various pilots in each cluster to demonstrate in a common manner the design proposed for each use case and offer a view into each cluster's toolset.

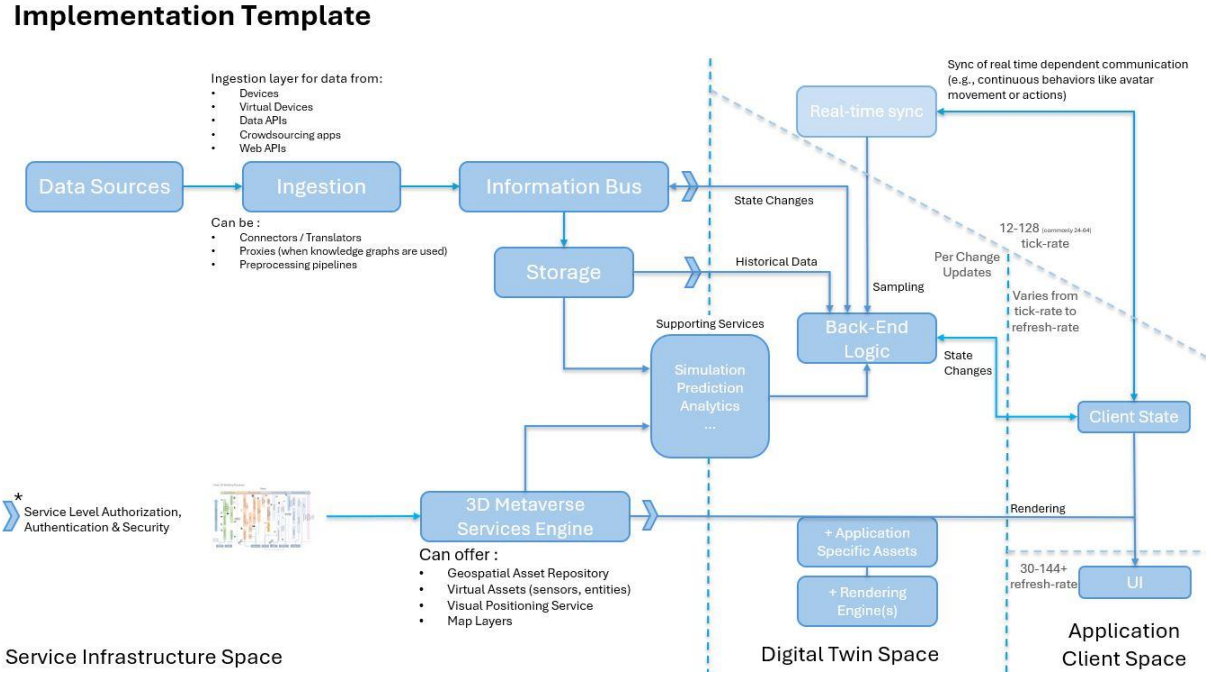

FIGURE 3: IMPLEMENTATION TEMPLATE.

In the implementation template, the relations of different components and the integration with the, so far, undescribed application layer are better visualised. We are also proposing the distinction between the Metacity's digital and physical infrastructure space and the DT space which lies mainly inside the application layer. Additionally, we clarify the separation of application clients and the DT. Finally, we showcase the expected refresh speeds for different aspects of the implementation, discussed in more detail in Chapter 4 towards the Metaverse transition.

Each cluster presents a short description of their digital and physical infrastructure implemented for all use cases per cluster and the corresponding versions of the implementation template (9 in total). While the template covers significant areas that are referenced in other sections and relate to the transition to the Metaverse (such as visual positioning services, real time synchronization mechanisms, advanced visualization methods etc.) not all use cases require all components, therefore each version might not include all building blocks. Additionally, not all blocks will be accompanied by the specific tool, API, hardware or software used since they are subject to change during the implementation process of the pilots.

2.5.1 Greek Cluster

For the Patras Ecosystem, the Fiware Platform is used for Use cases 1 and 3, while use case 2 is designed upon the Yodiwo Smart Platform. Since all three use cases are in the same thematic area, most of the design is repeated throughout. The inputs and the supporting services are the main differentiating factors, as seen in Figures Figure 1Figure 4Figure 5Figure 6. In general, input Data is collected from municipality sensors via LoRa, supplemented by simulated devices that serve as test inputs, and enriched with information from the data acquisition layer interacting with various public APIs, ranging from bus arrival times and traffic data (such as from TomTom) to maps and GIS services (like Google Maps and Leaflet) and even crowd-sourced incident reports from the Sense-City application. Most of this data is routed to an Orion Context Broker from the FIWARE ecosystem in use cases 1 & 3 and through the Yodiwo Platform in use case 2. This is achieved using several translator/connector middleware layers that convert the incoming data into NGSI and Smart Data Model compliant messages, ensuring standardised and reliable context management (in use case 2, appropriate connectors for the MQTT bus are implemented).

The Orion Context Broker (or the MQTT broker in use case 2) acts as the central hub for state management, distributing contextual information across the system. To ensure long-term storage and further processing, a Cygnus FIWARE component is employed to persist the data into a relational database, such as MySQL, this is slightly different in use case 2 where a custom writer is used and data are stored both in a MySQL database and a InfluxDB one. This persistence layer not only provides a historical archive but also supports additional services, including analytics and modelling. These supporting services utilise the stored data to generate insights and run simulations, which are then fed into the DT application.

At the core of the project is the DT application space, which integrates live data from the context broker with the results from the analytics and simulation components. This fusion creates a detailed 3D representation of the urban environment that is continuously updated. A separate geospatial service manages both a geospatial asset repository, comprising custom assets and assets from Google's 3D Tiles API, and a virtual asset repository for models representing sensors and other entities. The visualisation of this DT is realized through layered rendering techniques that employ several libraries, including the three.js engine, leaflet and mkkellog's Gaussian splats 3D libraries. Custom city scans, captured using tools like RealityCapture and Jawset Postshot, will serve as hero-locations where a photorealistic quality higher than that of Google's 3D tiles is required.

Security is a critical aspect of this architecture. A dedicated security and authentication layer, implemented using Nginx as a reverse proxy in conjunction with a custom auth server (can be implemented using the blockchain), ensures that communication between the context broker, storage, geospatial service and supporting services remains secure to the outer world. Additionally, a separate custom back-end component, developed in Python with Flask or Node.js with Express, handles back-end logic and delivers annotated information to the web-based client while also orchestrating the simulator component that creates additional analytics. This back-end not only facilitates simulation but also supports real-time interactions, enabling users to engage with the DT through an intuitive user interface.

Greek Usecase #1

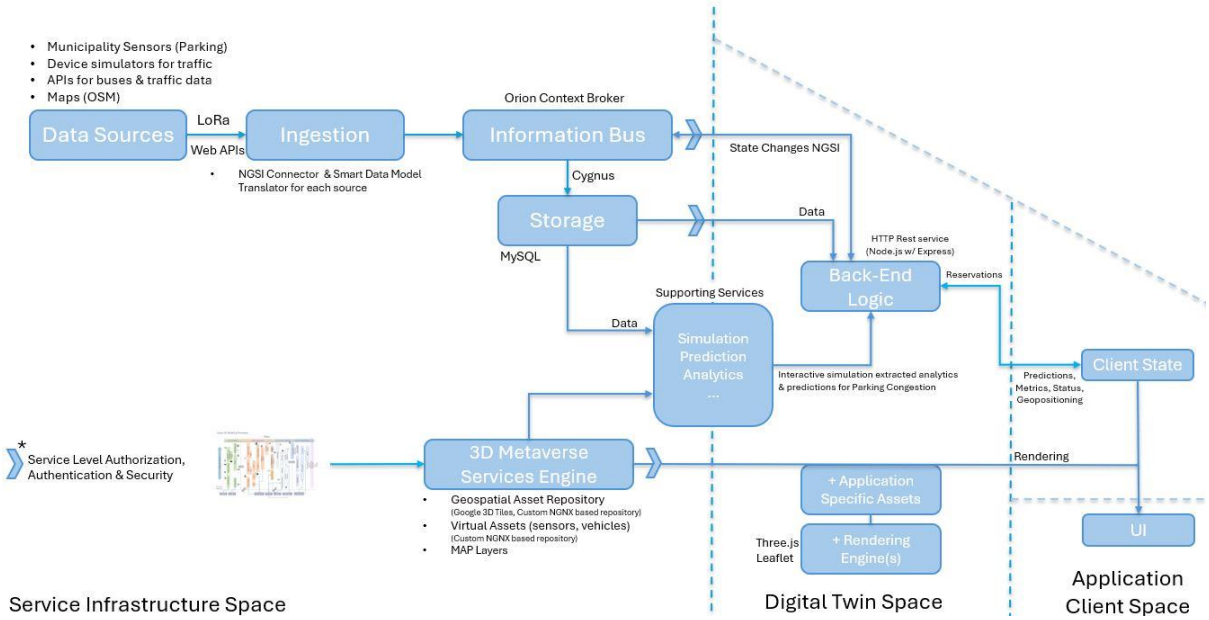

FIGURE 4: GREEK CLUSTER USE CASE #1 IMPLEMENTATION DIAGRAM.

Greek Usecase #2

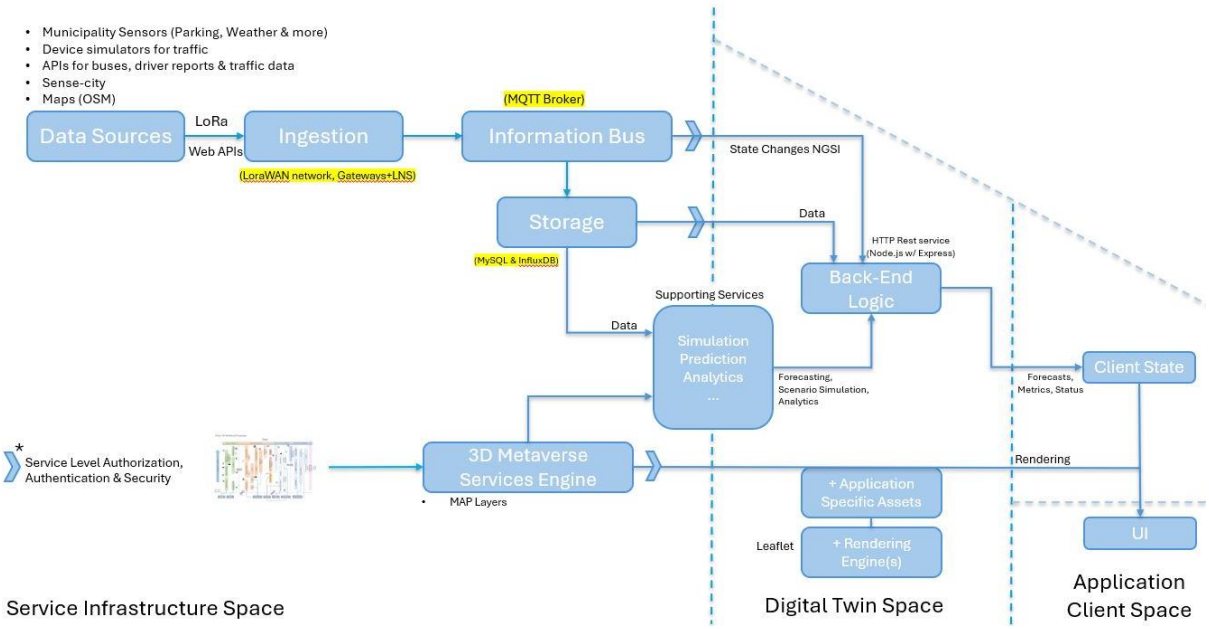

FIGURE 5: GREEK CLUSTER USE CASE #2 IMPLEMENTATION DIAGRAM.

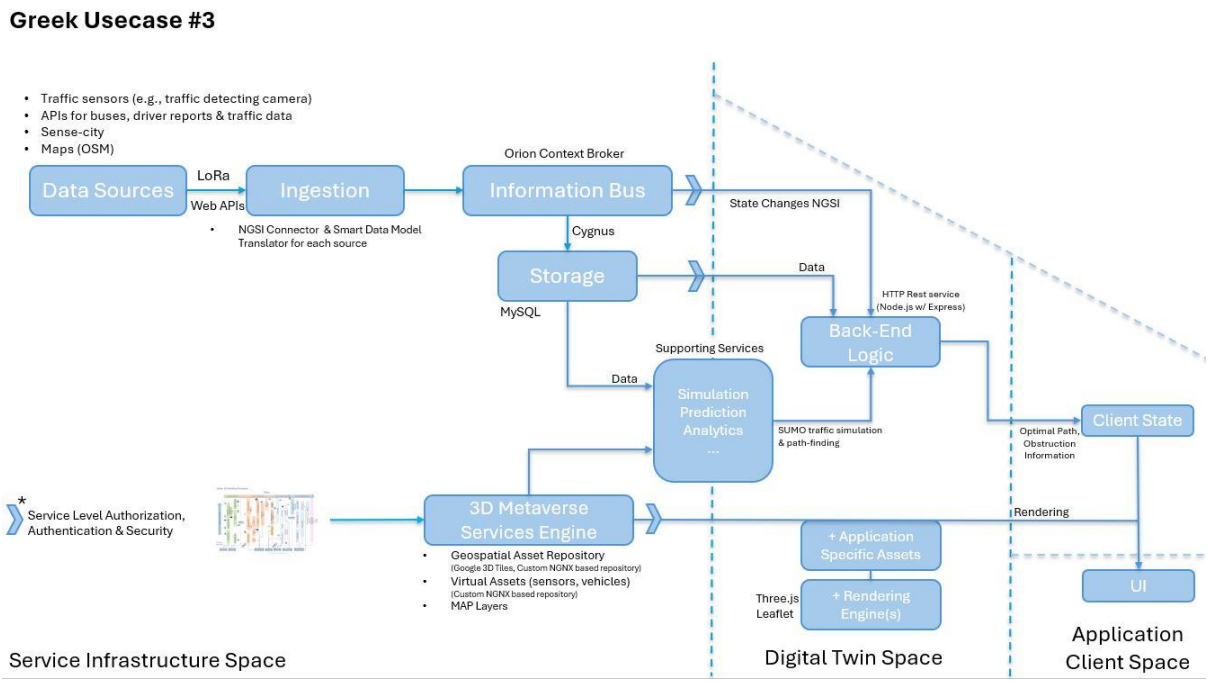

FIGURE 6: GREEK CLUSTER USE CASE #3 IMPLEMENTATION DIAGRAM.

2.5.2 Bulgarian Cluster

For aligning the needs with the technical requirements, the basic approach for the three pilot use cases is applied as follows: real-time data and registry data are compiled into a DT application with assured embedded capabilities for changing/ modification of the input data flows in order to get simulations with results answering the use case description.

Service Infrastructure space

In the three BG use cases, data is collected from the API of solar panels, solar capacity measurement, architectural data, orthophotos allowing aerial photography and geodetic measurements with high precision when presenting terrain characteristics and objects, GIS services, and even construction documents.

Data from sensors: Thermal, IoT devices, we collect them via Bluetooth, LoRa or Cellular 5G transmission protocols in building and urban conditions and build encrypted connections over the Internet to virtual storage. All the above data, different by type, is directed for processing in a multilayer visualisation system - a system consisting of separate virtual arrays, both disk and computing. For the use cases implementation own hardware systems with VMWARE virtualisation technologies, as well as external virtual systems are used.

Dual application and twin client space, Analysis and algorithm space, ability to change different input data as variables to obtain specific output data through simulation for different Use Cases

The multi-layer visualisation system in Use Case 2 displays instantaneously temperature and humidity data from sensors in full 3D visualisation of the building and sensors installed in it, in Autodesk Cloud platform, with references to a subsystem for time plotting of data in graphical and tabular form. To access the data freely and quickly, the storage system is also part of its own virtual platform, which the owner of the use cases - the Burgas Municipality – operates. Once accepted for processing and external sources, local access to the data occurs between the processing and visualisation systems. This way, the data and images can be processed and visualised simultaneously. All input data is

accepted via API services, with the clear idea that when creating DTs, the basics of simulations and analyses is to use different input data. The owner also has similar API services for output data. For the piloted use cases, a mandatory condition is that the DTs can both accept foreign input data and transmit output data to external systems. Web formats such as JSON, Geo-Json, ftp services, different views of PostgreSQL databases are the main methods and standards for communication between different platforms. Thus, the collected and processed data is submitted to the Autodesk Architecture service and BMS Building service platforms. Visualizing them in two different ways and the ability to change the data over time leads us to the simulation module with different data from different times and from different buildings. The results displayed in a BIM model of a building based on node.js and Revit format Autodesk cloud API service and their visualisation in different graphical and tabular formats allows the "client" easily to see the results of the different simulations.

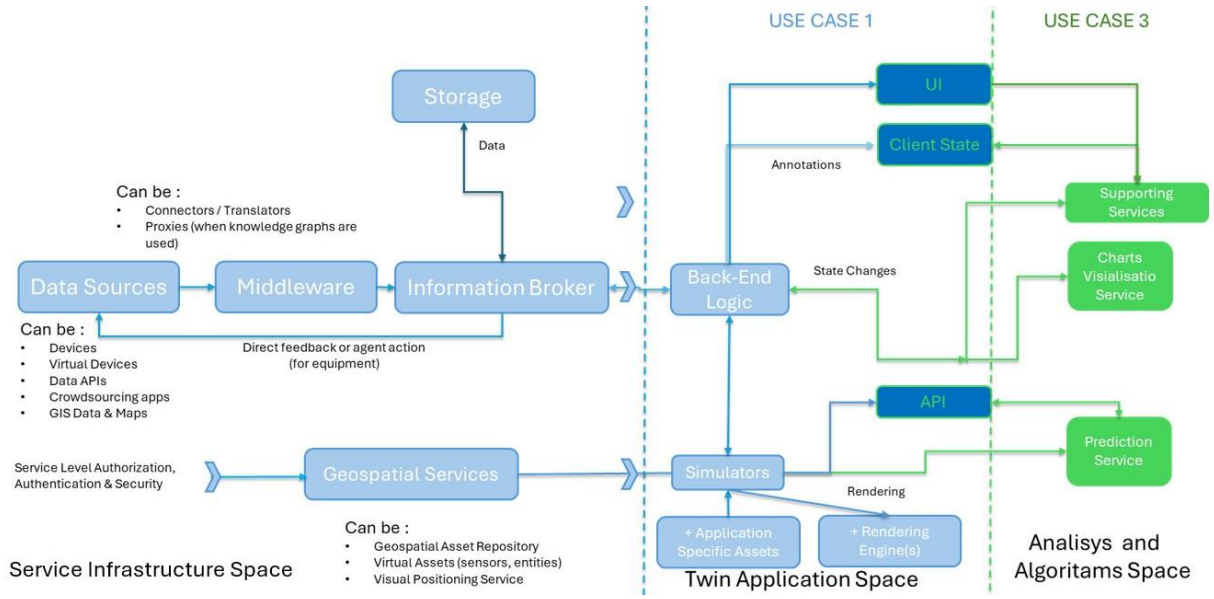

FIGURE 7: BULGARIAN CLUSTER USE CASES 1 & 3 INTERNAL DESIGN.

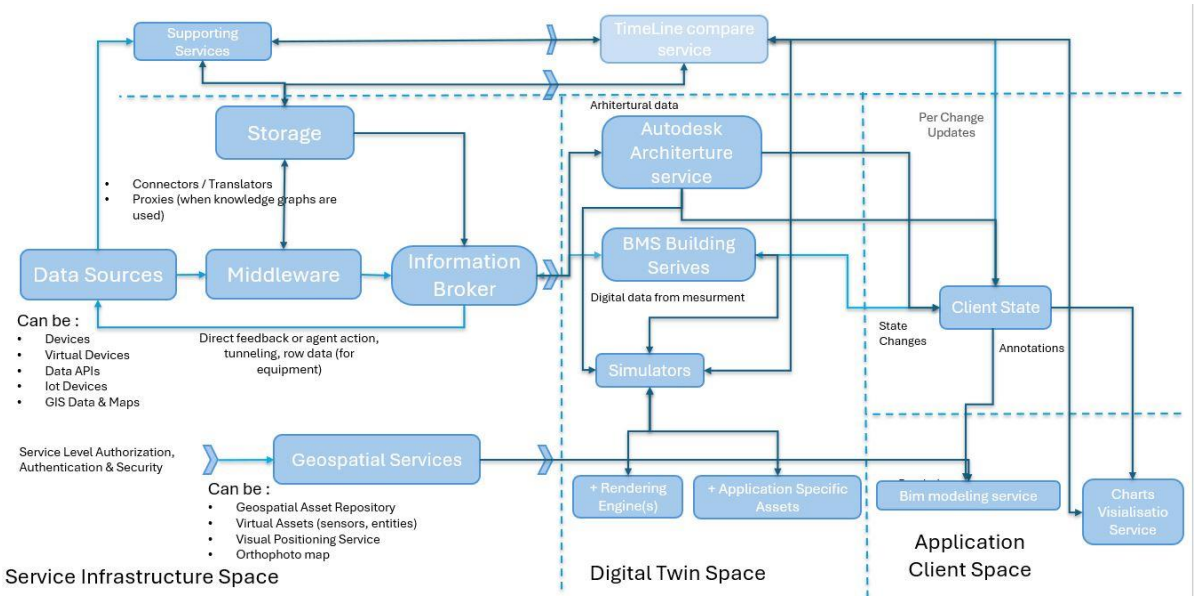

FIGURE 8: BULGARIAN CLUSTER USE CASE 2 INTERNAL DESIGN.

The logical approach to data collection in Use Case 1 is similar to Use Case 2, namely we collect data in our data clusters, just in different logical formats.There we mainly process map services. Here work is done with files with sizes larger than 70 GB. To visualise them, software such as Potree, and web-based multilayer drawing of GIS-based applications with Map Service are used. PostgreSQL cluster databases are the basis of data collection, drawing and map services. They are the backbone of the created virtual twins. Trying to use open-source software, all the systems owned by the Municipality of Burgas, are built on Linux-based operating systems, and virtualised in its own data center.

In Use Case 1 for processing large areas of orthophoto maps and lidar-scanning data, which have been captured specifically for the purpose, the chosen and applied approach is slightly different. The YOLOv8 library for object recognition is used, and namely for the solar panels and buildings. For the possibility of processing parts, we installed docker containers allowing parallel operation of different parts. Naturally, the data was checked and corrected where necessary with Label Studio software. This is how the Back-end logic module has been done. The own multi-layer drawing system allowed to plot the data on a single substrate, thus creating the prerequisites for conducting analyses and simulations to measure solar capacities. They are naturally tied to input data for different time periods, sometimes with live data. The map services used allowed easy drawing of the data in new layers. Thus, a DT system has been created.

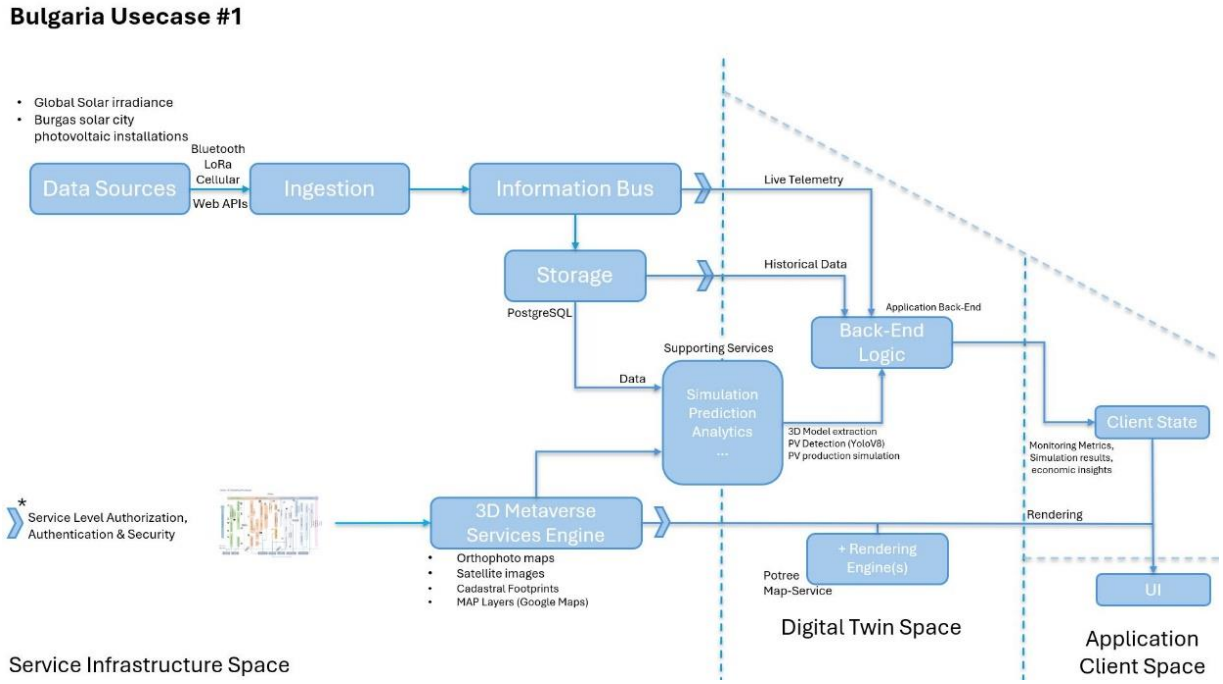

FIGURE 9: BULGARIAN CLUSTER USE CASE #1 IMPLEMENTATION DIAGRAM.

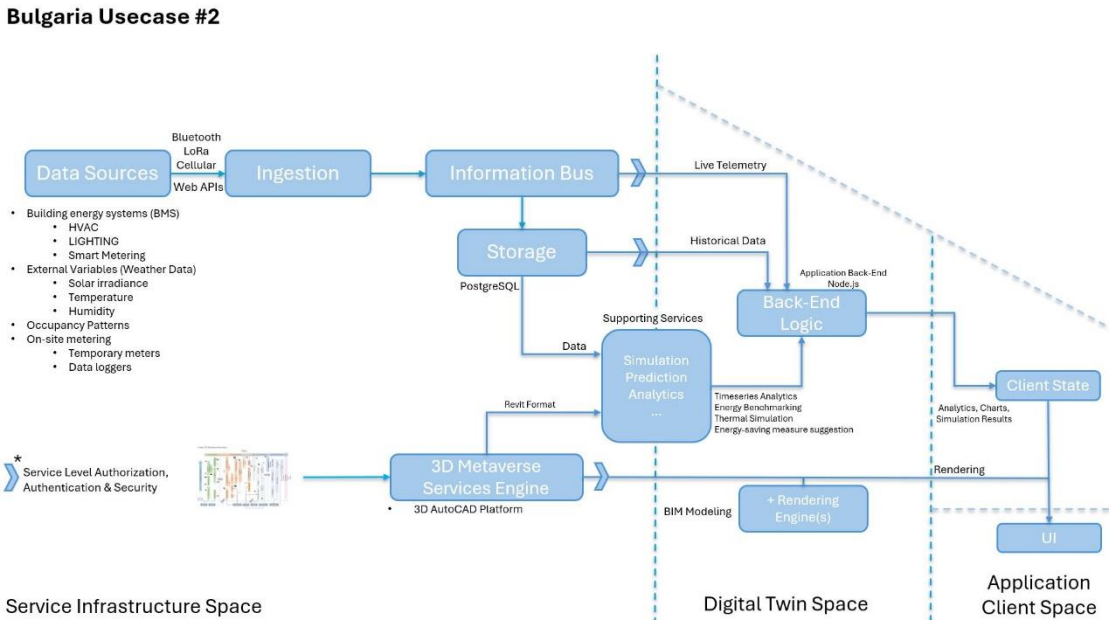

FIGURE 10: BULGARIAN CLUSTER USE CASE #2 IMPLEMENTATION DIAGRAM.

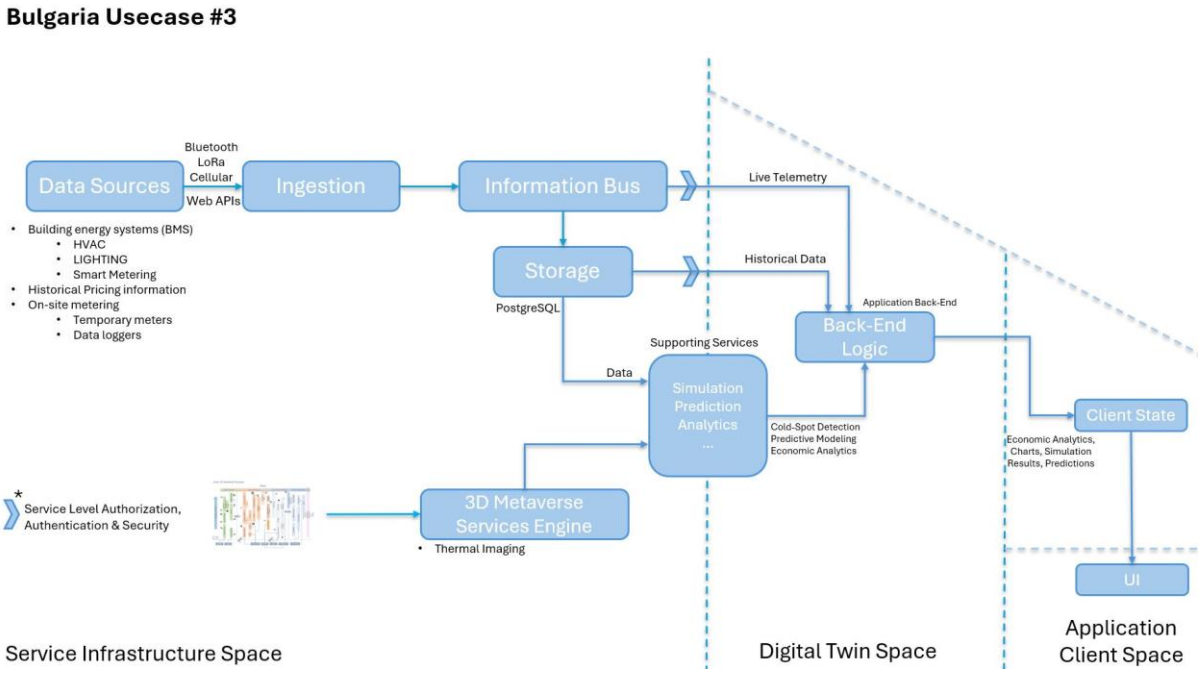

FIGURE 11: BULGARIAN CLUSTER USE CASE #3 IMPLEMENTATION DIAGRAM.

2.5.3 Cypriot Cluster

For the Cypriot cluster the implementation details are as follows.

Data Acquisition Layer
Data is collected from municipal Smart City APIs, including traffic, weather, tree stock, and environmental sensors. This is supplemented by publicly available data sources, including NASA and ESA Earth Observation satellites for thermal monitoring, as well as community-driven measurements for air quality and noise levels. For geospatial data, APIs provide high-resolution maps and GIS layers. In the smart parking use case, physical parking sensors are deployed with LoRa connectivity or simulated for testing. These devices publish data to the FIWARE Orion Context Broker using NGSI-compliant messages formatted through Smart Data Models.

Processing and Storage Layer
The Orion Context Broker manages real-time state across the platform, receiving sensor data through NGSI connectors. Contextual data is persisted using Cygnus or custom pipelines into PostgreSQL for structured records and PostGIS for geospatial analysis. MongoDB is used for semi-structured and unstructured datasets. Cesium ion is used to store and manage 3D geospatial assets for the DT, including terrain, building models, and simulation overlays. These layers enable spatial indexing, temporal tracking, and multi-source data fusion essential for modelling heat islands and parking behaviours.

Service Layer
A custom-built directory service, implemented in Python using Django, handles authentication, identity management, role-based access control, and API security. This layer orchestrates how historical and real-time data are used across the platform, enabling spatial queries, simulation execution, and analytics generation. Modelling components ingest historical patterns to simulate future states, such as urban temperature reduction scenarios or parking congestion forecasts. These services are containerised and modular for easy scaling and deployment.

Application Layer
The DT interface is rendered using TerriaMap for interactive geospatial visualization, displaying real-time data streams, environmental overlays, and simulation outputs. Unity is used to generate immersive 3D visualisations that show the results of simulated actions over time. This helps stakeholders like city planners visually understand the effects of their interventions or changes detected by real-time sensors. For smart parking, a mobile app integrates navigation and sensor data, guiding users to available spots in real time based on vehicle type, proximity, and traffic conditions. These interfaces serve stakeholders ranging from city planners to everyday drivers, enabling decision-making through a unified DT experience.

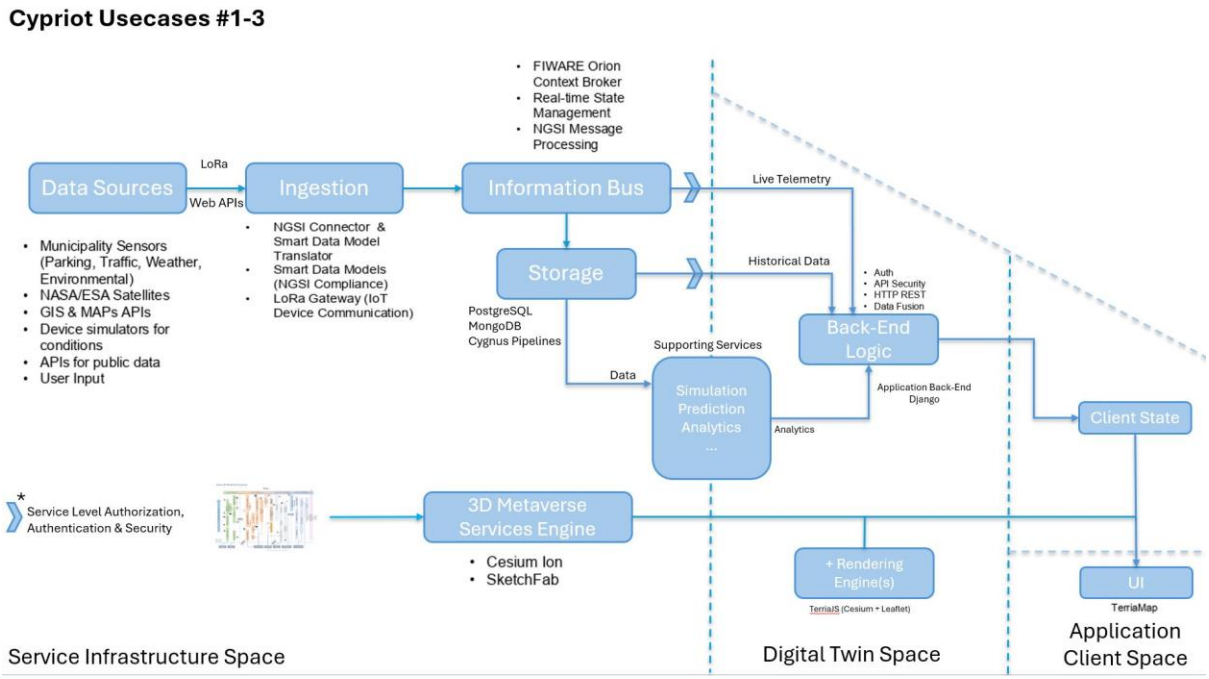

FIGURE 12: CYPRIOT CLUSTER USE CASE #1 IMPLEMENTATION DIAGRAM.

3 Instantiation of Smart City Digital Twins

3.1 Guidelines

These guidelines outline key activities and offer standardised steps for the implementation of DTs in different domains, providing a systematic approach for utilising the capabilities and enablers of the city. The need for a city to support this topic usually comes into place on the basis of evolving and/or implementing regional innovation strategies and policies for smart specialisation in various priority domains and in the context of existing/developing specific smart city ecosystems.

This section is intended to help future DT governance enabling bodies, and elaborates on the general reference methodology for creation and implementation of DTs, but with emphasis on three pilot domain areas: Smart mobility DT in Greece, Urban planning DT in Cyprus, and Green and Climate adaptive resource management DT in Bulgaria.

For the instantiation of a DT, the following should be considered.

3.1.1 Definition of objectives and goals

***Key objectives**: Typically, when a city initiates a DT Project, the process begins by providing policymakers and urban planners with accurate, data-driven insights. These insights will enable better decision-making regarding the instantiation of the DT in any chosen priority domain.*

For the participants of the METACITIES project, the chosen domains are as follows:

- ***Greek Cluster:*** To implement a DT as a powerful instrument for supporting Smart mobility related services and generally longer term policies improving road safety, smart parking, quality of life and accessibility. The primary objective of the chosen Greek pilot is to ensure the safe and efficient movement of vehicles, pedestrians, and bicycles in complex urban areas, in alignment with the Smart Transport priorities of Safety, Quality of Life, Green Initiatives, Accessibility, and Inclusivity outlined by the City of Patras.
- **Cyprus Cluster**: To deploy and expand a DT ecosystem that integrates real-time urban data, simulates the impact of planning interventions (e.g., greening strategies and mobility systems), and supports sustainable urban growth, enhance evidence-based policymaking, and foster smart, inclusive, and resilient city planning in alignment with Cyprus's national digital transformation strategy.
- **Bulgarian Cluster:** To implement a DT by up-scaling of the existing SmartBurgas City Platform, emphasizing on applications related to energy efficiency and climate adaptive policies that help better resource management and citizen awareness.

Scope: All the DTs aim to integrate and operate heterogeneous networking technologies and big city data to find appropriate business models for their operation. DTs are designed and developed, and subsequently seamlessly and timely prepared for integration into the Metaverse in the city's communication network.

3.1.2 Governance and stakeholder engagement

Having a Governance Enabler is essential in the DT implementation, focusing on stakeholder mapping, communication, instantiation, performance measurement and data governance.

The Governance Enabler should be an internal or external digital transformation governance structure to assure a framework for decision-making, implementation, and ethical use of technologies and data. A winning process may be the setting-up of a smart city or digitalisation office/unit/body within the city/city administration, that will plan, implement and manage all the related initiatives.

Governance structure: The existence of this enabler will allow the implementation of the digital transformation strategy over time, making sure it is aligned with the overall vision and budget of the community.

The initial steps that the **assigned enabler/governance structure** should take include:

- ***Identification of the stakeholders*** - this is an important process because they shape the vision of the community for the DT implementation. This step captures the right understanding of the concerns, goals and ambitions of the community.
- ***Definition of a change management strategy*** for the community by identifying the skills and knowledge required for the successful adoption of new smart technologies. Based on this the community may decide to hire and/or upskill the workforce and/or work with external partners who can provide specialised/technical knowledge.
- ***Definition and design of communication strategy*** for engaging with key stakeholders according to their needs and preferences *to ensure that a clear and consistent road map implementation is conveyed.* The application of a QH approach is essential for educating the community about the benefits of the new technologies, assures easier adoption of the introduced innovative smart solutions, and fosters the culture of innovation within the city ecosystems.
- ***Definition of the reference KPIs and tools for monitoring*** that help to measure the progress toward the implementation of the DT Framework and transfer to the METAVERSE, already established in the strategic documents of the owner for the different priority domains. For example: how the implementation of DT and their integration within the Metaverse helps the city/region reach the strategic goals they have set for themselves in various strategic documents, such as reduction in energy consumption per capita, reduction of road accidents and injuries, indices for quality of life, etc.
- ***Establishing a data governance and data management strategy for the community,*** including rules for data collection, storage, sharing, and privacy, ensuring compliance with relevant regulations, assigning roles and responsibilities.

Greek Cluster: The governance enabler of the Greek cluster is a Steering Committee led by the Municipality of Patras and the University of Patras. In the Steering Committee, all technical partners have an advisory role. The Municipality of Patras is leading the digital transformation of the City providing the necessary deployment of sensing/device capabilities and infrastructure procurements, establishes the data and digital infrastructure accessibility policies, and establishes the data governance and data management strategy for the city. The Steering Committee advises on issues of digital technology options and solutions.

Cyprus Cluster: The governance enabler of the Cypriot cluster is a Steering Committee comprising the Municipality of Nicosia and CYENS. CYENS will be the coordinator of the effort, given its role as the ICT R&D arm of the Municipality and will act in conjunction with the Technical Services of the Municipality (Research Section and Parks and Gardens Section). These partners will work towards materialising the vision of the Municipality of Nicosia to make Nicosia a modern centre of knowledge, research and innovation; A creative, attractive, "smart", friendly and accessible city that focuses on people and the environment; and socially sensitive that responds to the needs of its citizens by offering them a high quality of life. Of importance are activities that protect the environment with measures and plans that "beat" climate change, promote sustainable urban mobility, and utilise and upgrade technology to provide the best possible service to our citizens

Bulgarian Cluster: The governance enabler of the Bulgarian cluster is the Municipality of Burgas. It plays a central role in the processes of establishing the city's DT by providing administrative support, regulatory alignment, and data access and financial support directly or by participation in different

projects. This ensures that the DT integrates seamlessly with the city's long-term urban development plans and intelligent transformation strategy. The Municipality of Burgas is a leader that defines the change management and communication strategy, monitors the reference KPIs, and establishes the data governance and data management strategy for the city. With its partnerships, membership in regional, national and international organisations, Burgas Municipality guarantees the efficient promotion and dissemination of results, as well as provides conditions for multiplication of the acquired experience.

Teams: A critical part of the innovation process of instantiation of a DT and its success is the formation of an **interdisciplinary team**, combining expertise in IT, engineering, environment, data science, and local governance. These experts should work closely together to support the design, implementation, and management of the DT system.

Engaging domain technical experts will ensure that the DT system is built on solid technical foundations while addressing the specific needs of the implemented use cases. Additionally, the inclusion of experts in local governance will ensure the DT system's alignment with urban planning goals and regulations.

The interdisciplinary team will ensure the involvement of cutting-edge business and academic research, which will enhance the system's technology acquisitions and drive effective innovation.

Public engagement is also an important aspect of stakeholder involvement. By involving citizens and local businesses early in the process, the project will ensure that the system addresses the real-world needs of the community. Stakeholder experience capability establishes operational mechanisms for regular user feedback, fostering a collaborative and iterative approach to ensure ongoing improvement of the DT platform in alignment with user needs and expectations.

Greek Cluster: The GR pilot is supported by several teams with expertise and technical backgrounds. MPAT is offering access to data and digital infrastructure, citizen-supported applications and tools. UPAT is in charge of building and maintaining the pilot DT, interfacing with the digital infrastructure of MPAT. UOAT is also building the 3D representation and services required for the Proof-of-Concept pilot. UoP is developing the AI algorithms and auxiliary tools required for decision making and what-if scenarios. Business partners are providing their guidance and demos over the digital infrastructure for the enabling platforms (Yodiwo) and network /compute infrastructure (p-net). The region of Western Greece is seeking to disseminate results and methodology to other cities.

Cyprus Cluster: For the Cypriot pilot, CYENS – Centre of Excellence, with the experts of the iNicosia DT technical team, will be responsible for the platform upgrades, data processing, and maintenance of the system. In addition, the experts from the Technical Services of the Municipality will offer continuous guidance on the needs and requirements they have. The business partners (eBOS and Primetel) will offer their ICT and Business development expertise. From the Social actors' perspective, the Union of Municipalities and the Cypriot Consumers' Association will make sure that the provided solutions fulfil the widest possible citizen needs.

Bulgarian Cluster: For the Bulgarian pilot Innovative Systems - Burgas EOOD (ISBUR), and the experts of the project municipal technical team, are responsible for platform upgrades, data processing, and maintenance of the system. Their key role is to ensure that the DT is technically robust, scalable and accessible according to the latest cybersecurity requirements. In addition to the technical and municipal experts and partners, the Technical University of Sofia will provide valuable research input, particularly in the areas of ICT, data analysis, and renewable energy technologies. The QH approach

initiatives will be supported by the involvement of the ICT Cluster and DigiHub Burgas with their networking and collaboration knowledge, and will enrich the potential for technological transfer.

3.1.3 Technology selection and reference architecture

Reference architecture and technology selection entail the application of a standardised framework that provides a common structure for designing and incorporating various city components into a DT. This framework should define in a comprehensive manner the relationships between the city`s components to leverage the DT technology alongside the existing infrastructure. The realisation of an ODTF will facilitate the establishment of innovative decision-making processes crucial for the final users. This includes:

- Definition of specific use cases which should be supported, based on the best understanding of the priority needs, and adjustment to the chosen technical solution and Reference Architecture;
- Analysis of the current state of the art in terms of available technologies and applied ones up to now;
- Identification of the targeted services based on the identified use cases;
- Definition of the functional and non-functional requirements related to the defined use case implementation;
- Choosing the right approach for creating a DT which aligns with the specific technical requirements and scalability needs for the specific domain and those of the specific DT;
- Definition of the Components in the Reference Architecture to guarantee the quality and robustness of the solution;
- Analysis and ensuring that the components supporting the DT /either new or existing/ can integrate the existing systems which provide city data, to ensure seamless operation between different components and systems;
- Design of the specific Reference Architecture based on the use cases and defined requirements;
- Detailed description of the multi-layer Reference Architecture and necessary integrations between the included components /IoT devices, ICT infrastructure, city systems, open-data portals and multi-shared platforms/;
- Detailed description of the Technologies applied for integration between the Components.
- Plan for implementation, management, maintenance and upgrade of the Reference Architecture throughout its life-cycle.

Greek Cluster: The Greek cluster METACITIES pilot will utilize DT technology to address challenges:

- Smart Parking: By integrating data such as parking availability, the system will provide real-time updates on available parking spaces, estimate arrival times, and suggest optimal routes. The DT will visualise traffic and congestion in real time and run what-if scenarios to propose solutions for transport challenges, including optimizing traffic flow, pedestrian and cyclist routes, public transport options, parking management, and traffic regulation. Additionally, it will identify the areas of high demand for public transportation and recommend enhancements accordingly.
- Environmental Behaviour Analysis on Traffic Incidents: The system will combine environmental data (e.g., air quality, noise, and smoke levels) with traffic data to analyse their interrelationship and the impact of traffic and incidents on the urban environment. METACITIES will employ the DT to display real-time environmental and noise conditions alongside traffic congestion. An interoperable application will notify stakeholders of potential incidents that could negatively affect air quality.
- Emergency Management: Real-time data collection and analysis will support the creation of an emergency services operating centre, enabling authorities to coordinate actions during traffic incidents. These actions include re-routing traffic and ensuring swift access for emergency vehicles. Over time, this center will evolve into an advanced notification system for drivers,

cyclists, pedestrians, and public vehicles. It will also evaluate and propose solutions for traffic optimization, traffic light management, and justifications for infrastructure investments, such as additional lanes for emergency use.

GR will be based on the Fiware framework.

Cyprus Cluster: Urban planning is a technical and political process concerned with the development and design of land use and the built environment, including air, water, and the infrastructure passing into and out of urban areas, such as transportation, communications, and distribution networks. Urban planning aims to improve the built, economic, and social environments of communities through the organisation of land use, the environment, public welfare, and the efficient flow of traffic and communication.
The Cyprus cluster METACITIES pilot will utilise DT technology to address the following two challenges:

- Urban Heat Island (UHI) mitigation in Nicosia: Utilising real-time environmental monitoring through IoT-based sensors and satellite imagery, the system will visualise heat stress hotspots, enabling targeted interventions like strategic tree planting, creation of urban parks, and installation of reflective surfaces. Predictive analytics and advanced simulation tools within the DT will facilitate scenario testing, assessing how different urban planning strategies, such as expanded green spaces or microclimate corridors, can effectively reduce urban temperatures. Additionally, the DT will integrate detailed data on tree species, their growth characteristics, and cooling capabilities, guiding precise and impactful green infrastructure decisions to enhance urban resilience and resident comfort. By aggregating historical data on temperature trends, resource use and community feedback, the system will provide information to refine long-term UHI mitigation strategies.
- Smart Parking Management: The Cypriot METACITIES smart parking solution will address urban traffic congestion through an advanced Smart Parking Management system integrated within a DT environment. Sensors embedded in parking spaces will relay real-time occupancy data to drivers, enabling efficient navigation to available spots and significantly reducing search times, vehicle emissions, and traffic congestion. The DT will dynamically visualize parking availability, demand patterns, and traffic flows, providing valuable insights for policymakers. It will enable sophisticated analyses, such as identifying peak usage times, evaluating parking behaviors, and suggesting optimal locations for new parking infrastructure or dynamic pricing models. Moreover, the DT will integrate seamlessly with other city systems, such as public transport and emergency services, offering comprehensive mobility solutions and enhancing the overall urban living experience.

Bulgarian Cluster: The Bulgarian cluster METACITIES pilot to be implemented for the city of Burgas will instantiate its DT for Green and Climate adaptive resource management, focusing on 3 use cases

- Renewables (PV) potential and performance analysis tool: For this use case in METACITIES, the goal will be to identify and locate the PV systems installed in the city, register and estimate their current energy production performance, and model the city's PV adoption curve through time. This will be realized by using different data sets, including orthophotomaps, satellite images, data provided by existing platforms, historical data, etc. In METACITIES the approach for this use case will include a general feasibility study, performance analysis, and consideration of key aspects related to the installation of PV systems (resource assessment, site location, building architecture, design, etc.). The estimation of the technical performance indicators will be one key functionality of the DT, in addition to optimization of the energy consumption based on real-time monitoring, fault detection, and condition forecasting. Existing simulation tools will also

be analysed in order to be applied for the assessment of the performance of the PV systems and aid the DT construction. Through the DT, the feasibility of the PV installations in terms of the energy, cost, and design features will be mapped, and the possibility for the implementation of performance prediction algorithms will be analysed. By combining the input data, simulation models, and advanced analytics, the DT city model will become a dynamic and interactive platform for energy performance analysis of public buildings that enables continuous monitoring, pattern analysis, optimization, and decision-making to achieve long-term energy efficiency goals. With these data sources and the proposed technical approach, the DT city model can in addition support policy making on general energy performance improvement of the pilot and future PV implementations in the city.

- Buildings Energy Performance Analysis tool: By using a DT for a public building in METACITIES we will showcase to the users of the energy section of the smart city platform of Burgas the energy performance of a building. Through analysis and visualization of the gathered data, we will provide users with the ability to better understand the buildings' energy consumption. In analysing available data, the focus will be on the definition of the buildings` insulation capacity (i.e., thermal insulation performance) and the assessment of how external variables (e.g., temperature, humidity, solar exposure) influence the building energy performance/consumption. The goals are manifold and include: the understanding of energy performance of buildings, which will drive the analysis on the city's investment needs and (possibly) support the definition of potential financial approaches and mechanisms; understanding how energy consumption varies with meteorological conditions through root cause analysis; and better understanding the impacts of different energy-related interventions performed in the buildings (monitoring analysis), which can be used to better plan future interventions for public buildings and buildings with non-public ownership. In METACITIES the solution will involve gathering information on energy usage patterns and relevant parameters of the building's energy systems. Gathering data for energy consumption analysis will be based on the recording of energy consumption data from various systems, such as HVAC, lighting, and the application of pilot IoT and smart metering technologies. Data regarding energy consumption will be gathered in real time using smart meters and IoT devices matching it with external variables. With the implementation of the IoT devices, a deeper analysis can be made into the specific types of energy consumption in the building and the definition of the thermal insulation performance of the building. If necessary for capturing specific data, on-site metering will also be conducted. This involves installing temporary energy meters or data loggers. The energy performance analysis will also include information about the building's equipment, such as HVAC systems, lighting fixtures, and appliances. This includes equipment specifications, rated capacities, efficiency ratings, and operating schedules. This information will be available from the manufacturer data sheets, equipment manuals, or, if available, maintenance records. The overall goal is to integrate data from various sources to build up a comprehensive dataset that provides a holistic view of the building's energy consumption patterns.
- Budget Planning for Energy Usage and Buildings tool: Following the results from Use case 2, the DT model can be upgraded to become a valuable tool for policy-making decisions on budget planning and effective use of resources, recoupment of initial investments, and managing the costs of energy use both for public and private users. For this purpose, data related to historical costs and prices of resources should be added, preferably in a separate dashboard. In time, when data for more buildings is being constantly accumulated, it will help the experts of the city of Burgas to better estimate investment needs, define priorities for potential local investments, and evaluate financial mechanisms and business models-aimed at improving the energy efficiency indicators and overall energy performance of the city, all these in line with its strategic goals. The technical approach will follow the methodology of performing an overall life cycle cost analysis for the goal of assessing the economic viability of the proposed energy efficiency measures and

PV energy systems. The upfront costs, energy savings, operational costs, maintenance requirements, and the payback period of investments will be evaluated.

Within the METACITIES project, the three participating clusters have defined their version of the standard ODTF, described in detail in Deliverable D3.2. The standard ODTF, comprising the descriptions of the Requirements, Components, Technologies, and Relations, will be detailed in this phase, in order to allow further specification and implementation of each one pilot use case.

3.1.4 Infrastructure

Alignment of the city **Infrastructure Strategy** to the determined **DT objectives** and **use cases** should ensure that all the requirements for the **Infrastructure as an enabler** are met.

Infrastructure strategy assures defining and applying a comprehensive plan for the systematic deployment, upgrading, and maintenance of physical and digital components aimed to be integrated into the Reference Architecture during the realization of the city project, aligned with the city's digital goals to enhance technological innovation – the DT.

That is the reason for which it is very important for the city to be able to create and apply efficient measures for assuring the city`s **Infrastructure Capabilities,** including:

Device platform and device management capability: This capability includes the aspects of planning and executing efficient deployment, maintenance and integration of IoT devices and relevant IT equipment to guarantee the operational efficiency of the smart city ecosystem. The capability can be divided into 2 major sub-capabilities:

- **Device Management** is a major factor that considers what devices are needed, what their requirements are in relation to storage, computing, updating, data processing, connectivity, interoperability and security. The ODTF will serve as the basis for determining which IoT devices will be implemented and installed to assure the city acquisition and maintaining and processing data for DT.
- **Device Platform Management** ensures the different thematic device platforms operate providing: technical ease, scalability, flexibility, extensibility, universality, security, cost, speed, visibility and support. The ODTF will serve as a basis for reviewing your current IoT platforms on compatibility and compliance with the requirements identified.

Greek Cluster: For the Patras use cases and Smart Mobility DT instantiation we investigate the possibility of integrating IoT sensors and networks for real-time data collection on mobility and parking (see Patrasissmart platform), establishing scalable digital infrastructure that supports predictive analytics and decision-making based on the Fiware paradigm, and fostering interoperability with public and private mobility systems and other third party platforms (like Google 2D and 3D maps, applications for illegal parking etc). Traffic estimation and congestion from Google maps and other traffic services, Double/illegal parking incident evaluation platforms, estimated arrival time simulation, bus arrival data from coach and municipal bus platforms, scooter position and availability platforms, third party user input from applications (crowd sourcing incidents, e.g., from sense.city). Furthermore the GR Smart Mobility DT will interface smart city solutions form business partners (e.g smart city platforms and tools from Yodiwo).

Cyprus Cluster: Cyprus Cluster: For the Cyprus cluster, the device platform combines real sensors and simulated devices to support both the smart parking and urban heat reduction use cases. Real-world data is collected through LoRa-enabled parking sensors, weather stations, and environmental sensors

already installed in the Nicosia Smart City infrastructure. Where physical sensors are not yet available or are under testing, simulated devices are used to generate realistic data inputs to ensure that the system can function and be tested under different conditions. All devices and simulated sources are integrated through FIWARE components, using NGSI-compliant data models, for use in the Orion Context Broker. The system supports remote updates, monitoring, and secure connectivity, ensuring that devices can be maintained and scaled efficiently. This setup provides flexibility, supports interoperability, and enables the reliable flow of data across the digital twin platform.

Bulgarian Cluster: For the Burgas pilot the existing data providing devices and platforms, such as the solar city module and the Building Information Management System (BIMS) module of the SmartBurgas platform have been assessed in order to determine their ability to support the new DT application, as well as the necessities for new devices and/or upgrades to be made to add new functionalities, such as 3D modelling of energy infrastructure, predictive analytics for energy consumption and production as well as proposals for adaptations and improvements based on them, related to the available data. The used approach is based on hybrid cloud technology, because this solution delivers a scalable, secure and performant environment. For public presentation of the DT model we use an open urban platform.

Integration Capabilities/Integration, interoperability: This capability refers to the community`s ability to have seamless connectivity and collaboration among different devices, systems/platforms and third services. It assures applying of unified data exchange through standardized communication protocols and helps for adoption of open standards to be the base for a connected, responsive and sustainable digital environment. A city that is mature enough to have a DT should have already implemented its own strategy for integration and interoperability for data, devices, hardware and software. This includes rules for use of APIs, common interoperability standards, the integration of different domain platforms, and services.
The design of the specific DT must ensure future interoperability with current and future infrastructure, based on realization of IoT infrastructure changes and the applied reference architecture. The minimum level of interoperability must be as close as possible to the specifications already identified in the MIMs.

- **Open Source:** According to the EU directives, the city`s digital initiatives should use open-source software. In cases where open source is not an options, availability of common or standardised interface options are sought.
- **Open Standards:** Open standards provide a common ground for interoperability among diverse systems. By aligning with existing open standards and actively participating in their development, the envisaged local DT can easily integrate with other open-source solutions and technologies. Examples include CEN, CENELEC, ETSI and ISO standards.
- **Shared Data Models:** The new DT instantiation should consider the best practices for the adoption of a common set of data models that standardizes the representation of data across different applications. It is important that the design is aligned with main external common data model that establishes protocols for mapping and translating data between systems that may use different data structures and integration of the requirements of EU for the use of shared data models, aligning with MIM2 – Data models https://mims.oascities.org/mims/oasc-mim-2-data-models and capitalizing on results/insights from EU project on Data Space for Smart and Sustainable Cities and communities https://www.ds4sscc.eu/.
- **Open APIs:** The design of the DT is necessary to specify the API requirements to enable secure communication between the different components included in the reference architecture which definitively explains the interaction between the components and third external

systems/services. The use of open APIs, such as RESTful web services is preferable, for their simplicity, scalability, and ease of integration.

- **Building Blocks:** It is highly recommended that the design of the DT considers using a building blocks approach with micro services or task specific containers, to improve interoperability and cost efficiency when deploying similar services for similar use cases. In such cases a catalogue of the building blocks will support the maintenance of future additions.

Greek Cluster: Regarding the Greek Cluster, data from a variety of urban sources is collected in real time and standardized into an NGSI-compliant FIWARE ecosystem based on the Smart Data Models paradigm. This information is then stored in a relational database and utilized by analytics and simulation services to generate insights. A DT application combines these real-time inputs with analytical outputs to deliver a continuously updated 3D visualization of the city.

Supporting this process, a geospatial service manages both physical and virtual assets, which can be displayed and enriched by the analytics from the twin. A robust security layer ensures that data is exchanged safely, while a custom backend further enhances the experience by providing annotated information, orchestrating simulations, and supporting real-time interactions within the immersive urban model. The final integration of geospatial services and the twin's state takes place in the layered, web-based client presented to the users.

Cyprus Cluster: For the Cyprus cluster, the ODTF has been designed with interoperability and open integration at its core. It leverages FIWARE components, including the Orion Context Broker, to ensure NGSI-compliant data exchange and alignment with the Smart Data Models initiative. Open APIs based on RESTful architecture and described using Swagger enable secure and scalable communication between services and third-party systems. Geospatial and 3D assets are integrated using Cesium ion and visualized with Cesium.js and TerriaMap, allowing rich, real-time representation of urban environments. The backend architecture is built on Django and connects to both PostgreSQL (with PostGIS) and MongoDB to manage structured, spatial, and semi-structured data. Simulation outputs are visualized through immersive 3D scenes powered by the Unity engine, a high-performance visualization tool selected for its advanced rendering capabilities in scenarios where open-source alternatives are still evolving. The modular and standards-based design allows for flexible integration of new components and reuse across different use cases and services.

Bulgarian Cluster: Regarding the Bulgarian Cluster, data from a variety of urban sources is collected in special designed data storages and standardized into an NGSI-compliant ecosystem. Burgas urban data have been systematized in a data lake. Part of them, representing real time data, has been analyzed, transformed and visualized on a public platform.

Storage Capabilities /External cloud services vs. Local Data Centres/cloud storage on-premises/: Storage Capabilities must be carefully assessed during the instantiation of the DT to assure the city's ability to securely and reliably store city data. This includes the necessity to design physical and virtual components such as servers, databases, cloud storage, and other technologies that facilitate the storage and management of data.
The Storage strategy of the city must be aligned to the new ambitions for instantiation of the new DT. The designed architecture should consider the needs for: on-premises storage and/or cloud storage.

- **On-Premises storage:** The implementation of on-premises storage measures (e.g., effectiveness, redundancy, scalability, low latency and/or adaptability) should ensure alignment to the DT

infrastructure strategy. The implementation of tools for provisioning and clean-up to automate resource allocation and optimize storage utilization is a must.
- **Cloud storage** /in case it is used/: The implementation of a cloud storage should ensure alignment to the DT infrastructure strategy. Tools that facilitate cloud automatic storage management to enable storage optimization should be applied.

According to the scale and complexity of the data, a **hybrid approach using both local data centers and cloud resources** may be necessary. Local data centers will ensure data security and privacy, while cloud resources can provide the flexibility and scalability needed for large-scale data processing. This approach will allow the DT to operate efficiently under varying workloads, ensuring that the system remains responsive and reliable even as more data is collected and processed.

Greek Cluster: A combination of local data centers and cloud based solutions will be used (the second mainly for backup and forecast).

Cyprus Cluster: CYENS has two local data centers, one for basic computing and storage and one with HPC capabilities. The local DC will keep all digital and geolocated data and the results of all simulations runs. The HPC resources will be used to process the data and perform analyses, models and forecasts that require significant computing capacity.

Bulgarian Cluster: The local data centres will keep all digital and geolocated data. The cloud resources will be used to process the data and perform analyses, models and forecasts that require significant computing capacity. The storage capacity and server performance will be extended if needed.

Computing capacity: Computing capacity refers to the processing power and capabilities of a system or network, including the hardware and software components responsible for performing calculations, running applications, and handling data. The infrastructure strategy of the city related to computing must be aligned to the new ambitions for instantiation of a new DT. The designed architecture should consider the needs for: computing capacity, on-premises, cloud and cloud-advanced technologies.
- **On-Premises:** Instantiation of a DT must include implementation of on-premises computing to assure effectiveness, redundancy, scalability, and/or adaptability. Reviewing existing tools for on-premises computing provisioning and cleanup to ensure alignment with the new design is a must.
- **Cloud:** The architecture solution must reflect all the measures related to computing power provided by cloud and identify tools to facilitate cloud computing automatic management to enable resource optimization and resource allocation if needed.
- **Cloud - Advanced Technologies** DT architecture should determine and implement if needed advanced cloud technologies (e.g., Edge computing, virtual machines, containers and serverless computing). The design should assess the value of each advanced technology considering the specific use case needs.
  - Edge computing enables real-time processing with low latency, efficient handling of large data volumes, increased availability during network disruptions, and compliance with privacy and regulatory requirements.
  - Virtualization enables resource optimization, cost savings through shared resource utilization, improved flexibility in IT infrastructure, and enhanced security measures.
  - Containers enable improved portability of applications, scalability for efficient resource utilization, efficiency gains in Software development and deployment.
  - Serverless computing enables event-driven task execution, real-time analytics capabilities, cost efficiency in resource utilization, and automatic scaling for workload fluctuations.

Network capacity: This capacity is important to reflect the needs of the DT because it allows various components, devices, and systems to exchange information and data in unstoppable flow ensuring effectiveness, adaptability, connectivity, coverage, reliability and redundancy. During the implementation of the DT project ensuring the alignment of the infrastructure measures for providing network capacity is crucial.

- Ensuring the Network Effectiveness refers to the following needs:
  - The Network Capacity and its effectiveness must answer the needs of the reference architecture.
  - Implementation of network capacity monitoring tool to continuously assess network performance, identify potential failures, optimize resource allocation, and ensure the scalability of the infrastructure is inevitable for the smart city environment.
  - Increasing the network capacity and effectiveness to be able to sustain more than 1GB of traffic and/or more than 1000 Devices is a basic need.
- Network Connectivity refers to the following needs:
  - The city Network Connectivity Strategy should be aligned with the new ambition for DT implementation and the necessary bandwidths should be in place to answer the needs for data transmission.
  - Improvement of the quality of the city's public free Wi-fi network and coverage of the city territories with this service will assure accessibility for all the residents.
- Network Adaptability refers to the following needs:
  - Ensuring the adaptability of the network is becoming important with respect to integration of emerging technologies in a seamless, and agile way. A future proof of the network infrastructure must meet the new demands of a smart city in aspect of network scalability – the ability to accommodate a fast growing number of connected devices and users; low network l high-speed connections enable the necessary data transmission rates and support the operation of bandwidth intensive applications.
  - Network Coverage refers to the following needs: It may become a challenge for the smart city to provide dense Network Coverage for all the territories of interest but the city's technological and infrastructural initiatives must aim to increase the deployment activities covering more remote and less populated areas in order to provide equal access to the services.
  - Network Reliability and Redundancy refers to the following needs: More specific initiatives should be considered, such as diverse path routing, automatic failover detection systems and effective power solutions, various network paths, Load Balancing solutions and regular testing and simulation procedures should be considered to assure DT implementation.

There are various options regarding network technologies that address specific requirements for the data collections and/or sensor interconnection in a City environment and they are discussed in D3.1 and D3.2. To summarise the findings, smart city budgets usually opt for unlicensed, low-capacity networks like LORA-Wan and or Wifi; however, in some cases, where mobility and/or high-performance networks are required, 4G/5G networks are utilised.

Greek Cluster: In order to interconnect the hundreds of sensors (smart parking etc), City of Patras relies on LoRa wan networks while mobile units on vehicles are supported by NB-IoT and 4G/5G connectivity.

Cyprus Cluster: Information to the iNicosia DT will be provided via the Nicosia Smart City platform (NOKIA IoC). The underlying network collecting data from sensors is LoRa-based. Information from the LoRa gateways to the City NOC is through the municipality's own optical underground network.

Bulgarian Cluster: Data delivery from IoT devices is collected via Bluetooth technologies on local gateways, archived and sent to main data centres using secure IP tunnels through own or hired optical underground network or 4G/5G networks.

3.1.5 Data management capability

For instantiation of the DT the city must assure effective collection, processing, management, sharing and utilisation of data from various sources and domains, including relevant infrastructure, technologies and processes in place. It is needed that the city has a clear strategy related to data / e.g. rules for acquisition, storage, management, sharing, usage and governance of data/ which can support the development of new city digital services which improve quality of life for residents.

Data Governance: Establishing clear data governance policies and tools will ensure that the policies and standards, quality, security and compliance of the data used and collected by the city is essential. The activities should consider the following aspects:

Data Quality/data collection and management

- DT to Metaverse initiative drives the community towards a more data-driven paradigm by modernising data collection methods, as well as implementing and improving the collection of the data sources, e.g., based on specific events, and considering the integration of real-time data. *Real-time collection is one of the most important components for a smart city*, since it helps the community to make informed, timely decisions, enhancing efficiency and the quality of decision-making. The increase in the variety and quantity of data and data sources improves the city's information landscape and expands the opportunities for new insights to be produced as a result of the achieved integrated technology.
- Ensuring the *quality of data is crucial* for the accuracy and reliability of the DT. Data verification processes must be implemented to filter out any inaccurate or incomplete data. These processes should include cross-referencing data from multiple sources to ensure consistency. Regular data audits should be implemented to maintain high data quality standards. By maintaining data quality, the systems will provide reliable insights that stakeholders can trust for decision-making.

Data Analysis

- Data Analysis is closely related to the city`s DT use case implementation because based on the way the data is analysed meaningful insights from it can be derived enhancing decision-making, identification of patterns, and further on taking informed business decisions.
- The new technological innovation design should include reliable tools to support the data analytics.

Data Centralisation: For continuous and seamless success of the DT to Metaverse technology adoption of centralisation of the data of the city becomes an important requirement.

Data retention/backup: By increasing the variety and quantity of data sources that are covered by the city's data retention and backup strategy, sustainability, comprehensive analysis, and holistic understanding of the dynamics of the city are expected.

Greek Cluster: The DT will gather data from a variety of sources, including real-time parking sensors through the Patrasis smart platform, historical data from the same sources and third-party data from platforms (like Google 2D and 3D maps, applications for illegal parking, etc. 3D representation efforts feed the 3D service engines with various enablers.

Cyprus Cluster: The DT initiative for iNicosia drives a significant shift toward a more data-driven urban planning approach by modernizing real-time data collection methodologies across Cyprus. It integrates diverse local data sources, including IoT-based environmental and traffic sensors deployed throughout Nicosia, smart parking infrastructure, municipal records, and advanced satellite imagery provided by platforms like GAEA and Copernicus. Ensuring data quality is paramount; thus, rigorous validation processes are implemented, involving cross-referencing sensor data, satellite observations, and official city records, complemented by regular data audits conducted collaboratively with the Municipality of Nicosia. Centralisation of these varied datasets within a unified DT platform is critical for seamless and continuous urban management, enabling comprehensive data analysis through advanced analytical tools tailored to local conditions. Predictive models and simulation scenarios are utilised to address urban heat islands, optimise traffic flows, and effectively manage city resources. To further enhance sustainability and support a holistic understanding of urban dynamics, comprehensive data retention and backup strategies are employed, preserving historical data that enables continuous monitoring, comparative analysis, and informed, long-term decision-making for the city's ongoing resilience and improved quality of life.

Bulgarian Cluster: The DT will gather data from a variety of sources. Each data source will contribute to creating a comprehensive picture of Burgas' energy resource management landscape. Real-time IoT devices will provide live updates on energy production, while satellite images and weather forecasts will inform predictive models, helping to anticipate future energy output under different environmental conditions.

3.1.6 Cybersecurity

Cybersecurity Policy: A robust and scalable IT infrastructure is crucial for the effective operation of the DT. This infrastructure will include physical servers, cloud resources, and secure data storage facilities that can accommodate large datasets generated by real-time IoT devices and other data sources. The infrastructure must support high data throughput to ensure real-time data processing and analysis. Additionally, the DT implementation will depend on the ability to ensure sufficient computing power to run big data and/or simulations and predictive models without compromising performance.

Furthermore, the infrastructure will need to integrate with existing municipal administrative and intelligent smart systems, and provide an interface that allows users to easily access data and insights. To ensure the system is future-proof, it should be designed with scalability in mind, allowing for the integration of additional technologies and data sources over time.

All of the above must be considered when the city develops its Cybersecurity Strategy and policies. Measures such as access control procedures, authentication federation tools, and the data protection and privacy policies in place must be incorporated to ensure compliance.

Since the new DT technology demands are higher in respect of secure interoperability, the cybersecurity framework should emphasise network security and endpoints security, including:

- Effective investigating procedures that respond to security incidents and ensure a rapid and informed mitigation response.
- Rules for security patches ensuring compliance with the requirements of the systems.
- Real-time monitoring for city-wide security events to prevent, detect and respond promptly to potential cyber threats.
- Regular vulnerability assessments on the IT infrastructure to proactively identify and address potential security issues.

- Enhancing Security Advanced Measures, such as advanced threat mechanisms and implementing multi-layer security protocols.
- Implementation of public subnet security policies.
- Review the Disaster Recovery Plans related to Business Continuity Plan and the backup solutions, ensuring compliance with the city's cybersecurity approach and requirements.

Privacy Compliance: The DT must comply with relevant data protection regulations, such as the GDPR, to ensure that all data is handled responsibly and securely. Security is a critical concern, especially given the sensitive nature of some of the data being processed, such as building energy consumption and predictive models of the city's energy future. To protect against potential cyber threats, the DT must implement comprehensive cybersecurity measures. This includes encryption for data at rest and in transit, regular security audits, and the use of firewalls and intrusion detection systems. Additionally, access controls must be put in place to ensure that only authorised personnel can access or modify sensitive data.

Training personnel on cybersecurity best practices is also essential to minimise the risk of human error that could lead to data breaches. Regular updates to the system's security protocols will ensure that it stays protected against emerging threats.

This includes setting of rules who has access to the data, how it is used, and how it is shared with third parties. The DT must comply with relevant data protection regulations, such as the General Data Protection Regulation (GDPR), to ensure that all data is handled responsibly and securely. By implementing strong data governance policies, the project will protect sensitive information and ensure transparency in its operations.

3.1.7 Digital twin platform implementation

The existing local city digital platform is the major DT enabler. It serves as a foundational step for the full-scale implementation of the specific DT platform because it provides a robust and scalable foundation, facilitating incremental enhancements as the city evolves its digital landscape. Through leveraging the foundational capabilities, especially data and integration of third services, and deployment and integration of new comprehensive technological infrastructures designed to support various digital services, applications, and data-driven functionalities, the DT framework and reference architecture are implemented.

DT Implementation Design - Sample Design and Description: The DT Deployment encompasses the development of the DT from the Local Digital Platform, incorporating historical data and foundational functionalities, to a more advanced DT with real-time data and AI/ML integration, aligned with the city's objectives through continuous updates.

Based on the existing Local Digital Platform and on the designed DT implementation, different pilot DTs in different domains can be introduced to explore initial functionalities and scenarios that fulfil prioritised use cases, following the same methodology of implementation:

- Leverage the existing data models and incorporate them into the pilot DT, enabling the realisation of designed use cases;
- Ensure that the necessary historical data is needed;
- Ensure the incorporation of real-time data needed;
- Perform tests with the pilot DT to evaluate and validate its performance and functionalities;
- Based on the performed tests, evolve the pilot DT to production environment and start tracking and analysing the data flow in its dynamics;

- Refine the visualisation methods to enable users to understand and interpret the generated insights;
- Implement robust standards and protocols for data management, integrating the DT with the various city's components in a seamless way (e.g. IoT Devices, systems/ applications, among others);
- Assure interoperability with all city components from the reference architecture;
- Evolve the DT to address the defined strategic objectives, needs and use cases by using the incorporated simulation capabilities.
- Simulation Models: The core of the DT is the development of accurate simulation models for each use case. These models need to be highly adaptable, allowing the simulation of different processes. These simulations will help city planners understand how different factors impact the problem solution and where improvements can be made. These integrations will enable urban planners/users of DT to perform more detailed analyses and make informed decisions about future.
- Ensure the DT leverages all the related urban real-time data and predictive data to generate, monitor and visualise real-time insights, incorporating Big Data analytics, introducing data prediction models and simulation capabilities;
- Refine the 2D or 3D interface, ensuring it is aligned with the strategic use cases that will be delivered during the implementation;
- Incorporate into the DT, if needed, high-performance computing methods enabled through Artificial Intelligence and Machine Learning.
- Advanced Features: The DT, as a rule, needs to incorporate advanced features such as machine learning algorithms and AI-based predictive models. These features will enhance the system's ability to predict outputs, detect patterns, and optimize processes. The inclusion of these technologies will ensure that the DT is not only a tool for current analysis but also a forward-looking platform that can adapt to the city's evolving needs.
- Perform tests on the advanced features and prepare the incorporation of functionalities of the DT to the Metaverse;
- Engage stakeholders to capture feedback for the performance, usability and alignment with the community needs and objectives;
- Implement ethical and legal mechanisms to continuously provide data and evolve the DT implementation; Assess and plan the skills and knowledge required for the DT deployment and if necessary, hire additional professionals to assure up-skilling of the current workforce or work with external partners, all in line with the DT business model and management strategy.

Sample Design and Description: In the **Error! Reference source not found.**, there are drawings and the relevant text explaining in detail the technical principles on which the ODTF for the different clusters/ domains is built.

Data Security: Naturally, data security is of paramount importance. We used an approach in which we placed a Mikrotik VPN server and firewall system at the input and output of data from our virtual systems. We built separate virtual systems for receiving and transmitting data via API services. For JSON and GeoJSON requests, we use session keys for data transfer based on a user and password, or locking access by IP addresses. For access to views of some databases or map services, we build VPN connections with 128-bit encryption. And for the transfer of large data sets, we chose an SFTP service based on the SSH protocol.

Implementation capability: Implementation Readiness Capability ensures the city is prepared for the successful deployment of the DT. It involves a thorough review of the alignment with the objectives

and defined use cases and respective Reference Architectures, as well as the key foundational capabilities, such as Integration, Data, Processing, Storage, Network, Computing and Governance, encountering the following:

- The designed Reference Architecture should ensure the optimal fit of the DT with the city's technological and governance landscape.
- Implementation of foundational capabilities based on robust standards and protocols will ensure the seamless integration of the DT and various city components.
- The existence of Open Data Source(s) to provide essential information and data in real time will assure that the DT represents a realistic and dynamic picture of the physical world;
- The implementation of tailored Data Analyses reflecting the needs of the interested parties will assure effective real-time visualisation tools, and will be supported by advanced data processing, allowing advanced analytics such as artificial intelligence, machine learning, and big data analytics.
- The expansion strategy for the DT of the city should be considered carefully with respect to storage capabilities and network capacity to ensure optimal functioning in time.
- The use of advanced cloud, storage, and computing methods (e.g., containers, virtual machines, among others) should also be considered for ensuring alignment with the community's ambitions.
- Establishing and continuous improvement of Security capabilities and cybersecurity policies of the city will ensure safe and compliant usage of the DT, ensuring data protection and ethics

Training and Support: To ensure the successful implementation of the DT, a comprehensive and scalable training program must be provided for all users according to the ways that they will use the system. The program must cover all aspects - from basic system operations to advanced data analysis techniques. Providing the stakeholders with the respective skills and knowledge they need will ensure the use of the DT as an effective and valuable tool for decision-making.

Validation and Testing Capability: The validation process is critical for ensuring that the DT provides reliable and actionable insights. User experience feedback, when established as regular operational mechanism can foster resilient and collaborative approach in refining and improvement of the DT over time. Regular updates to the models will be necessary as new data is collected, ensuring that the DT remains accurate and up-to-date. Once the simulation models are developed, they must undergo rigorous testing to ensure their accuracy. This process involves validating the models by comparing their predictions with real-world data collected from users.

As the DT is designed to be a dynamic system that evolves over time based on feedback from its users. Feedback loops must be established to gather input from stakeholders, including city planners, technical experts, and building managers and others. Appropriate channels to gather user feedback will help to understand how well the digital platform is performing in real-world scenarios (e.g., beta-testing version). This feedback will be used to refine the system’s models, improve its user interface, and ensure that it meets the needs of its users.

By incorporating feedback into the system’s development, the project will ensure that the DT remains relevant and effective in supporting the city’s long-term energy goals.

Inform users about the implemented changes by highlighting how their feedback has influenced improvements, and establish mechanisms for users to share their feedback regularly to enable continuous improvement of the local digital platform.

Ongoing Monitoring and Refinement: Once the DT is fully operational, its performance will be continuously monitored to identify areas for improvement. As new data becomes available and as the city's energy landscape evolves, the simulation models will need to be updated to reflect these changes.

- The city should identify and set specific KPIs that align with the objectives and monitor them. These could include metrics like user engagement, conversion rates, click-through rates, reach and sentiment analysis, accessibility and useability.
- Establishing the process for continuous improvement based on insights gained from monitoring activities will guarantee upgrades to the DT that answer the evolving needs and dynamics of the city.
- Monitoring the technical performance of the DT, including response times, data processing speed, and overall system efficiency, will help address any bottlenecks or performance issues.

Ongoing technical support should also be provided to ensure that the system continues to operate smoothly after it is fully implemented.

3.1.8 Expand strategy

This enabler aims to define the city's goals related to the implemented DT and identify an expanding number of specific use cases that the city wants to implement.

The city's digital vision and ambition in the context of sing DTs guides the technology investments, and shareholders' involvement that enables using the full potential of DT capabilities for sustainable and resilient urban development, leveraging advanced technologies to enhance urban planning, optimise resource management, improve citizen services, and foster innovation.

The prioritised by the city use cases and the digital services should be selected choosing the most community effective one(s) for implementation after Business and financial analyses.

Expand to the Metaverse: When the DT is in place to reflect the real physical world, the integration of its different counterparts to the Metaverse can offer dynamic and interactive simulations, analyses, and optimised services or platforms. Within the immersive environment of the Metaverse, the DT serves as a critical tool, establishing users to engage with and/or manipulate complex systems in a controlled virtual environment.

The convergence of the DT and Metaverse technologies is particularly transformative. The synergy allows for real-time and predictive monitoring, as well as scenarios for testing without the constraints of physical reality, leading to enhanced efficiency, reduced downtime, and informed decision-making, which is very useful for city planning.

Moreover, the integration of a DT in the Metaverse facilitates collaborative endeavours across geographical or social boundaries, empowering stakeholders to work together on virtual models/processes. For the cities such a collaborative approach revolutionizes public policies design, urban planning, and operational activities, making DTs in the Metaverse indispensable assets for the cities.

By staying ahead of technological advancements, the DT upgraded to Metaverse is remaining a cutting-edge tool for supporting the city's sustainability.

When designing the reference architecture of the DT considering further expansion to the Metaverse is a must as discussed in more detail on Chapter 4.

Implementation and Integration/Instantiation

Pilot Projects: Before the DT is fully implemented, pilot projects will be conducted in selected public areas. These pilots will allow the system to be tested in a controlled environment, providing an opportunity to identify and address any technical challenges before full-scale deployment.

The pilot phase will also help stakeholders understand how the system can be integrated with existing processes and provide valuable feedback on its usability.

During the pilot phase, data will be collected from real DT systems and used to test the DT's ability to predict energy production and optimise system performance. Any issues identified during the pilot phase will be addressed, and the system will be refined accordingly.

Integration with Real City Planning Processes: One of the key benefits of the DT is its ability to integrate with existing urban planning systems and processes. By providing real-time data on energy production and consumption, the DT will enable city planners to make informed decisions about future energy infrastructure investments. For example, the system could help identify the most suitable locations for new PV installations based on current energy needs and projected population growth.

In addition to energy planning, the DT will provide insights that can support broader urban development initiatives. For example, by analysing the impact of different building designs on energy production, the system can help architects and developers design more energy-efficient buildings.

3.2 Roadmap towards Digital Twin Implementation

The guidelines elaborated above can ensure a structured and efficient implementation of DTs, which can be developed for different domains and specific use cases, leading to enhanced operational efficiency, decision-making capabilities and know-how sharing and socio-economic sustainability.

The document below will further shape the path for replication by other cities, adding more details and insights of each cluster DT implementation, piloted for the METACITIES project:

- We will go through the realisation of one's own for the specific cluster domain.
- The cluster roadmaps will outline the time frames and the resources needed.

TABLE 2 ROADMAP TOWARDS DIGITAL TWIN IMPLEMENTATION

Phase: DEFINITION OF OBJECTIVES AND GOALS					
Activity	**Responsible party**	**Timeline**	**Interaction with third parties**	**Resource /Assets/Events/ Tools**	**Result**
Definition of key objectives	The owner of the use case	During the initial stage of strategic planning	Citizens, NGOs, businesses, academy	Policy makers, city strategy makers, administration of the city	Defined key objectives
Definition of scope of use case / use cases	The owner of the use case	During the stage of action planning	Citizens, NGOs, businesses, academy, cluster partners	Policy makers, city strategy makers, administration of the city	Defined scope of use case/use case
CY Cluster Objectives and Goals: To implement a DT capable of supporting sustainable urban planning and enhancing environmental resilience in Nicosia. The system will leverage real-time and historical environmental and mobility data to address two key challenges: (1) mitigate Urban Heat Island (UHI) effects through strategic green infrastructure planning, and (2) improve mobility and reduce traffic congestion through a Smart Parking Management system. The					

overarching goal is to align urban development with the Municipality's vision for a green, livable, and technologically integrated city that places citizens' well-being and climate adaptation at its core.

Responsible Party: CYENS and Municipality of Nicosia

BG Cluster

Objectives and Goals: To implement a DT by up-scaling of the existing SmartBurgas City Platform, emphasizing on applications related to energy efficiency and climate adaptive policies that help better resource management and citizen awareness

Responsible Party: Municipality of Burgas

GR Cluster

Objectives and Goals: To implement a DT to help vehicles, pedestrians and bicycles move safely and smoothly through complex urban environments, serving the goals that are set for the Smart Transport priority for Safety, Quality of Life, Green City, Accessibility and Inclusivity goals for the City of Patras.

Responsible Party: Municipality of Patras

Phase: GOVERNANCE AND STAKEHOLDER ENGAGEMENT					
Activity	**Responsible party**	**Timeline**	**Interaction with third parties**	**Resource /Assets/Events/ Tools**	**Result**
Identification of the stakeholders	The administration of each cluster members	During the stage of project planning	Citizens, NGOs, businesses, academy, cluster partners and other consultative bodies of the Municipality	Joined Stakeholders events	Identified stakeholders for the pilot implementation / use case
Definition of a change management strategy	**Assigned enabler/ governance structure /**The administration	During the preliminary analysis	Policy makers and administration of owner of use case	Preliminary analysis and strategic action plan	Defined management strategy

	of Municipality/				
Definition and design of communication strategy	**Assigned enabler/ governance structure /**The administration of Municipality/	During the preliminary analysis	Policy makers and administration of owner of use case	Preliminary analysis and strategic action plan	Defined and designed communication strategy
Definition of the reference KPIs and tools for monitoring	**Assigned enabler/ governance structure /**The administration of Municipality/	During the preliminary analysis	Pilot implementation team	Preliminary analysis and strategic action plan	Defined the reference KPIs and tools for monitoring
Establishing a data governance and data management strategy	The administration of Municipality	During the preliminary activities and pilot implementation	Pilot implementation team including BG cluster experts	Pilot data management strategy	Established data governance and data management strategy for the pilot
Teams	**Per Cluster**	During all phases of the pilot instantiation	QH parties	Human resources	Established pilot management and implementation team to assure compliance to defined goals and technical standards

CY Cluster

The governance enablers of the Cyprus cluster are: The Municipality of Nicosia, CYENS Centre of Excellence, municipal Technical Services, business partners, and civil society actors. The Municipality leads policy direction and integrates DT outcomes into urban planning and climate strategies. CYENS coordinates technical implementation, including sensor integration, data analysis, and 3D visualisation. Municipal departments, particularly Parks and Gardens, contribute environmental expertise, while CYENS and others support smart mobility solutions like smart parking. Companies such as eBOS and Primetel provide ICT development and analytics. Civil society groups ensure that citizens needs are reflected, fostering community engagement and acceptance.

Identification of the stakeholders: The Municipality of Nicosia, CYENS Centre of Excellence, Technical Services of the Municipality, eBOS, Primetel, Union of Municipalities of Cyprus, Cypriot Consumers' Association

Teams: CYENS is the main technical partner, supported by the Municipality of Nicosia's Technical Services for domain expertise. eBOS and Primetel provide ICT and integration support. Civil society actors, including the Union of Municipalities of Cyprus, ensure alignment with citizen needs.

BG Cluster

The governance enabler of Bulgarian cluster is: the Municipality of Burgas. It plays a central role in the processes of establishing the city DT by providing administrative support, regulatory alignment, and data access. This ensures that the DT integrates seamlessly with the city's long-term urban development plans. The Municipality of Burgas is a leader that defines the change management and communication strategy, monitors the reference KPIs, establishes the data governance and data management strategy for the city. With its partnerships, membership in regional, national and international organizations, Burgas Municipality guarantees the dissemination of results and provides conditions for multiplication of the acquired experience.

Identification of the stakeholders: The administration of Burgas Municipality, DigiHub, ICT Cluster and ISBUR.

Teams: Innovative Systems - Burgas EOOD (ISBUR), as the main technical partner for the pilot,other municipal technical partners providing complementary services, the Technical University of Sofia providing input, particularly in the areas of ICT, data analysis, and renewable energy technologies. ICT Cluster and DigiHub Burgas assuring QH involvement with their networks and collaboration knowledge to enrich the technological transfer.

GR Cluster

The governance enablers of the Greek cluster are: the Municipality of Patras, the Region of Western Greece, Patras Hospitals, and the Chamber of Commerce of Achaia, which engages in a detailed stakeholder analysis, exploring technical dimensions. The Municipality of Patras, pivotal in this collaboration, leads European funding programs for urban infrastructure and technological integration, utilising smart city initiatives to enhance

transportation systems. The Region of Western Greece, focusing on demographics, tailors policies to meet the diverse needs of its populace, ensuring inclusivity in smart mobility solutions. Patras Hospitals provide a technical perspective by integrating advanced medical transportation technologies, optimising emergency response systems, and supporting telemedicine for remote healthcare. At the same time, the Chamber of Commerce of Achaia conducts economic analyses, identifying opportunities for technology-driven businesses and aligning them with smart mobility initiatives.

Identification of the stakeholders: The administration of the Municipality of Patras, the Region of Western Greece, Patras Hospitals, and the Chamber of Commerce of Achaia.

Teams: Yodiwo, as the main technical partner for the pilot, other municipal technical partners providing complementary services, the University of Patras providing input, particularly in the areas of ICT. University of Peloponnese providing services like data analysis. PNET supports network deployments and Metaverse tranisition .

Phase: TECHNOLOGY SELECTION AND REFERENCE ARCHITECTURE					
Activity	**Responsible party**	**Timeline**	**Interaction with third parties**	**Resource /Assets/Events/ Tools**	**Result**
Definition of specific use cases which should be supported by the digital twin	The owner of the pilot /the Municipality / together with the cluster partners	During the METACITIES project planning	Stakeholder consultation based on the QH approach	Smart city working groups, demand analysis based on inquiries	Defined specific use cases
Analysis of the current state of the art	Enabler and pilot implementation team	In the beginning of the project implementation	Pilot implementation team including cluster experts	Research and analysis based on inquiries and technological and knowledge state of the art research	Analysis of the current state of the art in Deliverable 3.1

Identification of the targeted services based on the identified use cases	Enabler and pilot implementation team	In the beginning of the project implementation	QH partners	Statistical analysis, analysis of the existing services, technical research, demand research,	Identified targeted services See appendixes
Definition of the functional and non-functional requirements related to the defined use case implementation	Enabler and pilot implementation team	During the preliminary design phase of instantiation process	QH partners	State of the art analysis, service demand analysis, feedback from citizens, technical analysis	Defined functional and non-functional requirements related to the defined use case implementation See Deliverable 3.2
Choosing the right approach for creating a Digital Twin which aligns with the specific technical requirements and scalability needs for the specific domain and those of the specific digital twin	Owner of the pilot, pilot enabler and pilot implementation team	During the preliminary design phase of instantiation process	QH partners	State of the art analysis, service demand analysis, feedback from citizens	Chosen approach for creating a Digital Twin. For aligning the needs with the technical requirements, the basic approach for several use cases is applied as follows: real-time data and registry data is compiled into digital twin application with assured embedded capabilities for changing/ modification of the input data flows to get simulations with results answering the use case description.

Definition of the Components in the Reference Architecture to guarantee the quality and robustness of the solution	Pilot implementation team and municipal team for implementation of Smart city projects	During the initial design phase of instantiation process	Technical partners - service providers and infrastructure providers	Technical meetings of pilot implementation team	Defined Components in the Reference Architecture See Deliverable 3.2
Analyzing and ensuring that the components supporting the Digital Twin /either new or existing/ can integrate the existing systems	Pilot implementation team and municipal team for implementation of Smart city projects	During the initial design phase of instantiation process	Technical partners - service providers and infrastructure providers	Analysis of the available resources /existing and potential expansion needs	Analyzed potential for supporting the future digital twin development ensuring that the components will support the new integrations See Deliverable 3.2
Design of the specific Reference Architecture based on the use cases and defined requirements	Pilot implementation team and municipal team for implementation of Smart city projects	During the instantiation phase	Cluster members and partners	Specifications and architecture of digital tools	Reference Architecture for the defined use cases See Appendixes
Detailed description of the multi-layer Reference Architecture and necessary integrations	pilot implementation team and municipal team	During the instantiation phase	*	**	Detailed description of the multi-layer Reference

between the included components /IoT devices, ICT infrastructure, city systems, open-data portals and multi-shared platforms/	for implementation of Smart city projects				Architecture for the different use cases See Appendixes
Detailed description of the Technologies applied for integration between the Components	pilot implementation team and municipal team for implementation of Smart city projects	During the instantiation phase	Providers of the smart city systems technologies for the Municipal systems related to the use cases	Technical specifications for the applied technologies	Detailed description of the applied technologies for the defined use cases See Appendixes
Plan for implementation, management, maintenance and upgrade of the Reference Architecture throughout its life cycle	Owner of the pilot, pilot enabler and pilot implementation team	During the initial design phase of instantiation process and during all phases of implementation and life cycle	Technological providers for the relevant interfaces for the components used for the use cases	Delivery and implementation schemes, implementation, management, maintenance and upgrade draft/ awarded contracts	Implemented, managed, maintained and upgraded architecture for the use cases
CY Cluster Specifications and architecture of digital tools: iNicosia platform, Nicosia smart city infrastructure, CYENS data services, environmental sensors, mobility data tools Cluster members and partners: CYENS, Municipality of Nicosia, eBOS, Primetel, and city contractors					

*CYENS, Municipality of Nicosia, eBOS, Primetel, and city contractors

**iNicosia platform, Nicosia smart city infrastructure, CYENS data services, environmental sensors, mobility data tools

BG Cluster

Specifications and architecture of digital tools: GIS Burgas platform, Burgas Solar city platform and SmartBurgas platform as basis for upgrade in relation to the new defined specific requirements for use case 1.

Cluster members and partners: Project Partners, Sofia University, AI departments, University of Architecture, Civil Engineering and Geodesy;Suppliers of photographic equipment and server space; AI and technology oriented companies; Suppliers and manufacturers of PV systems; Consultative Unit for Climate Adaptation, Energy office Burgas, Energy cooperatives.

*Technical teams which implement the GIS Burgas platform, Burgas Solar city platform and SmartBurgas platform and maintain the components

**Specifications of city infrastructure related to PV roof systems owned by municipality. Data specification of the Burgas Solar city platform; Data exchange specifications for GIS Burgas and SmartBurgas platforms.

GR Cluster

Specifications and architecture of digital tools: Google maps, municipality of Patras infrastructure, Patras smart city platform, fiware infrastructure of University of Patras, Yodicity platform

Cluster members and partners: University of Patras, University of Peloponnese, Yodiwo, P-NET, Municipality of Patras and their contractors

*University of Patras, University of Peloponnese, Yodiwo, P-NET, Municipality of Patras and their contractors

**Google maps, municipality of Patras infrastructure, Patras smart city platform, fiware infrastructure of University of Patras, Yodicity platform

Phase: INFRASTRUCTURE					
Activity	**Responsible party**	**Timeline**	**Interaction with third parties**	**Resource /Assets/Events/ Tools**	**Result**

Device platform and device management capability assessment	Owner of the pilot, pilot enabler and pilot implementation team	During the initial phase of instantiation process	Device platform and device management providers	Assessment of devise platform and device management capabilities needed to be assured for the use case	Assured devise platform and device management capability for the use cases
Integration Capabilities/Integration, interoperability assessment	Owner of the pilot, pilot enabler and pilot implementation team	During the initial phase of instantiation process	Integration Capabilities/Integration, interoperability providers	Assessment of Integration Capabilities/Integration, interoperability for the use case	Assured Integration Capabilities/Integration, interoperability for the use cases
Analysis of Storage Capabilities /External cloud services vs. Local Data Centers/cloud storage on-premises/ and computing capacity	Owner of the pilot, pilot enabler and pilot implementation team	During the initial phase of instantiation process	Storage Capabilities /External cloud services vs. Local Data Centers/cloud storage on-premises/ providers and available computing capacity	Assessment of Storage Capabilities /External cloud services vs. Local Data Centers/cloud storage on-premises/ and computing capacity for the use case	Assured Storage Capabilities /External cloud services vs. Local Data Centers/cloud storage on-premises/ and computing capacity for the two use cases
Computing capacity	Owner of the pilot, pilot enabler and pilot implementation team	During the initial phase of instantiation process	Computing capacity providers	Assessment of Computing capacity for the use case	Specific data governance framework for the use cases

Phase: DATA MANAGEMENT CAPABILITY					
Activity	**Responsible party**	**Timeline**	**Interaction with third parties**	**Resource /Assets/Events/ Tools**	**Result**
Data Governance	Owner of the pilot	During the initial phase of instantiation process	Policy makers and citizens	National and local data governance framework	Local data quality and data collection and management procedures for the use cases
Data Quality/data collection and management	Owner of the pilot, pilot enabler and pilot implementation team	During the initial phase of instantiation process	Municipal data manager, technical implementation team for the municipal smart systems team	Local data quality and data collection and management internal municipal rules for the use case	Analyzed data for the two use cases
Data Analysis	pilot enabler and pilot implementation team	During the initial phase of instantiation process	Data Analysis providers - universities, AI platforms, etc.	Specific Data Analysis for the use case	Assured Data retention and backup for the two use cases
Data Centralization Data retention/ backup	pilot implementation team	During the initial phase of instantiation process	Technical experts and providers related to Data Centralization Data retention/ backup processes	Data Centralization Data retention/ backup procedures and process assurance	Defined specific use cases

Phase: CYBERSECURITY					
Activity	**Responsible party**	**Timeline**	**Interaction with third parties**	**Resource /Assets/Events/ Tools**	**Result**
Cybersecurity Policy	Owner of the pilot, pilot enabler and pilot implementation team	During the initial phase of instantiation process	Cybersecurity technological providers	National and local Cybersecurity framework, municipal policies for assuring cybersecurity	Assured cybersecurity implementation rules related to the use cases
Privacy Compliance	Owner of the pilot, pilot enabler and pilot implementation team	During the initial phase of instantiation process	GDPR manager	National and local Privacy Compliance rules	Assured Privacy Compliance rules for the use cases
Phase: DIGITAL TWIN PLATFORM IMPLEMENTATION					
Activity	**Responsible party**	**Timeline**	**Interaction with third parties**	**Resource /Assets/Events/ Tools**	**Result**
Digital Twin Deployment	Owner of the pilot, pilot enabler and pilot implementation team	During the instantiation phase for the use cases	QH	Digital twin reflecting aspects relevant to the use cases	Front end for the use cases within the Deployed Digital Twin
Implementation capability	Owner of the pilot, pilot enabler and pilot implementation team	During the instantiation phase for the use cases	Technical and digital architecture providers	Digital twin reflecting aspects relevant to the use cases	Front end for the use cases within the Deployed Digital Twin

Training and Support	Pilot implementation team	During the instantiation phase for the use cases	Technical providers	Program for training, monitoring and support	Trainings related to pilot implementation
Validation and Testing Capability	Pilot enabler and pilot implementation team	During the instantiation phase for the use cases	Technical providers	Validation and Testing procedures	Validation after testing of pilot implementation
Ongoing Monitoring and Refinement	Owner of the pilot, pilot enabler and pilot implementation team	During the instantiation phase for the use cases	Technical providers	Monitoring programs and procedures	Ongoing Monitoring after pilot implementation
Phase: EXPAND STRATEGY					
Activity	**Responsible party**	**Timeline**	**Interaction with third parties**	**Resource /Assets/Events/ Tools**	**Result**
Expand to Metaverse	Owner of the pilot, pilot enabler and pilot implementation team	After pilot phase	Third party technical providers	Metaverse applications	Interaction of the user through Metaverse related to specific user story
Phase: Pilot use case implementation					
Activity	**Responsible party**	**Timeline**	**Interaction with third parties**	**Resource /Assets/Events/ Tools**	**Result**

4 Transition to Metaverse environment

The METACITIES conceptual model represents an evolution of the notion of smart city, which usually implies the use of ICT technologies for the processing of data and their statistical manifestations in the form of dashboards. To this end, METACITIES is in line with the very recent position of the European Commission, which refers to this evolution with the term Local DTs[3]. In this context, the DT is the digitisation of every element that makes up the physical world, accurately emulating every process and behaviour that characterises it. Yet a Metaverse-ready city demands more than soloed twins. **The METACITIES vision for the Metaverse is as a persistent, evolvable network of interconnected virtual city spaces where every stakeholder's actions continually shape** the shared digital fabric and the decisions that will loop back to the physical world. This direct bond between the physical and digital worlds is also leveraged by cities to enter the Metaverse era. Using the ODTF provided in Task 3.2, Task 3.3 proposes the transition strategies for DTs to Metaverse environments. Reference ICT architectures and infrastructures suitable to support the transition of DTs to Metaverse environments are identified in this section. In practical terms, this means that the next iteration of the ODTF must support:

- **Uniform access of Metaverse platforms to the heterogeneous "local" DTs** (via standard interfaces, data models, scene descriptors and asset exchange formats).
- **Live, bidirectional event streams** for avatar interaction, dynamic asset movement or changes, object physics, and co-simulation.
- **Cloud-edge intelligence loops** that keep analytics, prediction, and optimization services
- **Built-in trust, privacy, and governance** that scales across local and national boundaries.
- **Near–real-time scene fusion** of perception layer data (such as measurements, feeds, state changes) with reconstructed or virtual assets and scenes

The chapter is organised as follows: subsection 4.1 revisits the current METACITIES ODTF reference architecture and its strengths/limitations, while subsection 4.2 proposes concrete transition strategies that could transform those twins into nodes of an interoperable large-scale Metaverse.

4.1 Current Digital-Twin Reference Architecture & Characteristics

4.1.1 Interfaces and Data Models

The METACITIES ODTF was designed to facilitate the integration of heterogeneous local DTs through a set of well-defined interfaces and shared data models. In its current iteration, the ODTF follows a layered architecture comprising, among others, (a) a Device Layer where raw sensor data and edge computing nodes reside, (b) a Data Acquisition Layer, both employing distributed service buses to pre-process and route incoming information, (c) a Storage Layer featuring relational, document, BLOB and time-series databases and (d) a Service Layer that hosts micro-services for analytics, rule execution, and the DT core itself . Across these layers, interfaces are intended to utilise REST-ful and message-based APIs, often built upon NGSI conventions, or similar, inherited from existing smart-city platforms and initiatives. Likewise, data models largely derive from programs such as FIWARE Smart Data Models or other similar initiatives.

Although this design enables basic interoperability among local twins and twin sub-verticals, allowing, for example, traffic sensors and parking management modules to exchange status updates through uniform API calls, even between different Metacity instances, the current ODTF-endorsed interfaces falls short of supporting the continuous, sub-second synchronisation that is essential for a Metaverse-grade ecosystem. Most NGSI-based brokers, but also other information BUS-es such as MQTT brokers,

[3] European Commission, "Local Digital Twins: Forging the Cities of Tomorrow," Shaping Europe's digital future Digital Strategy Library, https://digital-strategy.ec.europa.eu/en/library/local-digital-twins-forging-cities-tomorrow

buffer updates and disseminate them at intervals in the order of seconds, introducing latency that falls short of the sub-100ms expected in the virtual world for immersive interactions. In practical terms, when two DTs, or clients of the same DT, attempt to maintain a shared state, such as real-time vehicle positions in adjacent districts or avatar interactions, each BUS update arrives with both considerable and unpredictable delay, causing perceptible "jumps" or temporal misalignment when their data are merged. As a consequence, avatars or physics-driven objects traversing distinct local twins, or even through the same DT, cannot occupy a single, consistent virtual coordinate space at truly synchronous time steps. While such issues might be easily attributed to network connectivity, discussed below, the implementations of DT Data interfaces suffer from this lack of consideration for real-time synchronisation, inherited from IoT-based platforms where latency and continuous update feeds were not a focal point.

Beyond synchronisation, the underlying data models still exhibit significant gaps, most notably in the representation of precise georeferencing and geo-positioning information. While most schemas include Geojson compliant attributes for location data, high-precision orientation, altitude and often times even positioning attributes are missing (almost all smart data model entities comply with address based location attributes[4] unsuitable for native integration with Metaverse-ready worlds. In practice, existing data models may record a vehicle's latitude and longitude as a nominal point in WGS84[5], but it does not retain geopose-like attributes or even altitude. As a result, even if two twins "agree" on a common coordinate system, slight variations in how each one interprets and stores geospatial data can lead to drifting misalignment when objects move across the boundary between twins. This, however, indicates deeper localisation challenges for the Metaverse transition since the accuracy required is rarely present in existing systems, and this is reflected in the data models. Initiatives like the Geopose Protocol and the Visual Positioning Service ecosystem built around it are attempting to introduce both services, interfaces and new model attributes to include Metaverse-required positioning information.

4.1.2 3D Service Engine

Inside the ODTF, the 3D Service Engine is the conceptual slot where reconstructed city geometry, representation assets and spatial-positioning utilities are gathered so that other services, like dashboards, simulators, or immersive viewers, can fetch them in a flexible manner. After a reconstruction work-flow completes as mentioned in D3.2 section 5.1, the resulting assets are deposited as static resources such as glTF objects or 3D-Tiles pyramids in cloud "buckets" or external hubs such as Cesium Ion[6] where they can be downloaded through ordinary REST calls, proprietary streaming protocols, or access methods. In addition, visual-positioning services can be catalogued next to the repositories so that AR clients or autonomous devices can request camera pose estimations to place overlays or path-plan with centimetre-level accuracy, leveraging the reference frame created during alignment.

This set-up already supports several everyday tasks: dashboards can pull a façade mesh to annotate energy data, a VR prototype can download a neighbourhood and walk a planner through it, analytical micro-services can combine time-series readings with stored geometry when running simulations. Yet two structural gaps remain before the same facilities can behave as true Metaverse nodes.

[4] FIWARE Foundation, "Smart Data Models – Location Common Definitions," https://fiware.github.io/data-models/specs/howto.html#location

[5] National Imagery and Mapping Agency, Department of Defense World Geodetic System 1984: Its Definition and Relationships with Local Geodetic Systems, NIMA TR8350.2 (3 January 2000)

[6] Cesium GS, "Cesium ion," https://cesium.com/platform/cesium-ion/

First, scene description is still file-centric and often geometry-focused and explicit. Clients retrieve static geometry definitions and then stitch them with separately processed context data, a pattern seen in Amazon Web Services TwinMaker[7], Azure Digital Twins[8], Open Digital Twins [1], and in most Cesium.js based pilots. Existing scene description centered ecosystems such as NVIDIA Omniverse[9] or CityGML[10] describe both context data (like IoT measurements) and geometry data in the same structure in two different ways. Omniverse stores context data in key-value pairs or time series as static metadata in the scene descriptor file and relies on a live versioning protocol[11] to sync changes in both geometry and context data in the same manner. While this approach achieves a uniform way to access a DT and minimally involve client code to stitch aspects of the twin the ecosystem is quite restrictive and has no consideration for federated assets or data, meaning that each DT is a separate set of assets and data while also imposing serious limitations in the numerical aspect of connected clients. On the other hand, the CityGML format relies on a static scene representation that includes references to dynamic elements such as sensor measurements, but this functionality still lacks integration with clients and has minimum support for movement data. Additionally, both methods do not include support for alternative representation techniques, such as 3D Gaussian Splatting or 3D-Tiles, or external streamed representation resources. Better scene description methods and services or more widespread and meaningful integration of existing approaches is needed for a transition to a Metaverse-ready set of DT nodes.

Second, precise geoposing is currently only offered by a few providers as an external proprietary service with either limited coverage or the need of local actors to use the service first and create the needed maps. Additionally, the level where this capability is offered varies by provider (e.g., Google VPS[12] is only accessible as part of a mobile application SDK while other providers like Immersal[13] or Augmented Cities[14] serve it to compatible third-party clients). Consequently, interoperability between multiple providers and in different areas is hindered, while this might not be a problem for stand-alone DTs where a specific area and one provider are considered, in a Metaverse scenario, the requirements conflict with the existing landscape.

These limitations do not undermine the value already delivered, static visualization, historical playback, what-if simulations, but they explain why additional work will be needed before the ODTF 3D Metaverse Service Engine can power fully synchronous, shared virtual spaces.

[7] Amazon Web Services, “AWS IoT TwinMaker,”https://aws.amazon.com/iot-twinmaker/

[8] Microsoft, “Azure Digital Twins documentation,” Microsoft Learn, https://docs.microsoft.com/azure/digital-twins/

[9] NVIDIA Corporation, “Omniverse Platform for OpenUSD,”https://www.nvidia.com/en-us/omniverse/

[10] Open Geospatial Consortium, “CityGML 3.0 Conceptual Model Standard,” OGC Standard 20-010,https://www.ogc.org/publications/standard/citygml/

[11] NVIDIA Corporation, “Live Sync — Omniverse Connect (Unity),” https://docs.omniverse.nvidia.com/connect/latest/unity/manual/live_sync.html

[12] Google Developers, “ARCore Geospatial API overview,” https://developers.google.com/ar/develop/geospatial

[13] Immersal , “Immersal City-Scale Visual Positioning System,” https://immersal.com/immersal-city-scale/

[14] Augmented.City, “Augmented.City – AR cloud & platform ecosystem,” https://augmented.city/

4.1.3 Networking Fabric

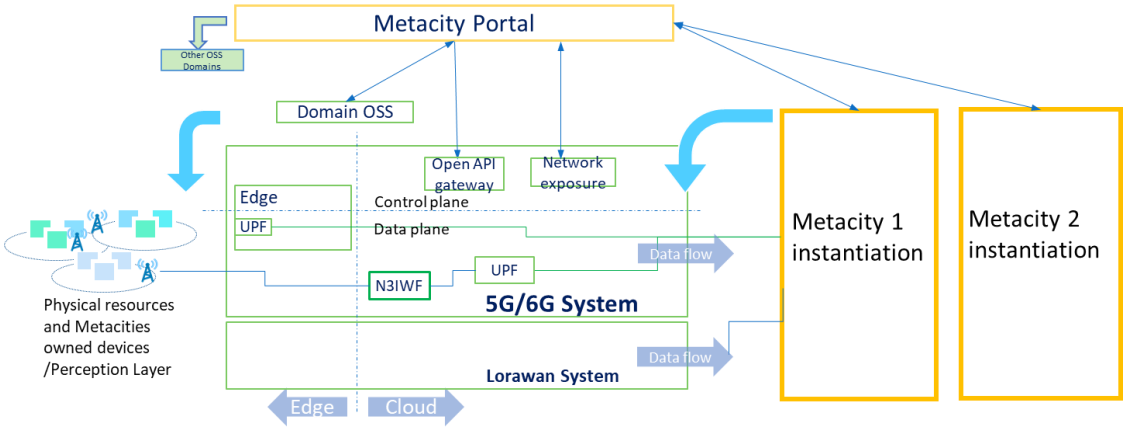

FIGURE 13: METACITIES OVERARCHING ARCHITECTURE FOCUSED ON CITY NETWORKING INFRASTRUCTURE.

For METACITIES DTs, 6G[15] will enable continuous, high-resolution data exchange between physical assets and their virtual replicas, facilitating instant monitoring, predictive analytics, and remote control across complex systems. With integrated AI capabilities and support for massive IoT, 6G will serve as the foundational infrastructure for hyper-connected, intelligent virtual-physical ecosystems.

In this section, the vision of METACITIES about the interaction of the METACITIES ODTF with the city digital infrastructure is described, and envisages their role towards the transition to Metaverse, with emphasis on how available and possibly future network and digital infrastructure technologies available in METACITIES may support their end-to-end requirements as underlying networks and tools. As shown in the figure following the notion of Section 2.4, City stakeholders will interface with the METACITIES portal to request the on-boarding of the applications required. Here we assume that in the future in order to create automated application on-barding, METACITIES platform offers the API through which these requests are received indicating all the assets that make up the ODTF City application along with specific high-level KPI requirements (see Figure 13) and Figure 2 where all the set of tool sets and mechanisms for deploying and operating METACITIES use cases are shown. As the latter are virtual representations of real-world objects, processes, or services, they are designed to support a range of applications. We will describe what we will call the METACITIES service for discovering and interconnecting any METACITIES service with the requested resources of their physical verticals, as well as the underlying networks together, end-to-end. Equally important and part of the offerings of the framework is the mapping of high-level requirements to network level operations. Overall, the framework provides a scalable and flexible solution for supporting the deployment and operation of METACITIES services enabling the seamless integration of METACITIES use cases with the underlying network by means of new APIs. The framework also exploits the flexibility of the underlying softwarised network functions in order to realize the platform to be available for DT instantiation.

The Network architecture of the communication plane suitable for METACITIES comprises the heart of the digital infrastructure as a necessary interconnection element for the data to be scouted, collected, processed and analysed. The network also allows the actuation of specific interconnected elements and all user interaction with the digital infrastructure, along with the visualisation of data.

[15] https://www.ericsson.com/en/6g

As described, Use Cases and applications that may be deployed in METACITIES may require access to the data received from various mobile devices. Evidently, all the above sensing and IoT technologies will be interconnected to the edge and cloud with various network technologies and protocols. The list may contain other technologies as well, together with a list of corresponding gateways.

Ensuring that the METACITIES DTs can be instantiated in each of the cities, requires some tools and an overall digital infrastructure architecture that captures the key architectural artefacts, the basic interactions with the 5G/6G system, the flow of information, namely, data, control, monitoring, and the relevant functionalities involved. The METACITIES network architecture structures may serve as the starting point for any Smart City project/pilot execution. However, architectural extensions may be identified for the 5G/6G as implementation progresses that may benefit from the selected applications and specifications/requirements that are currently being solicited there in. Examples include the use of network slicing, edge computing, usage of AI in 5G/6G, monitoring, end-to-end service orchestration, etc. These features provide significantly higher functionality and enable support for diverse use cases that relate to the new 5G services, from enhanced mobile broadband (eMBB) to ultra-reliable low-latency communication (URLLC) and massive machine-type communications (mMTC) as discussed in D3.2[16].

Based on these the METACITIES platform is interacting with the OSS and the Cloud orchestrator of each facility which in turn feeds with data the Metacity digital instantiation and relevant applications. The uniform capturing of the aforementioned high-level service requirements, as a basis for their subsequent translation to the respective network resources, may be achieved by leveraging prominent efforts in the area, such as the Generic Slice Template (GST)[17]. Such ventures attempt to bridge the gap between the city/user and the operators, simultaneously facilitating the signing of a Service Level Agreement (SLA) between the stakeholders and enabling interoperability. The METACITIES service now has all the necessary information to contact the 5G/6G infrastructure for the onboarding and the deployment of the specific requested application.

The orchestration and the coordination of the operations are applied end-to-end across different network segments ranging from the RAN to Edge Cloud, to Transport, to 5G/6G Core and finally the Cloud. The 5G-Network architecture flavour proposed for METACITIES is in line with 3GPP TR 26.928, titled “Extended Reality (XR) in 5G”[18], which aspires to extend and generalise it by means of the concept, adopting the decoupling of the control and the data plane counterparts of an application, thus the network interaction and the data flow, respectively. From this perspective, the METACITIES applications and services described in previous chapters become the “application” to be deployed in the 5G network. A core microservice required for these deployments relies on the Application Function (AF), a control plane function within the 5G core network, that provides network-related application logic to the subscriber, in our case, the City element to be instantiated. To that extent, AFs interact with various functional elements of the 5G Core such as the Network Exposure Function (NEF) and the Policy Control Function (PCF), enabling the City framework to get monitoring data from the network or influence its behaviour in the data path. Therefore, AFs will play an instrumental role in making 5G/6G ready for the Metaverse and DTs of next-generation Cities, hence can be assumed as the main network assets to be exposed to the METACITIES platform.

[16] D3.2 METACITIES Deliverable

[17] GSMA, Generic Network Slice Template, Version 7.0, 17 June 2022

[18] https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3534

Finally, the METACITIES architecture accounts for non-3GPP networks, such as LoRaWAN, BLE, NBIoT etc., as there is already a widely deployed base that is already connected with resources. These resources can become available through the Non-3GPP InterWorking Function (N3IWF) and enrich those brought by the vertical through the 5G/6G network.

Future digital infrastructure and especially 6G networks are expected to play a transformative role in enabling the Metaverse and DTs by providing far more than ultra-high-speed, low-latency, and highly reliable connectivity[19]. These next-generation networks will support automation and real-time, immersive experiences in the Metaverse, such as holographic communication, XR, and seamless interaction in virtual environments. 6G will support seamless machine-to-machine (M2M) and device-to-cloud interactions without the need for constant human intervention. This allows DTs to autonomously collect, process, and respond to real-time data from sensors, IoT devices, and other systems, enabling predictive maintenance, real-time optimization, and adaptive control in METACITIES. Although the infrastructure technologies are not shown in the implementation diagrams of Chapter 2, all pilots in the three ecosystems, rely on high performance networking technologies. In some cases, like in the GR cluster, there are more than one networks that are being used, for example the municipal LoRaWAN network and private 5G network infrastructures (operated by p-net and University of Patras) interconnect various data sources, as reflated in the diagram above.

In the Metaverse, 6G will allow decentralised platforms, avatars, and XR environments to interact and synchronise in real time, supporting fully immersive, responsive, and persistent virtual experiences. The convergence of AI, edge computing, and 6G will thus create self-orchestrating networks where digital and physical systems continuously co-evolve, communicate, and adapt autonomously.

4.1.4 Supporting and Compute services

In DTs, in order to achieve multiple simulations under different scenarios and input data, one of the main methods used to give a practical result is the possibility of using different bases/spatial maps/3D realities in which to apply the data, in addition to different input data. To achieve the results, (1) constant algorithms or logical solutions are used as the basis of basic analyses, together with (2) libraries with artificial intelligence elements for designating objects or specific details under different bases/spatial maps/3D realities.

These tools and algorithms are formed as containers with standard input and output data for the purpose of systematic analysis under different scenarios of live data and spatial maps, 3D realities or other types of base maps.

Depending on the application area (smart mobility, smart urban planning etc) the variety of available useful simulators and tools vary. Simulators enable minimising the dynamics, operations, and responses of the physical asset using mathematical models, physics-based models, or AI/ML techniques. In GR use cases in order to address the relations between real and virtual moving objects, various engines have been incorporated like SUMO[20]. One of the modern challenges is the processing of large data sets and it is well solved by using AI-based solutions to easily and quickly mark the inputs and outputs of our algorithms or logical solutions.

The ODTF's compute backbone today delivers on-demand analytics and simulation at city scale by dynamically allocating containerised services to process streams of sensor data, run physics-driven models, and generate three-dimensional urban renderings in near real time. These compute modules

[19] https://smart-networks.europa.eu/the-6g-ia-report-smart-city-trials-in-europe-summary-of-activities-in-smart-city-vertical-segments-use-cases-june-2024-is-out/

[20] https://eclipse.dev/sumo/

spin up elastically in response to workload spikes, whether to evaluate traffic scenarios, forecast energy consumption, or train machine-learning classifiers on live building-monitoring feeds, ensuring that planners and automated agents always have the freshest insights. At the same time, spatial query engines and geometry-processing services continuously transform raw point clouds and mesh data into optimised scene fragments, ready for immersive visualisation or further algorithmic enrichment without manual intervention.

To meet the sub-100-millisecond responsiveness that a Metaverse-grade city demands, the framework must evolve its compute fabric to support ultra-fast inter-service communication, GPU-accelerated inference close to the data source, and automated co-scheduling of mixed workloads. Future enhancements will include a unified service registry that transparently routes simulation requests to the optimal compute tier, whether that's a centralised cluster for batch scenario analysis or a near-edge node for instant augmented-reality object recognition, and a "just-in-time" asset preparation pipeline that pre-warms critical geometry and model weights ahead of peak usage. By abstracting these capabilities behind pliable APIs and encapsulating diverse solver engines into interchangeable compute micro services, cities can transition from a set of isolated dashboards to a cohesive, real-time DT ecosystem, one where every algorithm and every model scales seamlessly to power persistent, interactive urban experiences.

4.1.5 Edge & Cloud Infrastructure

METACITIES DT performance requirements can vary significantly depending on the relevant use case. Some use cases may require low latency and high throughput (for example XR related applications which require dynamic edge rendering). However, other use cases can work with higher latency but need high IoT density, for example applications which have to do with Smart Mobility or Infrastructure monitoring. In order for the DT system to be able to support all the various use cases it must be designed in a modular way so that the required computational capability is available to the applications. In this way we envision 3 layers of Cloud architecture which can serve the needs of the various applications:

- **Central Cloud servers** which hold the large databases of application users (and user data). This is the data which is not latency sensitive and can be stored central and far from the actual user
- **Mobile Edge Cloud (MEC)** which has to be close to the application in order to serve the low latency and high throughput (high data rates) required by various Metacity Applications. This is usually located at the edge of a 5G Stand Alone architecture for example within a municipality or within a 5G base station itself.
- **UE on Device Processing Unit (UE)** which is a function within the device itself and can handle some applications which require "instantaneous" processing, for example applications using dynamic XR which need to correlate objects in physical and digital space simultaneously.

The Metaverse-related services that weigh heavily on the utilisation of Edge deployment are as follow:

- **Visual Positioning Systems (VPS)**

  AR applications rely on VPS to recognise and localise a device within a real-world scene by matching live camera frames against a precomputed feature map. Since these feature maps are organised by geographic region or even by specific building interiors, requests originating from a given point A will almost always require the same local subset of map data. By hosting both the feature-extraction algorithms and the corresponding map tiles on edge servers situated in or near that location, an AR client can reduce round-trip times dramatically, often by tens of milliseconds, compared to a cloud-only architecture. This local hosting not only speeds up initial localization but

also allows rapid incremental updates (e.g., when new landmarks are added), keeping the map data fresh with minimal back-haul traffic.

- **Avatar-to-Avatar Communications**

  In AR-based social or collaborative Metaverse scenarios, multiple users in close physical proximity often share a common scene. Exchanging positional and gesture data between two clients, so that each user sees the other's avatar actions in real time, demands both low latency and synchronised state. Edge computing can establish a microservice relay for avatar event streams that reside in the same local PoP (point of presence). Because the two AR devices are near the same edge node, end-to-end latencies can be kept low, ensuring fluid, lifelike interactions. This is true for other dynamic Metaverse native objects besides avatars, vehicles or doors might come to mind. By contrast, VR avatar communications in a global cloud setup might involve participants on different continents, making edge acceleration less impactful for latency reduction.

- **Local Asset Repositories and Caching**

  Both VR and AR experiences consume 3D assets, models, textures, animations, that may be hundreds of megabytes or larger. Pushing those assets from origin servers to clients over congested back-haul links can introduce noticeable stalls. Edge-hosted asset repositories, augmented by popularity-based caching, enable clients to pull commonly used assets from the nearest PoP. In AR scenarios, where users at the same site often interact with shared virtual objects (for instance, a group of tourists viewing the same digital overlay on a landmark), an edge cache means one user's asset download benefits the entire group. This not only minimises redundant upstream data transfers but also offers near-instant asset retrieval. While this pattern might remind the reader of traditional Content Delivery Network Nodes, as described in Chapter 8 of D3.1, Metaverse applications require advanced geometry-centric repository services (e.g., Omniverse Nucleus[21], Cesium Ion), rather than simple file caching, that can benefit from local deployment since geometry is not just consumed but also edited and synced around clients, requiring real-time synchronisation of local AR and VR clients.

While edge computing benefits both AR and VR, its impact on AR is especially pronounced due to the heavy geospatial coupling of AR services. VPS and avatar interactions in AR are inherently bounded by the user's physical location, making edge placement logical and efficient. In VR Metaverse environments, where interactions often occur in entirely synthetic spaces and users can be scattered across the globe, edge nodes may not align with participant locations, limiting latency gains. Consequently, AR workloads stand out as prime candidates for edge acceleration.

4.1.6 Privacy and security

The architecture proposed integrates block-chain technology with rule engines and DT analytics. Its goal is to enhance transparency, trust, and data integrity in decentralised environments, such as those used for urban mobility, environmental monitoring, or emergency management. Block-chain is used at the core of the system to record data, decisions and system states, ensuring that all actions are verifiable and traceable. Rule engines are powered by AI and machine learning models and use smart contracts to automatically enforce business logic based on real-time data inputs, such as sensor readings or traffic events. These smart contracts execute rules when predefined conditions are met and store the outcomes on the block-chain to ensure full auditability. Meanwhile, DTs serve as real-time virtual models of physical entities (like roads, vehicles, or city infrastructure), which use sensor

[21] NVIDIA Corporation, "Nucleus Overview," Omniverse Nucleus documentation, https://docs.omniverse.nvidia.com/nucleus/latest/index.html

data to simulate and predict future states. Block-chain guarantees the integrity of these simulations by validating and logging the data inputs and outputs. Oracles help connect the off-chain data sources with the block-chain, ensuring that external data (such as weather reports or IoT sensor values) is trustworthy before it is used to trigger smart contracts or update DTs. The proposed architecture supports secure collaboration among multiple stakeholders, such as municipalities and private companies, by enabling verified data sharing without the need for a central authority. For large datasets, the system uses off-chain storage like IPFS while storing cryptographic hashes on-chain to ensure integrity. It also emphasises AI explainability, with blockchain used to log the factors influencing machine decisions, making them transparent and reviewable. This solution creates a resilient, decentralised, and auditable platform that brings together blockchain, AI, and DTs to support trustworthy decision-making in smart cities.

There are some critical functional requirements for the architecture to protect user data and interactions within the Metaverse. First of all, the system must be able to collect real-time data from IoT devices and external data sources such as sensors, weather services, and traffic feeds. All IoT data must be hashed and stored on the blockchain to ensure data integrity and immutability. External data must be validated before being recorded to guarantee that only verified inputs are used for processing by rule engines and updating DTs. Smart contracts must define business rules, logic, and automated decision conditions. Rule engines must be capable of triggering these smart contracts based on real-time or external events, with every decision immutably recorded on the blockchain for future auditing and traceability. Rule engines must also operate autonomously, executing logic according to predefined conditions in smart contracts.

Artificial intelligence and machine learning models must be integrated to process input data and make decisions or predictions. All model outputs must be stored on the blockchain to guarantee transparency. Additionally, training datasets must be hashed and stored immutably to verify their integrity over time. The system must also support AI explainability by storing the input data, logic, and reasoning behind model decisions. DTs must be synchronized in real time with their physical counterparts through IoT data streams, and critical state changes must be stored on the block-chain to provide a verifiable and tamper-proof history. Simulations and analytics run by the DTs must also be logged for transparency and traceability of predictions and system behaviour.

Security features must also include decentralised identity management and role-based access control, ensuring that only authorised users can trigger smart contracts or modify rule logic. All actions across rule engines, AI models, and DTs must be fully traceable, with a historical log accessible for auditing by stakeholders. The system must be scalable and capable of processing high volumes of real-time data without latency. Blockchain transactions must be efficient and able to support continuous logging of DT and AI system activity. Lastly, the architecture must be compatible with multiple blockchain networks, such as Ethereum and Polygon and must allow integration with external services through standard APIs and data formats.

DTs must respond to in-world triggers (e.g., gestures, virtual tools, avatar actions) and reflect real-time updates from the physical world. Changes or commands issued through Metaverse interfaces must be validated, logged, and auditable, so as there will be no unauthorised alterations to critical state data or simulations. The architecture must allow for interoperability with standard Metaverse platforms (e.g., Unity, Unreal Engine, WebXR) and support integration with digital assets and NFTs that represent infrastructure elements or user entitlements. All simulations, annotations, or decisions made in the Metaverse must be mapped to the corresponding blockchain-verified events in the DT system.

4.2 Transition Strategies Towards City Metaverse

As Smart Cities evolve, the integration of immersive technologies and intelligent systems paves the way for their transition into Metaverse environments, persistent, interactive digital layers that re-frame how urban spaces are experienced, analysed, and governed by citizens and administrators/stakeholders. This transformation begins with the development of rich urban DTs powered by real-time sensor data and simulation capabilities, enabling predictive analytics, behavioural modelling, and complex scenario testing. Layered atop this are immersive interfaces, accessible via XR technologies such as VR, AR and MR, that allow intuitive, embodied engagement with the city's systems. Modern developments in Artificial Intelligence allow for new novel ways of understanding and interpreting these environments; they can be enhanced by agentic models and AI-driven assistants that interpret data and simulate outcomes in natural, human-like ways, allowing users to explore questions and consequences conversationally or through direct manipulation. Citizens and professionals alike become active participants in shaping urban futures through collaborative design tools, spatial public forums, and gamified decision-making. The transition is iterative and context-driven, emerging through focused applications in planning, mobility, education, crisis management, and cultural heritage, ultimately converging into a civic Metaverse where participation, understanding, and governance are deeply intertwined. This section outlines the key technological, analytical, and human-centred components required for transitioning from traditional Smart City frameworks to immersive, agentic city experiences grounded in urban DTs.

4.2.1 Digital Twin Foundations

Urban DTs form the core infrastructure for a Metaverse-capable Smart City. These are high-fidelity, spatially accurate 3D models of the urban environment enriched with real-time data from IoT networks, environmental sensors, transportation systems, and public utilities. Technologies such as *Building Information Modelling (BIM), LiDAR scanning, and GIS-based semantic modelling (e.g., CityGML)* are essential for establishing a responsive and scalable digital framework. Interoperability through open standards such as the ODTF proposed in METACITIES, and robust APIs ensures that these models can be extended, queried, and visualized in immersive environments.

A key requirement for the scalability and longevity of DTs is *interoperability*. This is achieved through adherence to open standards such as *CityGML*, *Industry Foundation Classes (IFC)*, and *OGC APIs*, which ensure that various datasets, platforms, and applications can interoperate effectively. Cloud-based platforms like Cesium, Bentley iTwin, or Unreal Engine's Datasmith pipeline increasingly facilitate the hosting and visualisation of these models at city scale. Furthermore, semantic enrichment, embedding metadata and domain-specific knowledge into the model, enables contextual querying and data analytics. For example, *a wall is not just a mesh but is understood as part of a structure with material, energy, and acoustic properties*.

Beyond visualisation, DTs serve as computational platforms where *simulation engines and AI models can be integrated to predict, optimise, or test urban interventions*. This capability lays the groundwork for the Metaverse layer by enabling persistent, data-rich environments that are not only representational but also actionable. As such, DTs are no longer static documentation tools but active instruments of urban planning, infrastructure management, and public engagement.

4.2.2 Simulation and Predictive Analytics

Simulation and predictive analytics are essential components of Metaverse-enabled Smart Cities; they transform DTs *from static representations into dynamic, decision-making support systems*. Urban

systems are inherently complex and interdependent, with a lot of complex subsystems; *transportation, energy, water, and population behaviour all influence one another*. To manage this complexity, DTs should incorporate *simulation engines* capable of modelling both physical processes (e.g., fluid dynamics for drainage systems, or heat dissipation) and socio-technical phenomena (e.g., pedestrian movement, traffic flow, or energy consumption). Technologies such as agent-based modelling (ABM), discrete-event simulation, and multi-agent systems enable scenario testing across multiple temporal and spatial scales. These simulations can be powered by historical datasets, live data from IoT sensors, or projections and outcomes generated by machine learning models.

When embedded within immersive environments, simulations become not only computational tools but, importantly, *communicative* ones. Users can *visualize* the outcomes of specific interventions, such as changing a bus route, closing a road, new construction work or adding green spaces, in a *spatial (3D), real-time (temporal) interactive context*. Predictive analytics driven by AI techniques (e.g., time series predictions for energy or traffic demand, reinforcement learning for process optimisation) can guide city managers toward better decisions, while citizens can explore "what-if" scenarios through intuitive interfaces. This integration of simulation with spatial computing creates a feedback loop between the real and virtual city, where hypotheses can be tested rapidly and collaboratively. The result is a Metaverse layer where planning is not only informed by data but made explorable, contestable, and participatory.

4.2.3 Immersive Interfaces, Spatial Computing

Immersive interfaces represent a paradigm shift in how urban data and systems are experienced. By leveraging XR technologies - virtual reality (VR), augmented reality (AR), and mixed reality (MR) - users can spatially and intuitively engage with a city's DT. Unlike traditional dashboards, these interfaces allow users to navigate, annotate, and interact with the virtual city as if they were physically present. XR can reveal otherwise invisible phenomena, such as underground infrastructure or dynamic heat-maps of pedestrian activity overlayed in the virtual word, making complex data more legible. Real-time rendering platforms such as Unity's Reflect (centred around BIM), Epic's Unreal Engine, Nvidia's Omniverse and CesiumJS provide scalable, high-performance environments for rendering real-time, geospatially *accurate 3D content on a variety of devices* such as desktop, mobile, web and several XR devices.

Importantly, the next generation of immersive interfaces prioritises human-centered interaction, allowing people to engage with urban data and simulations through more *natural modalities*. Instead of relying on menu-driven UIs or technical parameters, these interfaces integrate gesture recognition, eye tracking, voice commands, and even emotion-sensing inputs and brain computer interfaces to provide fluid, adaptive interaction. Users can simply point to a building and ask, "What's the air quality here?" or use gaze to select a region and summon relevant traffic patterns. These interactions are mediated by spatial understanding and contextual awareness, systems that know where the user is looking and what they are trying to do, both in a virtual space (VR) and in the physical (AR and MR). Multimodal input - combining voice, gesture, and touch, creates more *inclusive and accessible* experiences, especially for users unfamiliar with complex data tools and certain disabilities.
In multi-user settings, immersive interfaces also support collaborative presence, allowing several participants, whether planners, citizens, or even AI agents[22] - to inhabit the same digital environment, annotate elements, and simulate outcomes together. This opens the door to richer, more democratic participation in city-making processes. Interfaces can be adapted to roles: a policymaker may view macro-level overlays, a resident may explore their neighbourhood's transformation in detail, and a

[22] Sharespace project: https://sharespace.eu

data analyst might access simulation parameters directly. The immersive interface becomes not just a viewport into the DT, but a cognitive and social workspace where people, data, and decisions co-exist in real time. These developments position immersive, human-centric interaction as a cornerstone of the Metaverse's potential to re-imagine urban engagement.

In recent years, agentic systems—AI-powered tools capable of autonomous decision-making, contextual reasoning, and human-like interaction—have gained significant momentum across various fields, including software automation, digital assistants, and embodied AI. Unlike traditional rule-based systems, these agents can interpret user intent, adapt to changing conditions, and take initiative within defined boundaries. This shift marks a move from passive data interfaces to proactive, conversational collaborators.

In the context of an urban, Metaverse-ready DT, agentic systems can become key intermediaries between complex urban data and human users. They can guide citizens through immersive planning scenarios, assist city officials in real-time simulation queries, or help coordinate virtual public events. Whether embodied as avatars, ambient assistants, or voice-driven companions, agentic systems promise to make the digital city more navigable, responsive, and personalised, bridging the gap between data-rich environments and human-scale decision-making.

Under the hood, these agentic systems combine spatial understanding and reasoning, NLP (natural language processing), semantic models, and predictive analytics to deliver contextual insights. As these systems evolve, we envision that they can adapt to user profiles, preferences, and professional roles, offering domain-specific support while ensuring inclusiveness for broader audiences. This move toward naturalistic interaction is key to democratising access to complex urban data, reducing friction in decision-making, and opening new possibilities for exploratory, non-linear thinking. By embedding intelligence directly within the city's Metaverse layer, cities can enable not only more data-rich but also more human-scaled interaction models.

4.2.4 Citizen Participation and Co-Creation

The *Metaverse re-imagines civic participation by transforming passive observation into active spatial co-creation*. Traditional participation processes, surveys, workshops, public hearings, often exclude citizens due to technical, linguistic, or logistical barriers. Immersive environments, however, allow citizens to explore design proposals first-hand, modify them in real-time, and express preferences directly within the spatial context of their neighbourhoods. XR planning sandboxes, scenario voting systems, and collaborative urban design platforms all contribute to a more equitable and engaging public dialogue. By visually demonstrating trade-offs and consequences, these systems also help bridge gaps in understanding between stakeholders.

Crucially, gamification and role-play mechanisms can foster sustained engagement and deeper understanding. Citizens may assume different perspectives (e.g., mobility-impaired, tourist, service provider) to evaluate how design decisions impact diverse user groups. In turn, planners gain access to real-time feedback rooted in spatial experience rather than abstract opinion. The integration of agentic systems ensures that even non-expert users can navigate the space and meaningfully contribute. This participatory model strengthens trust, transparency, and collective ownership over urban transformation, turning the Metaverse into a civic commons rather than a top-down visualization tool.

4.2.5 Thematic Use Cases

Transitioning to an urban Metaverse does not require full-system deployment from the outset; rather, cities can adopt an incremental strategy by piloting targeted use cases that align immersive DT capabilities with domain-specific needs. Each of these use cases relies on a modular stack: geospatial 3D models (3D reconstructions, point clouds, 3D design/layouts), real-time or historical datasets, a simulation engine or rule-set based on the use case, and an immersive interface, augmented by agentic interaction where relevant.

Metaverse-enabled urban DTs could support a range of advanced, human-centred city applications. For example, planners might use immersive environments to review proposed developments at full scale, importing BIM models into a spatial twin and exploring them in VR. Citizens could walk through future buildings, assess shadow casting or sightlines, and suggest modifications in real time. Parametric tools might allow on-the-fly design changes, while embedded AI assistants could answer natural-language queries like, "How does this affect nearby green space?" or "Will this increase traffic noise?"

Other potential use cases include emergency response simulations, where responders train in XR environments replicating real city layouts, or educational modules that guide students through urban history via interactive timelines. Traffic planners might test new routes or street closures in real time, using agent-based models and immersive flythroughs to communicate outcomes. In each case, the Metaverse layer adds spatial context, interactivity, and intelligibility, turning the DT into a collaborative space for testing, learning, and decision-making.

4.2.6 Creative Expression/Cultural Layers

A Metaverse-ready DT offers unprecedented opportunities for integrating creative practices into the digital fabric of the city or even cultural spaces like theatres[23]. Beyond utility and governance, the immersive twin becomes a platform for cultural expression, where artists, performers, curators, and citizens can co-author new narratives rooted in place. Public spaces in the Metaverse—virtual squares, parks, and streets— can host digital installations, augmented performances, or site-specific storytelling that would be impossible or ephemeral in physical space. These experiences may be interactive, temporally dynamic, or responsive to environmental data, thus weaving artistic expression into the lived experience of the city in novel ways.

Furthermore, the DT allows cities to *preserve and reinterpret intangible heritage and localised histories through immersive media*. Artists and cultural institutions can reconstruct lost or hidden urban stories, overlay them in AR on the physical world, or stage experimental performances entirely in virtual replicas of iconic spaces. AI-generated avatars or spatialised soundscapes can be used to embody cultural memory or provoke civic reflection. In collaborative scenarios, residents themselves can co-create artistic layers - annotating space with personal memories, graffiti-style interventions, or participatory rituals. This transforms the Metaverse not just into a planning or analysis tool, but into a living cultural ecosystem, where the digital city evolves not only through data but through the shared imagination of its inhabitants.

4.2.7 Governance, Ethics, and Infrastructure

The creation of a Metaverse-ready Smart City raises fundamental questions of governance, ownership, and equity. As immersive platforms become part of public infrastructure, cities must define regulatory frameworks that safeguard data privacy, digital identity, and access rights. Issues

[23] Premiere project: https://premiere-project.eu/

such as biometric data from XR devices, AI decision-making transparency, and data monetisation must be addressed early and proactively. Governance models should balance public stewardship with private-sector innovation, ensuring that urban Metaverse infrastructure remains open, transparent, and accountable. Citizen data sovereignty and algorithmic accountability are key pillars of ethical deployment.

From an infrastructural perspective, supporting real-time, multi-user immersive environments requires significant investment in network and compute resources. Edge computing, 5G/6G networks, spatial cloud services, and distributed/cloud-based rendering architectures are essential for reducing latency, lowering hardware requirements for consumers, and supporting concurrent interactions. Additionally, cities should invest in public XR infrastructure - such as immersive kiosks or mobile apps, that ensures access regardless of economic status. Long-term sustainability also hinges on interoperability: cities should prioritize open data standards, modular system architectures, and portable XR content. Governance, infrastructure, and ethical frameworks must evolve together to ensure that the urban Metaverse is not only technologically viable but socially just.

4.2.8 Conclusion and Roadmap

The transition from Smart Cities to immersive, agentic, and participatory urban Metaverses is a multi-dimensional journey. It begins with the development of rich, interoperable DTs, enhanced by real-time sensor data and simulation engines. These foundations are then extended through immersive interfaces and intelligent agents that allow users, experts and citizens alike, to intuitively interact with complex systems. Through strategic thematic applications in planning, education, crisis response, and culture, cities can prototype and iterate toward scalable, high-impact solutions. The Metaverse is not simply a technological overlay but a reconfiguration of how we perceive, shape, and govern urban life.

A successful roadmap includes phased deployments: starting with simulation-enhanced DTs, layering immersive visualisation tools, integrating human-centred AI systems, and progressively embedding these into urban workflows. Attention must also be paid to governance, ethics, infrastructure, and public trust. Cities that invest in these foundations now will not only improve operational efficiency and public engagement but also lay the groundwork for a fundamentally new mode of urban experience, one that is interactive, inclusive, and continuously evolving. The Metaverse, in this context, is not an escape from reality but an expanded framework for understanding and shaping it.

5 Implementation Challenges and Solutions

This concluding section outlines the key challenges encountered during the implementation of DTs in urban contexts, as well as the practical solutions adopted or proposed to overcome them. The challenges are grouped into six thematic areas: data interoperability, real-time performance, cybersecurity, immersive user experience, governance coordination, and Metaverse infrastructure readiness. Each area reflects a critical dimension in the DT life-cycle, and together they form a comprehensive foundation for successful deployment and long-term operation. Solutions are sought in the spectrum of technologies presented in Section 4.1.

5.1 Challenge 1: Data Interoperability and Integration

As described in Chapter 4.1.1, we designed our system as the METACITIES ODTF, which is based on a layered architecture through well-defined data models and interfaces. However, although this design enables basic interoperability among local twins and twin sub-verticals, the current ODTF-endorsed interfaces fall short of supporting the continuous, sub-second synchronisation that is essential for a Metaverse-grade ecosystem. Most NGSI-based brokers, but also other information BUS-es such as MQTT brokers, buffer updates, and disseminate them at intervals in the order of seconds, introducing latency that falls short. Furthermore, network-enabled real-time state updates and communication dictate the need for a more in-depth network fabric and application integration that will be enabled by future 6G networks.

Solution:

- **Design systems on a B5G/6G SA architecture** which can handle the low latency and high throughput requirements and enable local MEC processing of high data volumes. This implies the direct interface and onboarding of DT and Metaverse platforms on next-generation networks in an automated way.
- **Adoption and Alignment of Cluster DT Systems,** thus eliminating the need for interaction of various heterogeneous systems
- **Use of semantic ontologies** enables contextual understanding of urban data, allowing systems to interpret relationships between different data types and sources.
- **Enable Middleware integration platforms** which can act as harmonise inputs, abstract technical complexity, and enable seamless interoperability between legacy systems and modern cloud-native applications. Examples include Orion Context Broker or open-source Enterprise Service Buses (ESBs).
- **Adoption of open standards and smart data models** ensures that data from various systems can be described and shared in a common, machine-readable format. These standards also facilitate long-term compatibility and vendor neutrality.

5.2 Challenge 2: Metaverse Geo-positioning and Geo-localisation

The underlying data models exhibit significant gaps, most notably in the representation of precise georeferencing and geopositioning information. While most schemas include geojson compliant attributes for location data, high-precision orientation, altitude and often even positioning attributes are missing (almost all smart data model entities comply with address-based location attributes unsuitable for native integration with Metaverse ready worlds).

Solution:

- **Geospacial Standards**: various standardization associations and groups are working on this specific topic which is specialized. Namely the Open Geospacial Consortium (OGC), the Open AR

Clour (OARC) and the Metaverse Standards Forum (MSF) are working actively to define and evolve the Geopose standard which is fast becoming the main industry reference for such issues. In this way heterogenous Metaverse AR graphics applications can now interoperate. P-NET (which is one of our partners) has become an official Metaverse Forum Lab in order to install and test this standard and the integration with 5G SA systems.

This set-up already supports several everyday tasks: dashboards can pull a façade mesh to annotate energy data, a VR prototype can download a neighbourhood and walk a planner through it, analytical micro-services can combine time-series readings with stored geometry when running simulations. Yet two structural gaps remain before the same facilities can behave as true Metaverse nodes.

5.3 Challenge 3: Interoperability of 3D Environments

Achieving seamless interoperability among three-dimensional environments remains impeded by substantial technical and procedural obstacles, even with the emergence of widely adopted asset-exchange formats and scene-description standards. Divergent mathematical conventions for geometry, coordinate-system handedness, or unit scaling frequently introduce numerical drift or visual artifacts when assets traverse pipelines. Material and shading models, often tied to proprietary rendering engines, resist faithful translation, undermining the intent of physically based look-development. Moreover, the increasing reliance on extensible arbitrary metadata, variant sets, and dynamic layering, while powerful within individual ecosystems such as USD, complicates bilateral compatibility because vendors prioritise idiosyncratic extensions over strict adherence to common cores.

Additionally, precise geo-positioning is currently only offered by a few providers as an external proprietary service with either limited coverage or the need of local actors to use the service first and create the needed maps. Additionally, the level where this capability is offered varies by provider (e.g., Google VPS is only accessible as part of a mobile application SDK while other providers like Immersal or Augmented Cities serve it to compatible third-party clients). Consequently, interoperability between multiple providers and in different areas is hindered, while this might not be a problem for stand-alone DTs where a specific area and one provider is considered, in a Metaverse scenario the requirements conflict with the existing landscape.

Solution:

- **3D Digital Representation Standardization:** A pragmatic standardisation path sees every mesh, point-cloud or neural representation kept outside the twin itself: an asset-repository entity may expose each representation, whether USD , glTF , 3D Tiles or more novel asset types such as Gaussian Splats [2], at an addressable URI together with a declared access method (simple REST call, tiles API, SDK hook, etc.). The digital-twin descriptor should then build scenes only from lightweight nodes that carry transforms, hierarchy and metadata, plus a pointer back to those repository items, unifying geometry, materials and other digital-twin parameters without ever embedding heavy asset files. Because any client that understands descriptors can resolve the referenced assets, swap formats on the fly and honour multiple candidate sources per object, this decoupled model turns asset repositories into interoperable libraries and lets heterogeneous 3D Twin Environments compose, stream and update shared scenes with no format lock-in or per-vendor glue code.
- **VPS Standardisation:** This is ongoing work in the OGC and MSF and we see some standardisation of VPS systems through the Geopose protocol[24]. There have been recent demonstrations where

27 OpenARCloud, “OSCP GeoPose Protocol v1,”,https://github.com/OpenArCloud/oscp-geopose-protocol

Google VPS and Augmented City have been able to interoperate. However, it is still at the R&D level, and it will take some time before these systems are fully interoperable.

5.4 Challenge 4: Scalability and Real-Time Performance

As urban systems evolve and expand, DTs must handle increasing volumes of data, support real-time responsiveness, and accommodate thousands of concurrent users. This requires scalable architectures that can dynamically adapt to load changes without compromising performance.

Solution:

- **Deployment of cloud-native architectures** using containerised microservices (e.g., Docker, Kubernetes) allows horizontal scaling and modular service design, promoting flexibility and efficient resource allocation.
- **Enabling a 5G/6G MEC Architecture** is introduced to process time-critical data closer to its source, reducing latency and relieving the burden on centralised cloud infrastructure. The orchestration and the coordination of the operations are applied end-to-end across different network segments ranging from the RAN to Edge Cloud, to Transport, to 5G/6G Core and finally the Cloud. The 5G-Network architecture proposed for METACITIES is in line with 3GPP TR 26.928, titled "Extended Reality (XR) in 5G" which is the foundational standard for 3GPP and XR integration. Future digital infrastructure and especially 6G networks are expected to play a transformative role in enabling the Metaverse and DTs by providing far more than ultra-high-speed, low-latency, and highly reliable connectivity.
- **Implementation of real-time data pipelines,** such as Apache Kafka, Apache Flink, or Spark Streaming, supports high-throughput ingestion, transformation, and routing of urban data streams for immediate analytics and feedback.
- Implementation of robust **real-time synchronisation** layers that dynamically propagate state changes and user interactions across all Metaverse-enabled DT clients, ensuring a consistent shared environment through edge-optimized distribution, intelligent update prioritisation and improved service buses.

5.5 Challenge 5: Cybersecurity and Data Privacy

DTs often deal with sensitive and personal data, such as real-time mobility patterns, utility consumption, and citizen interactions. This raise concerns around data breaches, misuse, and unauthorised access, especially in light of tightening data protection regulations (e.g., GDPR). As the proposed architecture addresses the complex challenge of building secure, transparent, and trustworthy systems for smart cities and the Metaverse by integrating blockchain, AI-powered rule engines, and DT analytics, the key challenges, including ensuring data integrity, real-time processing, AI transparency, and secure multi-stakeholder collaboration in decentralised environments, remain. In Chapter 4, in order to overcome these, the system may incorporate blockchain to immutably record all actions, data, and decisions, while AI models and rule engines trigger smart contracts based on validated real-time inputs. Hence, the METACITIES DT architecture, in order to synchronise physical and virtual environments, may simulate and predict system states, with all changes logged on-chain for full auditability secure, interoperable, and future-proof. However, this is a very challenging area, and some aspects can be discussed as:

Solution:

- **Zero-trust security models** presume that no entity (internal or external) is inherently trusted, enforcing strict identity verification and continuous validation at every access point.
- **Privacy-by-design principles** are embedded in system architecture from the outset, ensuring data minimization and secure processing practices.

- **Differential privacy and anonymisation** techniques ensure that aggregated insights can be derived without exposing individual-level data.
- **Encryption protocols** protect data both at rest and during transmission, while role- or attribute-based access control (RBAC/ABAC) ensures that users only access the data necessary for their role.
- **Decentralised identity management and role-based access control**, off-chain storage for scalability, and compatibility with multiple blockchain and Metaverse platforms, ensuring the system remains secure, interoperable, and future-proof.

5.6 Challenge 6: 3D Visualisation and Metaverse User Experience

Challenge (1):

Designing immersive, intuitive, and interactive DT interfaces that visualize complex urban systems in a 3D or XR format is technologically, cognitively and compute-wise demanding.

Solution (1):

- 3D game engines like Unity[25] and Unreal Engine[26] or other lightweight environments such as PlayCanvas[27] enable real-time rendering of urban environments in high fidelity, allowing for the integration of layered 3D assets and other tabular or time series data and annotations in a wholistic view of the DT.
- Level of Detail (LOD) optimization techniques are applied to manage system performance, ensuring that graphics fidelity is balanced against rendering speed. In an urban scale the efficiency of the 3D-tiles [3] format for both rendering and streaming is unparalleled.
- Tailored user interfaces are developed for diverse user groups (e.g., citizens require simplified visual cues; planners need detailed analytical tools) and usecases (urban planning, education, simulation, gaming etc).
- Human-centered design ensures that XR interfaces are intuitive, accessible, and ergonomically adapted to various devices (AR glasses, VR headsets, mobile phones, desktops etc.).

Challenge (2):

Metaverse-based DTs must maintain persistent states across sessions, support concurrent multi-user interactions, and provide synchronous collaboration features.

Solution (2):

- Decentralized and trusted storage functionalities (e.g., IPFS, block-chain) ensure durability, auditability, and transparency of shared assets.
- Real-time synchronization services like Colyseus[28] or Fusion, employing protocols such as WebRTC[29] or Photon[30], enable seamless multi-user collaboration, avatar presence, and shared manipulation of digital objects.
- Collaborative agents and virtual assistants can facilitate stakeholder interaction and decision-making in the shared DT space.

28 Unity Technologies, “Unity – Real-Time Development Platform,”https://unity.com/

29 Epic Games, “Unreal Engine,”https://www.unrealengine.com/

30 PlayCanvas, “PlayCanvas WebGL Game Engine,” https://playcanvas.com/

32 Colyseus, “Colyseus – Open-source Multiplayer Framework for Node.js,”https://colyseus.io/

33 W3C, “WebRTC: Real-Time Communication in Browsers,” W3C Recommendation https://www.w3.org/TR/webrtc/

34 Exit Games, “Photon Fusion,” Photon Engine documentation, https://doc.photonengine.com/en-us/fusion/current/getting-started/what-is-fusion

5.7 Challenge 7: Governance and Stakeholder Engagement

DT projects span multiple domains and stakeholders, including public authorities, technology vendors, researchers, and citizens. Poor coordination can result in siloed implementations, redundant investments, and limited societal uptake.

Solution:

- **Quadruple Helix (QH) governance models** foster structured collaboration among government, industry, academia, and civil society. This model ensures that all relevant voices contribute to project planning, validation, and operation.
- **Co-creation workshops, living labs, and participatory design methods** ensure that citizen needs and concerns are captured early in the process, fostering transparency and ownership.
- **Multi-actor feedback loops**, including iterative testing and agile pilot deployments, allow continuous refinement and alignment of solutions with real-world requirements.

5.8 Challenge 8: Transition to the Metaverse: Infrastructure and Network Constraints

The Metaverse layer of urban DTs demands unprecedented network performance, including ultra-low latency, high data throughput, and real-time coherence between virtual and physical spaces.

Solution:

- **5G and emerging 6G networks** provide the necessary bandwidth, coverage, and low-latency characteristics to support mobile and distributed XR applications.
- **Network virtualisation technologies** such as Software-Defined Networking (SDN) and Network Function Virtualisation (NFV) enable programmable, scalable, and resilient network infrastructures.
- **Edge computing and distributed cloud** deployments push compute resources closer to users and data sources, significantly reducing latency while improving scalability and fault tolerance. This is critical for synchronising real-time sensor data with virtual representations.

6 Conclusions

This deliverable outlines the foundational activities necessary for the instantiation of smart city DTs across three thematic domains: smart mobility, green infrastructure, and urban planning, within the METACITIES project. More than three reference architectures for the ODTF have been identified. Specifically, seven architectures have been developed by all clusters, as detailed in Section 2.5. Additionally, more than five state-of-the-art technologies have been integrated into the ODTF. These include 5G connectivity, AI-driven analytics, IoT platforms, AR/VR visualizations, and BIM integrations. The overall architecture is presented in Section 2.4, with implementation guidelines and supporting technologies discussed in Chapters 3 and 4.

A set of structured guidelines are presented that address objectives, governance, stakeholder engagement, reference architectures, infrastructure, data management, and cybersecurity considerations. These guidelines are tailored to the context of each cluster (Greece, Bulgaria, Cyprus), supporting readiness for future deployment in alignment with the ODTF.

The deliverable provides a roadmap for each domain cluster, outlining the steps and resources required for implementation. These roadmaps reflect the specific goals and constraints of each ecosystem and aim to support cities in organizing their planning, assessing readiness, and aligning their strategies with METACITIES objectives. The documented roadmaps serve as structured preparation tools for future pilot activities and offer a basis for replication in other cities.

The deliverable also introduces an approach for transitioning DTs into Metaverse environments. It identifies required ICT components and outlines architectural considerations for immersive capabilities, while exploring potential use cases and user interaction models. Although still in the planning phase, this transition is expected to enhance urban simulation, participatory design, and service delivery in future iterations. Business impacts will be assessed in subsequent stages, once pilot actions begin. Identified best practices include the use of open standards and modular frameworks. Future improvements will focus on iterative testing, stakeholder feedback, and advancing the integration between DT platforms and extended digital environments.

7 References

[1] Julia Robles, Cristian Martín, and Manuel Díaz, "OpenTwins: An open-source framework for the design, development and integration of effective 3D-IoT-AI-powered digital twins," *arXiv preprint,* p. ttps://arxiv.org/abs/2301.05560, 2023.

[2] Bernhard Kerbl et al., "3D Gaussian Splatting for Real-Time Radiance Field Rendering," *ACM Transactions on Graphics,* vol. 42, no. 4, 2023.

[3] Zhan Wenxiao, Chen Yuxuan, Chen Jing, "3D Tiles-Based High-Efficiency Visualization Method for Complex BIM Models on the Web," *ISPRS International Journal of Geo-Information,* vol. 10, no. 7, 2021.