MetaCities Excellence Hub in South-Eastern Europe

Deliverable D3.2 Requirements and Specification of the ODTF

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Glossary of terms and abbreviations

Abbreviation / Term	Description
AI	Artificial Intelligence
AR	Augmented Reality
ARC	Advanced Research Centre
BIM	Building Information Model
BLE	Bluetooth Low Energy
BMS	Building Management System
CAN	Controller Area Network
D2D	Device-to-device
DLT	Distributed Ledger Technology
DT	Digital Twin
EE	Energy Efficiency
EMBB	Enhanced Mobile Broadband
EMS	Emergency Medical Services
ETSI	European Telecommunications Standards Institute

GAEA	Granting Access to Employment & Entrepreneurship in Agriculture for Women
GIS	Geographic Information System
HVAC	Heating, Ventilation, and Air Conditioning
ICT	Information and Communications Technology
IoT	Internet of Things
ITIMS	Intelligent Transport and Incident Management System
IUDX	India Urban Data Exchange
JMS	James McCune Smith Learning Hub
LOD	Levels of Detail
ML	Machine Learning
mMT	Massive Machine-Type
MQTT	Message Queuing Telemetry Transport
MR	Mixed Reality
NFC	Near Field Communications
OASC	Open & Agile Smart Cities
ODTF	Open Digital Twin Framework
Patras-ITIMS	Patras Intelligent Transport and Incident Management System
PoE	Power over Ethernet
PV	Photovoltaic
PwD	People with Disabilities
R&I	Research and Innovation
RES	Renewable Energy Solutions
RFID	Radio Frequency Identification
RGBD	Red, green, blue, and depth
SESCAP	Sustainable Energy Strategy and Climate Action Plan
STF	Smart Territory Framework
UHI	Urban Heat Island
UPTI	Urban Parking and Traffic Impact
URLLC	Ultra-Reliable Low-Latency Communication
VMS	Video Management Server
VR	Virtual Reality

Executive Summary

The main goal of METACITIES is to develop a common Open Digital Twin framework (ODTF) for 3 different domains of smart cities that will take advantage of the functionalities of Digital Twins and Metaverse. This deliverable (D3.2) presents the results of Task 3.1 and Task 3.2, focusing mainly on the specifications of the Open Digital Twin Framework, and their relationship to the requirements and the use cases of the three ecosystems. Its main purpose is to describe the main characteristics of the technical components of the ODTF and propose a transition to the Metaverse while mentioning the main technologies that will be deployed (Blockchain, Network technologies and Edge network resources).

The main purpose of this deliverable is to specify the ODTF that will enable the research collaboration between the three regional clusters. The work presented in this deliverable was carried out in five main steps. First, the use cases were finalized along with their input data sources and a high-level technical approach. Then, taking into account the requirements that were specified in D3.1, the specifications were defined. The third step was to specify all the details of the components that were introduced in D3.1 and correlate them with the requirements and the use cases. At the next step the transition to Metaverse and the 3D representations in general is introduced. Finally, in the last step, we conclude to the main technologies that will be deployed to create the common ODTF including Blockchain, Network technologies and Edge network resources.

1 Introduction

The METACITIES initiative is at the forefront of reshaping the future of smart cities and regions in Southeast Europe (SEE) by integrating cutting-edge digital technologies into urban ecosystems. Central to this effort is the development of the Open Digital Twin Framework (ODTF), a foundational platform designed to seamlessly interconnect the physical, digital, and human dimensions of cities. The ODTF serves as a critical enabler for creating interoperable and scalable Digital Twins (DTs), which provide accurate, data-driven simulations of urban systems and environments. These DTs empower stakeholders—including policymakers, city planners, businesses, and citizens—to evaluate potential outcomes, optimize decision-making, and implement solutions with confidence.

The importance of the ODTF lies in its ability to unify diverse data sources, technologies, and stakeholders under a common architecture. As urban challenges grow increasingly complex, the ODTF offers a sustainable and adaptable approach to managing the dynamic interplay between urban infrastructure, environmental sustainability, and societal needs. By facilitating the co-development of domain-specific Digital Twins—such as those for Smart Mobility, Green City, and Urban Planning—the ODTF not only supports the efficient allocation of resources but also fosters cross-sector innovation and collaboration. The framework's emphasis on openness ensures that it can be tailored to diverse use cases and regional contexts, making it a versatile tool for addressing the unique needs of cities and regions across the SEE landscape.

This document, Deliverable D3.2, presents the final version of the socio-economic requirements and technical specifications of the ODTF. Taking into account the outputs of the deliverable D3.1, specifically the functional and non-functional requirements and the proposed high-level architecture of METACITIES Digital Twin, this deliverable focuses on the three critical domains of the METACITIES project—Smart Mobility, Green City, and Urban Planning— explores the interrelation of each use case to the functional and non-functional requirements as well as to the architectural components and depicts them in suitable diagrams. The document also provides an overview of enabling technologies for the implementation of Digital Twins and prepares forthcoming activities by introducing transitioning approaches towards the Metaverse and Metacities.

1.1 Mapping METACITIES outputs

This section presents the METACITIES Grand Agreement (GA) commitments, as extracted from the formal deliverable and task description, in 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 check list to address everything that is needed 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 3.1 Elicitation of socio-techno-economic requirements	This task will capture the functional requirements and end-user needs from the use case partners, that will guide all research activities related to the specifications of the ODTF for the smart cities' ecosystem. Requirements' definition will involve the documentation, analysis and translation of end-users' needs into technical specifications considering not only the technological point of view but also the user-centric social and economic dimension. All use case partners will provide functional requirements, which will be analysed by the technological partners. The actors responsible for the data collection will also be assigned, including the definition of industry grade data collection tools and the on-line data repository.	Chapter 3	Chapter 3 presents the functional and non-functional requirements and their relationship with the architectural components.
Task 3.2 Specification of the Open Digital Twin Framework	This task will provide the specification of the ODTF, which will be used to create, maintain, and manage DT and Metaverses for future smart cities. Specifically, this task will translate the requirements elicited in Task 3.1 into functional and non-functional specification and describe a reference software architecture for smart city operation that can be used to build domain specific DTs enabled by the ICT infrastructures of the smart city. It will highlight the common functions that a smart city DT should implement together with the intelligent data model. Emphasis will be given on the digital model functions and interfaces.	Chapter 3, Chapter 4	In Chapter 3, the requirements are elaborated adding their specifications. In Chapter 4 the technical components of the architecture are described as along with their role in each use case. The specification is complemented with overviews of enabling technologies for DT

			implementations (chapter 6) and approaches for the transition to Metaverse (chapter 5)
DELIVERABLE			
Deliverable D3.2: Requirements and Specification of the ODTF: Requirements and Specification of the Open Digital Twin Framework. Initial version of the socio-economic requirements and technical specification of the open digital twin framework.			

1.2 Deliverable Overview and Report Structure

The Deliverable 'D3.2 – Requirements and Specification of the ODTF' of the METACITIES project is important since it provides the final version of the socio-economic requirements and technical specifications of the ODTF. Taking into account the outputs of the deliverable D3.1, this deliverable focuses on the three critical domains of the METACITIES project—Smart Mobility, Green City, and Urban Planning— explores the interrelation of each use case to the functional and non-functional requirements as well as to the architectural components and depicts them in suitable diagrams.

Based on the objectives and work carried out under tasks T3.1 and T3.2 this document starts with the Executive Summary followed by the introduction of the document in Chapter 1. Chapter 2 provides a detailed description of the use cases for Smart Mobility, Green City, and Urban Planning, focusing on the input data sources and presenting a high-level technical approach. Chapter 3 outlines the functional and non-functional requirements related to the use cases and identifies detailed specifications regarding functionality, architectural components, UI/UX requirements, performance metrics and data handling. In Chapter 4 each architectural component of the proposed architecture is related to specific functional and non-functional requirements and the set of suitable use cases; within the context of each use case is also identified the actor, the entity that interacts with each component, as well as a description of the interaction between the actor and the component. Chapter 5 explores Metaverse 3D services and potential technologies, focusing on ways to link the proposed ODTF to the Metaverse. Chapter 6 introduces blockchain-based mechanisms for enhancing data integrity, interoperability, and trust within the Digital Twin ecosystem as well as the main edge and network technologies that need to be implemented. Chapter 7 concludes with a synthesis of key findings, proposed architectural solutions, and next steps toward implementing the METACITIES vision. The Appendix provides a series of diagrams depicting system components' interactions and data flows through the system from acquisition to processing to storage and analytics and resulting outcomes.

2 Use Cases Description

2.1 DT for Smart Mobility

Traffic management problems in any city are acute. The modernization of legacy traffic control centers is necessary due to the increase in the information load on operators. The complexity of these transport management systems however increases with the number of people and modes of transport. Especially when the density of vehicles and people increases, the effect of small incidents on traffic congestion is unpredictable and taking actions becomes very demanding as it requires the handling of large amounts of traffic of vehicles and people. This issue compromises the accessibility goals set by the METACITIES Smart City R&I strategy (elaborated in D2.1).

In order to alleviate traffic issues in a city, one has to comprehend the use of vehicles in cities during rush hours and the events that may cause traffic congestion. It is established that searching for empty parking space for cars is a reason for more traffic generation and congestions. Shoup (2006) showed that even a short time for searching a parking space would generate a considerable amount of traffic. In his study of 11 US cities, it has been shown that 30% of the traffic spends an average of 8.1 min searching for parking spaces. Arnott and Rowse (2009) have examined the integrated model of parking and congestion in medium-sized U.S. cities and found that cruising for parking contribute 14% of the cars on road which generate almost 50% increase in time loss due to congestion.

Furthermore, short response time on traffic incidents is crucial to minimize the impact on congestion. In economic terms, the annual cost of congestion in the EU has been estimated to be 1% of GDP [[1]]. Congestion also has other negative externalities, such as increased levels of noise, pollution and the potential for accidents and reductions in the useful life of vehicles (OECD, 1999) and the capacity of the network to cope with incidents (its resiliency).

Furthermore, according to the European Commission, in 2020, 18800 people lost their lives on European roads; this number equates to about 360 people tragically dying every week [[2]].

These unacceptable numbers, both in absolute and relative terms, have remained largely unchanged for the past 20 years, despite the painstaking work of the United Nations and other road safety bodies. Recognizing the importance of the problem and the need to act, governments from around the world declared unanimously — through UN General Assembly Resolution 74/299 — a Second Decade of Action for Road Safety 2021–2030 with the explicit target to reduce road deaths and injuries by at least 50% during that period. Even more, in case of accidents, shorter response time can significantly reduce people's permanent disability and death rates [3]].

The above evidently compromise the safety and quality of life but also the environmental goals set by the METACITIES Smart City R&I strategy as elaborated in D2.1.

Enhancing Smart Mobility in Patras through the Metacities Project

Smart mobility solutions play a pivotal role in addressing contemporary urban challenges, especially in densely populated areas like the City of Patras. With the vision to use technological innovations to make Patras an inclusive, safe, resilient and sustainable city the Metacities project has emerged as a promising initiative. The proof-of-concept experiments that will run on the Municipality of Patras digital infrastructure will set up the base for the implementation of a Patras Intelligent Transport and Incident Management System (Patras-ITIMS). According to the METACITIES methodologies, policies that may assist in dealing with the Transport issues in the City of Patras will rely on the design of an efficient Smart Transport digital twin, that will monitor the necessary data and provide the "testbed" for various policies and solutions before actually implementing them.

The goal is 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. The City of Patras faces several mobility-related challenges that hinder the efficiency and sustainability of urban transportation systems. These include traffic congestion, illegal parking, inadequate public transportation information, limited electric vehicle infrastructure, and environmental concerns. Some use cases that are described here will demonstrate the need for smart mobility solutions.

2.1.1 Use case 1: Patras Smart Parking/Smart Mobility solution

One of the main problems in the City of Patras that affects **the quality of life, safety and accessibility** of various significant points of interest in the city center are the limited parking spaces and limited short term parking solutions, large number of people living in the outskirts of the city and bad parking behavior with respect to short term parking. In order to propose solutions and policies that will overcome the problem of the illegal parking induced congestion compromising the safety and the accessibility of cyclists, pedestrians and drivers that visit or work at the city center, one need to understand the problem.

It is also important to evaluate the problem, hence provide an index that comprises various parameters and evaluates the traffic congestion and parking capacity and availability in a city. In METACITIES we propose an index as follows:

- an urban parking and traffic impact heatmap **(UPTI index-** driving to closest available parking spot plus walking time/bus travel duration to destination)

The overall index will evaluate specific destination points in the City Center and give a real time estimation of it in a heatmap of the City. It is noted that in Patras there are three types of parking spots: free of charge municipal parking areas, free of charge parking spots by the street and private parking areas.

From the list of the existing sensors and data sources provided in Patras, we evaluate various solutions and investigate an index that can be extracted in almost real time for the city. This use case envisages not only providing drivers with real time information about the parking availability and traffic congestion, but also to give them healthier, greener (see next use case) and cost efficient solutions for their trip. The METACITIES Patras smart mobility application will interoperate with Patras ITIMS digital twin and will ultimately be able to give drivers valuable real time info with respect to the following:

- evaluated Estimated Arrival Time as an urban parking and traffic impact map (UPTI index-driving to closest available parking spot plus walking time/bus travel time to destination)
- free parking slots in the area of interest for drivers with optimal cost estimation
- Illegal parking incidents in City Centre (evaluated and actual).

The aim of this is for drivers to evaluate their plans to travel through the city center with their car. Moreover, the application will also provide suggestions and evaluation of alternative solutions together with some predictions. Specifically, Patras smart mobility solution will suggest location based (this can be used by the citizens as they travel to their destination):

- alternative parking spots in the outskirts of the city and estimation of walking time with cost estimation (UPTI)
- alternative transportation /intermodal transport for the places of interest (like for example park – to – bus, park – to – scooter and park-to-walk alternatives to their destination).

The application will also provide drivers and authorities with event/abnormality detection and event UPTI map predictions based on historical data and simulations.

The DT will also provide predictions for various what if scenarios (e.g. provide UPTI index for urban zones for varying parameters: available parking slots, traffic conditions).

2.1.1.1 Input data sources and preconditions

We will collect data from roadway sensors and cameras (specialized) to study the impact of illegal parking behavior on traffic congestion. Such behavior includes, among others, violations of restricted parking zones, double parking and violation of maximum allowed parking time.

These conditions will be monitored and identified by advanced sensor networks with edge analytics.

As far as the data to be used are concerned, these include:

- Smart parking sensor events from 328 Lora interconnected parking sensors (status and temperature data)
- Video streaming from specialized cameras for parking violation
- 28 Bluetooth sensors for Traffic Monitoring and Travel Time Calculation System
- Pedestrian sensor systems (people counting for crowd estimation)
- Entry-exit sensors in 5 outdoor municipal parking lots.

Also, various third party applications and simulations will be used:

- 2D and 3D data sets from google maps
- Traffic estimation and congestion from Google maps and other applications
- Double/illegal parking incident evaluation platforms
- Estimated arrival time simulation tool
- 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).

2.1.1.2 High Level Technical Approach

In METACITIES we will provide the design for the functional blocks and respective interfaces for a Digital Twin that will evaluate all the data mentioned in the previous section. The Digital twin will be at the core of the Intelligent Transport and Incident Management System which will in turn show in a visual way the UPTI heatmap for specific destination in the city in real time. In that way a driver can use the METACITIES Patras application to understand the accessibility of a specific destination by car, to visually exhibit the traffic situation and congestion in real time and in a location-based mode (depending on the location of the driver). The driver will also be offered various alternative ways to reach a specific destination.

Furthermore, in future models, simulations and algorithms may be developed that will be able to run specific “what if” scenarios in order to develop proposals for solving transport problems like optimization of traffic flow, pedestrian and cyclists flows, public transport alternatives, traffic management, parking management etc. In order to provide efficient and sufficient solutions historical monitored data from the traffic patterns and characteristics, various parking related incidents and drivers/pedestrian behavior may be exploited. Hence from the list of the existing sensors and data sources provided above, there are numerous combined and stand-alone data that can be used.

2.1.2 Use Case 2: Environmental patterns of traffic incidents

One of the main problems faced by big cities that compromise the quality of life of their citizens relates to the green dimension of the city life. Especially for the Smart Mobility priority it has been identified as a compromising factor that needs to be dealt with not only for specific stakeholders (cyclists, pedestrians), but for all citizens at large.

Monitoring the environmental indexes is a very important factor when trying to apply policies and actions that will make a city greener, healthier, more sustainable and more attractive for its citizens and visitors. The impact of traffic incidents on environmental indexes needs to be thoroughly analyzed by correlating traffic conditions with environmental (air quality, noise, smoke, etc.) measurements. As presented in the METACITIES R&I strategies, the Smart Transport priority would become green and environmentally friendly.

We will extend the application from previous use case to provide citizens and visitors valuable real time information with respect to the pollution and noise levels in the city. By providing a heatmap of the air pollution and noise levels, the cyclists and pedestrians may evaluate their plans to travel through their city center. The application will also provide evaluation and suggestions of alternative solutions together with related predictions. Specifically, Patras smart mobility solution will suggest location based (this can be used by the citizens as they travel to their destination) alternative routes and alternative transportation /intermodal transport to the places of interest.

2.1.2.1 Input data sources and preconditions

By monitoring specific indices through sensors (Municipality and University) and crowd sourcing means, and making use of the air quality forecasting models already applied to the city of Patras, one can correlate and understand the expected environmental conditions after an incident on a certain city location.

Hence all the data sources from the previous use case will be used here also in addition to the following:

- Third party weather data and noise level data
- Third party user input from applications (crowd sourced incidents, e.g. from “sense.city” application see D1.1)
- Third party user input from drivers’ applications.

2.1.2.2 High Level Technical Approach

In METACITIES we will design the main functional blocks that will comprise a Digital Twin that will evaluate all the environmental (air quality, noise, smoke, etc.) and traffic data in order to investigate their correlation and the effect that traffic and /or incidents may have on the environment in the city center.

The METACITIES Patras smart mobility application will be able to visually exhibit the environmental and noise situation and congestion in real time (combined with Use Case 1). Moreover, the digital twin will be able to train air quality forecasting models and will be able to run specific “what if” scenarios in order to develop proposals for compromising the effect on environment.

2.1.3 Use Case 3: Emergency Management

One main problem in large cities that affects the quality of life and the safety of citizens relates to road deaths and injuries that through UN General Assembly Resolution 74/299 — a Second Decade of

Action for Road Safety 2021–2030 are set to be reduced by at least 50%. It has become evident that for injuries, in case of road accidents, shorter response times can significantly reduce people's permanent disability and death rates.

To that respect an Intelligent Transport and Incident Management System (ITIMS) of a smart City, according to the METACITIES R&I strategies and goals for Smart Transport priorities should alleviate the issues of traffic congestion for emergency services. This use case looks into supporting Emergency service operations with a digital operations center that exhibits the real time traffic information required to the first responders about the congestion in the city, while it supports the coordination of routing their vehicles when trying to reach an incident.

METACITIES Patras smart mobility application will provide the operating center for emergency services (through which authorities can sync up their actions after a traffic incident) with the data that is required, such as alerts and re-routing info. These actions include vehicles' rerouting while facilitating emergency vehicles to access an incident when needed. By simulating various traffic re-routing scenarios, the METACITIES Patras smart mobility application may suggest to Traffic Police rerouting options to support emergency services.

2.1.3.1 Input data sources and preconditions

The data that are required will be similar to the ones mentioned in use cases 1 and 2. Data from roadway sensors and cameras may be used for traffic prediction and event prediction. Third party data may include

- Crowd sourced alerts (e.g. sense.city)
- Crowd sourcing updates for events (occupying large public spaces)
- Service level Traffic simulation (e.g., Sumo simulator with what if scenarios for routing).

2.1.3.2 High Level Technical Approach

Based on real time collected data and analysis, we will design the building blocks, interoperability center and interfaces that are required to be built for the Digital Twin that will comprise an operating center for emergency services through which authorities can sync up their actions after a traffic incident. These actions include vehicles' rerouting while facilitating emergency vehicles to access the incident when needed and route supervision through a bird's eye view of the city for the dispatcher. At a later stage, this operating center will become an advanced notification system for first responders but also for drivers, cyclists, pedestrians and public vehicles.

Similarly, to Use case 1, data will be used to train traffic models that will enable quick decision making in case of incidents that affect the traffic. The Digital twin will be at the core of the Intelligent Transport and Incident Management System which will in turn show in a visual way the traffic situation of specific roads, transport network and develop proposals for solving transport problems. Specific solutions will be run as what if scenarios when specific infrastructure changes will be made.

2.2 DT for Green City

As stated in the DIGITAL Europe Program "Making Europe greener and more digital are the twin challenges for our generation, and our success in meeting them will define our future." At the same time, the European Green Deal has set out an ambitious plan to reduce GHG emissions by 55% by 2030 and reach net zero emissions by 2050. These goals are reflected in the following strategic documents of the city of Burgas:

- Plan for Integrated Urban Development, 2021-2027. This is the main development strategy of the city, and it provides the framework for all the other plans and strategies. Its priority 6: Successful Management of Natural and Urban Ecosystems envisions measures to improve the adaptation potential of the city including increasing the share of Renewable Energy Solutions (RES), increasing the energy efficiency of buildings and the development of platforms to track environmental indicators.
- Sustainable Energy Strategy and Climate Action Plan 2021-2030 (SESCAP), elaborated under the Global Covenant of Mayors methodology, sets the following specific goals for the city for 2030:
    - reduction of CO2 emissions by 40%
    - decrease of primary energy use by 32.5%
    - increase the share of RES in the energy mix of the city by 32%.

The SESCAP also includes energy and emissions inventory for 2020. According to it, the building sector accounts for the largest share of primary energy use and greenhouse gas (GHG) emissions, 50% of the total primary energy use of the city and 54% of total GHG emissions in the city. At the same time, as of 2020 (last available data), the share of RES in the energy mix of the city is only 12%.

These goals were behind the rationale for the municipality`s focus on energy efficiency (EE) in the building stock and the increase of the RES potential of the city, which amounts to PV installations due to the restrictions on wind turbines because of the geographical location of Burgas on one of the biggest avian migration routes in Europe. The BG/Burgas pilot will implement three use cases in the development of the ODTF in order to automate the analysis and improve its investment decision-making into EE solutions.

The Bulgarian partners in METACITIES will use the Digital Twin (DT) for the Green City pilot to upgrade the existing GIS of the city and the Integrated Urban Platform SmartBurgas, with tools related to the solar potential of the city. This will allow for the up scaling of the existing digital platform for energy efficiency with new 3D functionalities to help better manage resources and utilize unused roof spaces of public and non-public ownership. The pilot will focus on gathering relevant and valid data sources to make 3D digital twins of one or more public buildings. Those will then be developed by using different approaches, as AI and machine learning algorithms, to detect patterns and provide solutions regarding energy efficiency, air quality, or climate conditions monitoring and control. Further in time, data collection will enable the formulation of data-driven decisions for applying investment strategies to ensure a more sustainable and efficient urban environment. The DT for Green City will be applied and evaluated focusing on the following three use cases.

2.2.1 Use Case 1: Renewables (PV) potential and performance analysis tool

The DT will identify PV systems existing in the city for municipal, private and business buildings and provide a new tool to create models that accurately assess and determine their production potential. This use case should provide users with the ability to monitor PV energy production potential, including functionalities enabling the consideration of different scenarios as to how to achieve the goals of the city for 2030, as well as inform building owner(s) and citizens about the economic feasibility of PV installations on the buildings.

2.2.1.1 Input data sources and preconditions

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.

2.2.1.2 High Level Technical Approach

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 feasibility study and performance analysis of PV systems is essential to assess the overall system energy consumption, to look for approaches for optimization of energy utilization, and to ensure reliable electricity supply. The analysis will also involve estimation of the combined efficiency and effectiveness of solar power generation and energy storage, if already in-place. The results from this analysis, the estimation of some of the technical performance indicators as a key functionality of the PV system, the data collected from the input data sources, and the application of data analytics, will be the base for the digital twin modeling and development.

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 analyzed in order to be applied for the assessment of the performance of the PV systems and aid the digital twin 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 analyzed. 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.

2.2.2 Use Case 2: Buildings Energy Performance Analysis

By using a digital twin for a newly built public building (kinder garden) 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 analyzing 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.

2.2.2.1 Input data sources and preconditions

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 (e.g., temperature, humidity, solar exposure). 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.

2.2.2.2 High Level Technical Approach

The energy performance of buildings depends on their physical features, including the overall insulation performance, climatic conditions, and business or other public activities, such as operating hours and occupancy characteristics. In METACITIES, a DT platform for energy performance analysis of a public building will be developed. For this, it is necessary to implement an adequate data collection methodology and perform a fair assessment of the energy consumption considering relevant public activities taking place in the building.

In METACITIES, the technical approach for this use case will start with a state of art analysis of various energy performance assessment methodologies and the choice of the specific approach that will be applied and implemented in the DT platform. Results will vary depending on how much the assessment reflects the features and conditions of the building. In many countries, various assessment methods for existing buildings can be selectively utilized, and insufficient data can be compensated for by using different simplified input data or data estimation methods. Many classifications and reviews of assessment methods could be found in the literature that could be used for proper design of the technical implementation of this use case. Based on this study, a respective performance assessment methodology will be chosen and implemented in the digital twin. In addition, methodologies for analysis of the thermal insulation of buildings will also be considered for the correct estimation of the thermal insulation at roof level.

Examples of key aspects that could be included in the DT based energy performance analysis include: the energy consumption, and evaluation of consumption patterns; energy benchmarking to identify energy-saving opportunities; building envelope analysis to analyze the extent of heat loss or gain through walls, roofs, windows, and doors; evaluation of the efficiency and performance of heating, ventilation, and air conditioning (HVAC) systems; analysis of the lighting system's efficiency, including the type of lighting technology, lighting controls, and lighting schedules; evaluation of the feasibility of integrating renewable energy photovoltaic (PV) panels; analysis of usage patterns, occupancy schedules, and user interaction with building systems.

Moreover, by inputting in the digital twin platform data related to the building insulation characteristics, equipment specifications, weather data, and occupancy patterns, the developed digital twin in METACITIES could be used to predict energy consumption, identify energy-saving measures, and evaluate their impact; evaluate the building's indoor environmental quality factors such as thermal comfort, indoor air quality, acoustics, and lighting levels; analyze factors that impact occupant health, productivity, and comfort; identify opportunities for improvements that enhance indoor environmental quality while maintaining energy efficiency.

2.2.3 Use Case 3: Budget Planning for Energy Usage and Buildings

Following the results from Use case 2, the digital twin 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.

2.2.3.1 Input data sources and preconditions

Data regarding energy consumption gathered from Use Case 2. If necessary, through the implementation of specific IoT devices, additional data will be collected for a deeper analysis into the particular types of energy consumption in each building, assuming a future breakdown of consumption considering the equipment existing at each delivery point. Gathering data on building Energy Usage by aerial radiometric thermal mapping and thermal inspection will be conducted as well to reflect the KPI`s after energy efficiency measures take. Thermal inspection will also identify both hot and cold spots which can indicate heat losses, air ingress or water ingress into the building shell. The specific information will be used in the modeling for adjustments of the predictive models.

2.2.3.2 High Level Technical Approach

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.

2.3 DT for Urban Planning

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 organization of land use, the environment, public welfare, and the efficient flow of traffic and communication.

Digital Twins (DT), as virtual replicas of physical objects or systems, play a pivotal role in tackling various challenges in urban planning by providing advanced tools and methodologies. The benefits of using DT in urban planning and management include real time monitoring and management, predictive analysis and planning through simulations, effective resource allocation leading to more sustainable urban environments, maintenance and operations by predicting which parts of the city infrastructure require maintenance, and urban development by supporting the design and testing of new urban development projects. Thus, DTs can assist in making informed decisions, optimize resources, engage citizens, and create more resilient and sustainable cities.

2.3.1 Use Case 1- Urban Heat Stress Reduction (Parks and Green)

Heat stress is an increasing problem in many European cities due to the ongoing climate change. Citizens experience higher levels of heat stress than people living in rural areas due to higher surface and air temperatures (the Urban Heat Island effect, lower wind speeds and higher levels of solar and thermal radiation coming from building materials). Heat stress has a negative impact on sleep, productivity, morbidity and mortality of urban residents. It is therefore essential to have a good understanding of the factors contributing to heat stress, identifying hot spots in a city, and assessing the effectiveness of adaptation measures

Urban areas usually experience the **urban heat island (UHI)** effect, that is, they are significantly warmer than surrounding rural areas. The temperature difference is usually larger at night than during the day. The main cause of the UHI effect is from the modification of land surfaces while waste heat generated by energy usage is a secondary contributor. A study has shown that heat islands can be affected by proximity to different types of land cover, so that proximity to barren land causes urban land to become hotter and proximity to vegetation makes it cooler. As a population center grows, it tends to expand its area and increase its average temperature. The term heat island is also used; the term can be used to refer to any area that is relatively hotter than the surrounding, but generally refers to human-disturbed areas. Urban areas occupy about 0.5% of the Earth's land surface but host more than half of the world's population. Compact, dense urban development may increase the urban heat island effect, leading to higher temperatures and increased exposure.

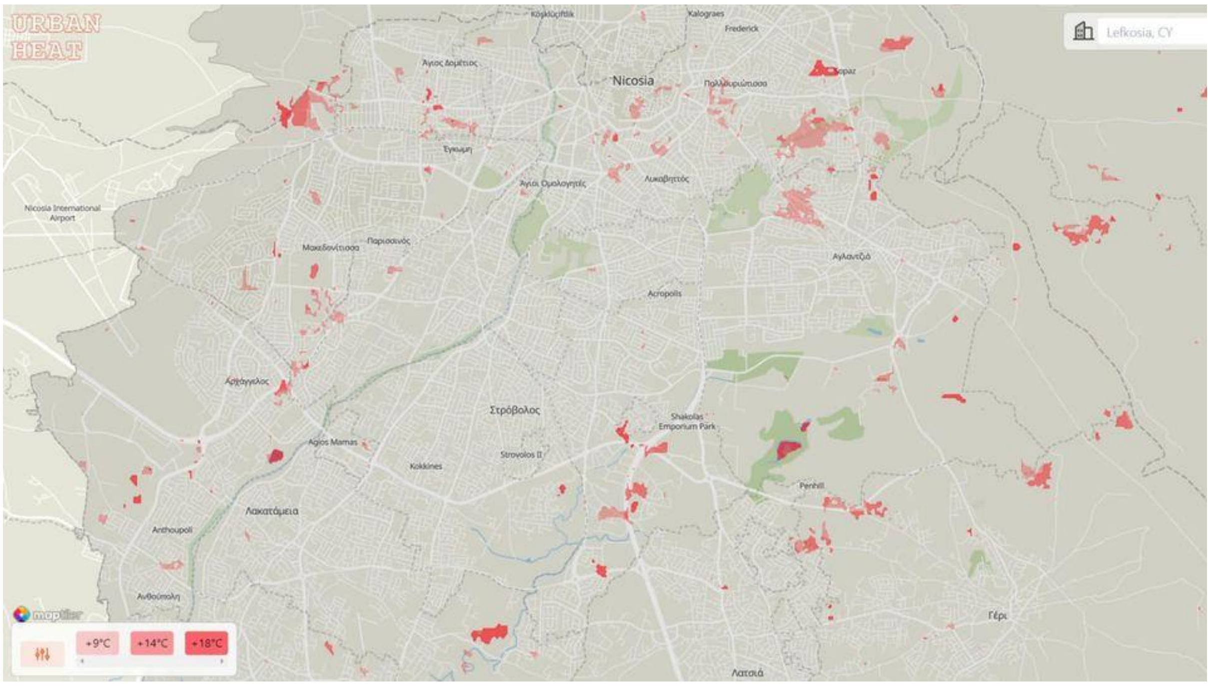


Figure 1: UHI for the City of Nicosia (taken from the Urban Heat app)

As shown in the image above, Figure 1, Nicosia has a large number of locations with extremely high UHI (usual values should be less than 10^{o}C). We want to measure, monitor, and visualize UHI in Nicosia and correlate actions taken in the city planning with the reduction of heat in the city.

2.3.1.1 Input Data Sources and Preconditions

We will fuse external open-source information (from GAEA, Heat Area and Copernicus) to the iNicosia DT to a) visualize, and b) offer to simulation and prediction tools for better selection of mitigating actions.

Some of the tools and technologies to calculate and visualize UHI are the following:

- Urban Heat app: Open-source application developed by Damien Allen, which aims to provide a convenient visualization of the Urban Heat Island Effect across European urban centers. Isotherm contours are generated from moderate resolution satellite imagery using client-side worker processes. Due to limitations in available processing power and cloud resources, this project is limited to cities included in the Eurostat GISCO Urban Audit (2021).

- GAEA: Gaea's Geospatial Application is a comprehensive and versatile platform that offers a range of essential tools for analyzing and understanding geographic data. Enhanced with suitable satellite imagery it can offer a more specialized view of Nicosia.

The Municipality of Nicosia has an extensive record of the total Tree Stock in the city. This is not digitized or able to be visualized easily. The existing information will be imported to the iNicosia Platform for easier visualization. The Municipality of Athens has created a very unique and interesting application named Athens Trees (https://athenstrees.cityofathens.gr), which can be re-used (with permission) or replicated to collect the proper Tree Stock information. The iNicosia DT or any Nicosia-Trees type platform can make use of the GAEA/Periopsis system which can also locate trees and identify their type in an automatic way.

TABLE 2: TOOLS AND TECHNOLOGIES - USE CASE 1 - URBAN HEAT STRESS REDUCTION (PARKS AND GREEN)

Technology/Asset/Platform	Partner	Description (input/output)
Smart Nicosia	CYENS and UCM (Municipality of Nicosia)	Implements smart city technologies in Nicosia, providing real-time data on traffic, environmental conditions, and parking spots etc. (input: sensor data, output: actionable insights).
GAEA	CYENS	Geospatial Application developed by CYENS. GAEA is a comprehensive and versatile platform that offers a range of essential tools for analyzing and understanding geographic data. With its three main services - Proximity General Service, Land Cover Service, and GeoHazard Service - users can gain valuable insights into spatial relationships, land composition, and potential hazards within specified areas on the Cyprus Map.
Urban Heat	Open Source	Application visualizing the Urban Heat Island Effect using satellite imagery and client-side processing (input: satellite imagery, output: isotherm contours and UHI visualizations).

2.3.1.2 High Level Technical Approach

Our specific solution in this use case is to enhance the city's Green Infrastructure (planting more trees) in a way that addresses UHI reduction. This means proper UHI Mapping and Monitoring based on satellite data and IoT-based sensors and Tree Planting Algorithms that also make use of AI and Predictive Analytics to simulate the impact of interventions and guide planning decisions. The Agronomists/Agriculturalists of the Municipality of Nicosia will create a database with the characteristics of the trees already planted and suitable to be planted in Nicosia. Cyprus has a very hot and dry weather, which means that certain varieties and tree species are better suited for its climate. Features, like growth rates, branch spans, leaf types, shading characteristics, water and fertilizer demands, pruning and pesticide demands, etc. will be collected. These will be used by the simulator to be developed, which will generate instances in the future, showing the way trees will grow and how they will affect the environmental parameters of interest (temperature, humidity, oxygen, pollutants, etc.).

All the components described above will form part of the iNicosia DT.

2.3.2 Use case 2 - Smart Parking

Urban centers face significant challenges with traffic congestion largely exacerbated by drivers searching for parking. People struggle to find parking on a daily basis, particularly in densely populated cities. Driving in circles around the metropolis for a parking spot is a daily occurrence. Any destination, whether for work, personal meetings at specific locations, recreation, or emergency visits to places such as hospitals, must be reached for the least amount of money possible. The increasing number of automobiles and vehicles in a city also contributes to the difficulty and expense of finding a parking space. Frequently, people enter a parking lot without knowing if a spot is available, making navigation problematic. In addition, the incorrect location may be chosen without the drivers' knowledge based on cost considerations such as time, money, or fuel consumption. Another significant issue is the driver's disregard for parking spaces that are closer to his or her destination or have a lower cost in terms of price, distance from the vehicle's current location, or distance to be walked from the parking space.

This results in increased pollution, fuel waste, and time lost, contributing to urban inefficiency and reduced quality of life. Urban traffic is responsible for 40% of CO_2 emissions and 70% of other pollutant emissions from road transport, and over 30% of urban traffic is caused by drivers looking for a parking space.

Recognising these issues, policymakers, such as city planners and local government officials, are in need of innovative Smart Parking solutions to alleviate the strain on urban infrastructure and improve overall living conditions.

2.3.2.1 Input Data Sources and Preconditions

TABLE 3: TOOLS AND TECHNOLOGIES - USE CASE 2 – SMART PARKING

Technology/Asset/Platform	Partner	Description (input/output)
Smart Nicosia	CYENS and UCM (Municipality of Nicosia)	Implements smart city technologies in Nicosia, providing real-time data on traffic, environmental conditions, and parking spots etc. (input: sensor data, output: actionable insights).
Pafos Smart Parking	UCM (Municipality of Pafos)	Smart parking system in Paphos, using sensors to monitor parking space availability and provide real-time information to drivers (input: parking sensors, output: real-time parking availability data).
iNicosia DT	CYENS	The iNicosia Digital Twin is a flagship project by CYENS Centre of Excellence that creates a comprehensive 3D digital replica of Nicosia, Cyprus. This model integrates real-time data from various sources, including smart city infrastructure and Internet of Things (IoT) devices, to accurately represent the city's physical and functional aspects. Utilizing advanced technologies such as photogrammetry and laser scanning, iNicosia enables simulations and visualizations for urban planning, traffic management, and environmental monitoring, thereby enhancing decision-making processes and improving the quality of life for residents and visitors.

Technology/Asset/Platform	Partner	Description (input/output)
Smart Nicosia	CYENS and UCM (Municipality of Nicosia)	Implements smart city technologies in Nicosia, providing real-time data on traffic, environmental conditions, and parking spots etc. (input: sensor data, output: actionable insights).
GAEA	CYENS	Geospatial Application developed by CYENS. GAEA is a comprehensive and versatile platform that offers a range of essential tools for analyzing and understanding geographic data. With its three main services - Proximity General Service, Land Cover Service, and GeoHazard Service - users can gain valuable insights into spatial relationships, land composition, and potential hazards within specified areas on the Cyprus Map.
Urban Heat	Open Source	Application visualizing the Urban Heat Island Effect using satellite imagery and client-side processing (input: satellite imagery, output: isotherm contours and UHI visualizations).

2.3.2.2 High Level Technical Approach

The Smart Parking Management System utilizes IoT technology to integrate sensors in parking spaces that communicate availability in real-time to a cloud-based platform. This platform processes data and provides information to drivers via a mobile app, which includes navigation to the nearest available spot, online reservation, and payment options. For the policy maker, the data is fed into algorithms and heuristics that answer specific questions that create value, like those described above. The algorithms can be part of the DT or operate as external applications, pulling information from the DT using suitable APIs.

The implemented DT could assist to the solution of the parking management problem in three steps. Firstly, Real-Time Data Processing is paramount, utilizing cloud computing capabilities to effectively manage and analyze the vast amounts of data generated by parking sensors in real-time. This enables swift decision-making and optimization of parking operations. Secondly, User Interface Design is crucial for ensuring seamless interaction between users and the system. By crafting intuitive applications, user adoption and satisfaction are enhanced, ultimately improving the overall effectiveness of the solution. Lastly, Integration with Other Systems is imperative. The parking solution must seamlessly interface with city traffic systems and navigation apps to provide a holistic mobility solution. This integration ensures smooth coordination between various elements, such as synchronizing parking availability with public transit schedules, optimizing traffic flow based on real-time parking data, and enhancing emergency response times by providing clear pathways. Together, these elements form a comprehensive digital transformation strategy that not only addresses the immediate parking challenges but also contributes to the broader goals of smart city initiatives, fostering a more efficient, sustainable, and liveable urban environment.

3 ODTF Requirements for Smart Cities

In this chapter, we present a comprehensive requirements' analysis for three pilots focusing on smart mobility, urban planning, and energy efficiency and renewable energy applications. These requirements have been extracted from the analysis of the results of surveys performed with the participation of all types of the Quadruple Helix (QH) stakeholders. By understanding the specific needs and expectations of citizens, government officials, academia, and industry representatives, we aim to develop innovative solutions that fulfill their diverse requirements.

In this chapter the identified requirements will be categorized into functional and non-functional aspects, allowing us to prioritize and design effective solutions. Functional requirements will define the specific functionalities and capabilities that the technical outcome must offer to achieve its goals, while non-functional requirements will focus on ensuring high performance, usability, and security. By leveraging the insights gathered from the Quadruple Helix actors, we can create tailored solutions that optimize smart mobility, streamline urban planning processes, and enhance energy efficiency and renewable energy applications. The integration of these requirements into the development process ensures that the resulting solutions align with the stakeholders' needs and contribute to the sustainable development and growth of the cities and communities involved.

3.1 Functional and non-functional Requirements for Smart Mobility

TABLE 4: FUNCTIONAL AND NON-FUNCTIONAL REQUIREMENTS FOR TRANSPORT.

RQ-ID	Use Case	RQ-Title	Detailed Specifications
F-RQ-T-1	CY/GR	Real-time information on parking availability	**Architectural Component:** Edge Equipment, Edge Processors, Traffic Data, Time-series Storage **Performance Metrics:** Granularity per minute or 30 sec.Granularity per minute or 30 seconds
F-RQ-T-2	CY/GR	Integration with other transportation and urban planning systems	**Architectural Component:** Simulators, Field-use apps **Performance Metrics:** Interoperability center
F-RQ-T-3	CY/GR	Ability to work across different parking systems and providers	**Architectural Component:** Edge Equipment **Performance Metrics:** At least two different parking owners and systems
F-RQ-T-4	GR	Ability to work with multiple parking sensor vendors	**Architectural Component:** Edge equipment, Rule Engines Guided AI/ML **Performance Metrics:** At least two different parking sensor vendors and systems
F-RQ-T-5	CY/GR	Ability to pay using different payment methods	**Architectural Component:** Semantics Transform, GIS/BIM Services **Performance Metrics:** Visa, MasterCard, Apple Pay and Google Pay
F-RQ-T-6	CY/GR	Ability to receive notifications about parking spot availability	**Architectural Component:** Edge Equipment, Semantics Transform **Performance Metrics:** Support mobile notifications, SMS notifications or email notifications
F-RQ-T-7	GR	Ability to receive navigation instructions	**Architectural Component:** GIS/BIM Services, Field-use applications

		to available parking spots	**Performance Metrics:** Support turn to turn navigation
F-RQ-T-8	CY/GR	User-friendly interface	**Architectural Component:** Field-use apps, User Input Data, Map Data, Relational Storage, GIS Data **Performance Metrics:** 60% in satisfaction survey using questionnaires
F-RQ-T-9	CY/GR	Reminders about parking time expiration	**Architectural Component:** Rule engines Guided AI/ML **Performance Metrics:** 2 reminders: one hour and 30 minutes before expiration through email or SMS
F-RQ-T-10	GR	Automatic creation of parking tickets (fines) in cases of violating parking time expiration	**Architectural Component:** Digital twin analytics, Rule engines Guided AI/ML, GIS/BIM Services **Performance Metrics:** parking ticket creation in 5 minutes after expiration
F-RQ-T-11	CY/GR	Ability to extend parking time remotely	**Architectural Component:** Directory Services **Performance Metrics:** Time extension for 30 minutes or 1 hour
F-RQ-T-12	CY/GR	Ability to view parking history and receipts	**Architectural Component:** Digital Twin analytics **Performance Metrics:** History results for two years
F-RQ-T-13	CY/GR	Showing number of handicap- accessible parking spots	**Architectural Component:** Edge equipment **Performance Metrics:** 80% success
F-RQ-T-14	GR	Automatically identify valid PwD (People with Disabilities) badge holders via use of Tags	**Architectural Component:** Edge Processors **Performance Metrics:** 90% success
F-RQ-T-15	GR	Issue parking ticket when vehicle without appropriate Tag parks in PwD spot	**Architectural Component:** Field-use applications **Performance Metrics:** 100% success
F-RQ-T-16	CY/GR	Integration of mobile payment system	**Architectural Component:** Gateways **Performance Metrics:** N/A
F-RQ-T-17	CY/GR	Capability to manage parking availability and spaces through a digital platform	**Architectural Component:** Digital Twin analytics, Modeling and Simulation **Performance Metrics:**80% success
F-RQ-T-18	GR	Notifications to emergency services	**Architectural Component:** Modeling & Simulation, **Performance Metrics:** Notification to police, fire department, Emergency Medical Services (EMS): 75%
F-RQ-T-19	GR	Identify type of emergency and number of injured persons	**Architectural Component:** Modeling & Simulation **Performance Metrics:** 70%
F-RQ-T-20	GR	Keep track of the available emergency vehicles and personnel	**Architectural Component:** Smart Vehicles, Modeling & Simulation **Performance Metrics:** 90%

F-RQ-T-21	GR	Real time dispatch of emergency services based on the severity of the incident	**Architectural Component:** Modeling & Simulation, **Performance Metrics:** Granularity of sub second, 80%
F-RQ-T-22	GR	Calculate shortest paths to the incident	**Architectural Component:** Smart Vehicles, Modeling & Simulation **Performance Metrics:** 90%
F-RQ-T-23	GR	Assist traffic controllers to optimally reroute traffic to minimize disruption	**Architectural Component:** Smart Vehicles, Traffic Data, Modeling & Simulation **Performance Metrics:** 70%
F-RQ-T-24	GR	Automatically monitor traffic volume via appropriate sensors	**Architectural Component:** Smart Vehicles, Traffic Data, Edge processors, digital twin analytics **Performance Metrics:** 90%
F-RQ-T-25	GR	Monitor air quality (pm rate)	**Architectural Component:** Edge Equipment **Performance Metrics:** Sampling interval ranging from 1 to 30 seconds and a sampling rate of 280 mL/min.
F-RQ-T-26	GR	Measure noise	**Architectural Component:** Edge Equipment **Performance Metrics:** 95%
F-RQ-T-27	GR	Keep a record of environmental and traffic volume of time series data	**Architectural Component:** Simulators, Field-use apps, Traffic Data, Time-series Storage **Performance Metrics:** 2 years record, 5 minutes interval for environmental, 1 minute interval for traffic volume
F-RQ-T-28	GR	Correlate environmental indices with traffic volume measurements	**Architectural Component:** Modeling & Simulation, Traffic Data **Performance Metrics:** At least two specific correlations
NF-RQ-T-1	CY/GR	Privacy - preserving mechanism to safeguard drivers' information	**Architectural Component:** Smart Vehicles, Field-use apps, Modeling & Simulation **Performance Metrics:** integration of at least two preserving mechanisms
NF-RQ-T-2	CY/GR	Protection of personal and financial information	**Architectural Component:** Field-use apps, Time-series Storage **Performance Metrics:** integration of at least two preserving mechanisms
NF-RQ-T-3	CY/GR	Accessibility and usability for people with disabilities	**Architectural Component:** Smart Vehicles, User Input Data **Performance Metrics:** 60% in satisfaction survey using questionnaires
NF-RQ-T-4	CY/GR	Real-time parking availability monitoring using IoT sensors	**Architectural Component:** Edge Equipment **Performance Metrics:** transmitting changes in ≤ 35 seconds with accuracy of at least 90%
NF-RQ-T-5	CY/GR	Predicting parking demand and optimizing space usage using AI algorithms	**Architectural Component:** Rule Engines Guided AI/ML **Performance Metrics:**70% success

NF-RQ-T-6	CY/GR	Data encryption and protection for security and privacy	**Architectural Component:** Field-use apps, Traffic Data, Relational Storage, Time-series Storage **Performance Metrics:** Support of at least two encryption techniques
NF-RQ-T-7	GR	Data must be encrypted in-transit and at-rest	**Architectural Component:** Edge Equipment, Field-use apps, Edge Processors, Traffic Data, Relational Storage, Time-series Storage **Performance Metrics:** Support of at least two encryption techniques
NF-RQ-T-8	GR	All API endpoints must employ authentication and must mandate encryption	**Architectural Component:** Field-use apps, Gateways, Edge Processors **Performance Metrics:** Support of at least two encryption techniques
NF-RQ-T-9	CY/GR	Mobile application interface for accessing the smart parking digital twin	**Architectural Component:** Field-use apps **Performance Metrics:** Support of at least one popular operating system e.g. Android, iOS
NF-RQ-T-10	GR	Users must uniquely authenticate with the Digital Platform	**Architectural Component:** Directory Services, Field-use apps **Performance Metrics:** Support of username/ password login procedure
NF-RQ-T-11	GR	Digital Platform must employ Role-Based Access Controls (RBAC) for logged in users	**Architectural Component:** Modeling & Simulation, Directory Services **Performance Metrics:** Support at least two roles

3.2 Functional and non-functional Requirements for Urban Planning

TABLE 5: FUNCTIONAL AND NON-FUNCTIONAL REQUIREMENTS FOR URBAN PLANNING.

RQ-ID	Use Case	RQ-Title	Detailed Specifications
F-RQ-U-1	CY/BG	Real-time data such as traffic, weather, and air quality	**Architectural Component:** Field-use apps, Weather data, Time-series Storage **Performance Metrics:** Granularity per minute or 30 seconds
F-RQ-U-2	CY	Access to detailed data about the city's infrastructure, including roads, buildings, and utilities	**Architectural Component:** Simulators, GIS Data, Relational Storage, Map Data, GIS/BIM Services **Performance Metrics:** Interoperability with at least 2 external datasets
F-RQ-U-3	CY	Ability to interact with a digital twin of the city and make changes	**Architectural Component:** Modeling and Simulation **Performance Metrics:** Connection with at least one external digital twin

F-RQ-U-4	CY	Access to historical data about the city's infrastructure	**Architectural Component:** Edge Processors, Relational Storage **Performance Metrics:** Connection with at least one historical dataset
F-RQ-U-5	CY	Access to future projections about the city's infrastructure, such as population growth and economic development	**Architectural Component:** Modeling and Simulation **Performance Metrics:** Connection with at least two future projections
F-RQ-U-6	BG	Compatibility with other planning tools and software used by city officials and planners	**Architectural Component:** Blob storage **Performance Metrics:** Compatibility with at least two other planning tools
F-RQ-U-7	CY	Ability to view the digital twin of the city in virtual reality or augmented reality	**Architectural Component:** 3D Metaverse Services Engine **Performance Metrics:** At least one VR or AR representation of the Digital Twin
F-RQ-U-8	BG	Real-time energy usage data and interactive 3D display options	**Architectural Component:** Blob storage **Performance Metrics:** At least one 3D chart with history time-line
F-RQ-U-9	BG	Data to improve budgeting resources and planning	**Architectural Component:** Blob storage **Performance Metrics:** Annual update of data from ortho-photo maps
F-RQ-U-10	CY	Access to real – time energy usage statistics and to benchmark indicators for future projects	**Architectural Component:** Edge processors **Performance Metrics:** Granularity per minute.
F-RQ-U-11	BG	Access to policies and best practices for energy usage and building renovation in Burgas and ability to compare energy usage and renovation options across buildings in the same area	**Architectural Component:** Relational storage **Performance Metrics:** Access to at least one policy and one best practice for energy usage and building renovation
F-RQ-U-12	BG	Ability to parametrize energy efficiency measures - thermal insulation options and air-conditioning and ventilation options	**Architectural Component:** GIS/BIM Services **Performance Metrics:** At least 3 data visualizations using charts

F-RQ-U-13	CY	Data updates	**Architectural Component:** Time-series Storage **Performance Metrics:** Weekly and monthly data updates
F-RQ-U-14	BG	Access to detailed data for managing the costs of energy use both for public and private users	**Architectural Component:** Relational Storage **Performance Metrics:** Access to at least one dataset for managing the costs of energy use
F-RQ-U-15	BG	Access to future projections about the city's overall energy performance	**Architectural Component:** Modeling and Simulation **Performance Metrics:** Access to at least two future projections
NF-RQ-U-1	BG	Accessibility and usability for people with disabilities, such as those who are deaf or have mobility limitations	**Architectural Component:** Application Level **Performance Metrics:** 60% positive responses in relative questionnaires
NF-RQ-U-2	CY	Security and privacy measures to protect user data	**Architectural Component:** Blob storage, Relational Storage, Time-series Storage **Performance Metrics:** Encryption of personal data and sensitive data (e.g., card details)
NF-RQ-U-3	BG	User-friendliness of the platform, emphasizing visual representations and ease of use	**Architectural Component:** Relational Storage, Time-series Storage **Performance Metrics:** 60% in satisfaction survey using questionnaires
NF-RQ-U-4	CY	Seamless integration of remote sensing and in-site monitoring, utilizing IoT sensors for data collection	**Architectural Component:** Edge Processors, Gateways **Performance Metrics:** Integrate with at least 3 IoT sensors.
NF-RQ-U-5	BG	Security and privacy measures to protect user data and the data of the city	**Architectural Component:** Relational Storage, Time-series Storage **Performance Metrics:** Integration of at least two preserving mechanisms

3.3 Functional and non-functional Requirements for Energy Efficiency and Renewable Energy application.

TABLE 6: FUNCTIONAL AND NON-FUNCTIONAL REQUIREMENTS FOR ENERGY.

RQ-ID	Use Case	RQ-Title	Detailed Specifications
F-RQ-E-1	BG	Real-time data such as energy consumption, CO2 levels in interior spaces, consumption of	**Architectural Component:** Time-series Storage **Performance Metrics:** Integration with at least two external datasets.

		electricity, water and heat, level of lighting	
F-RQ-E-2	BG	Historical data representing timeline	**Architectural Component:** Time-series Storage **Performance Metrics:** At least one historical representation
F-RQ-E-3	BG	Data updates	**Architectural Component:** Weather data, Time-series Storage **Performance Metrics:** Data update on a Daily/Weekly basis
F-RQ-E-4	BG	Interoperability between renewable energy sources, smart lighting, ventilation and air conditioning	**Architectural Component:** Application Layer **Performance Metrics:** At least 3 demo pilots.
F-RQ-E-5	BG	Use public buildings and residential buildings for the city digital twin	**Architectural Component:** Digital Twin Analytics **Performance Metrics:** At least 5 public buildings and residential buildings
F-RQ-E-6	BG	Real-time data such as PV energy production potential, weather, and air quality	**Architectural Component:** Weather data, Time-series Storage **Performance Metrics:** Integration with at least two external datasets.
F-RQ-E-7	BG	Access to detailed data about the city's infrastructure, existing PV systems in the city	**Architectural Component:** GIS Data, Map Data, Document Storage, GIS/BIM Services **Performance Metrics:** Integration with at least one such dataset.
F-RQ-E-8	BG	Ability to interact with a digital twin of the city and make changes	**Architectural Component:** Document Storage **Performance Metrics:** Interact with at least one digital twin of the city
F-RQ-E-9	BG	Access to future projections about the city's infrastructure, such as PV installations on the buildings, energy management data	**Architectural Component:** Modeling and Simulation **Performance Metrics:** Access to at least two future projections
F-RQ-E-10	BG	Compatibility with other planning tools and software used by city officials and planners	**Architectural Component:** Semantics Transform **Performance Metrics:** Compatibility with at least two other planning tools and software

F-RQ-E-11	BG	Ability to view the digital twin of the city in virtual reality	**Architectural Component:** 3D Metaverse services engine **Performance Metrics:** N/A
F-RQ-E-12	BG	Historical data such as PV energy production potential, temperature, humidity, solar exposure	**Architectural Component:** Time-series Storage **Performance Metrics:** Integration with at least one dataset with historical data
F-RQ-E-13	BG	Access to detailed data about the city's infrastructure, the buildings' energy performance, buildings insulation capacity at the roof level	**Architectural Component:** Relational Storage **Performance Metrics:** Integration with at least one external dataset
F-RQ-E-14	BG	Access to historical data about the city's infrastructure, buildings energy performance/consumption	**Architectural Component:** Relational storage **Performance Metrics:** Integration with at least one dataset with historical data
F-RQ-E-15	BG	Access to future projections about the city's infrastructure, such as buildings' energy performance/consumption, energy management data	**Architectural Component:** Semantics Transform **Performance Metrics:** Access to at least two future projections
NF-RQ-E-1	BG	Security and privacy measures to protect user data and the data of the city	**Architectural Component:** Directory Services **Performance Metrics:** Support of at least two encryption techniques
NF-RQ-E-2	BG	User-friendliness of the platform, emphasizing visual representations and ease of use	**Architectural Component:** , GIS Data, Doc Storage, Map Data, GIS/BIM Services **Performance Metrics:** 60% in satisfaction survey using questionnaires
NF-RQ-E-3	BG	Seamless integration of remote sensing and in-site monitoring, utilizing IoT sensors for data collection	**Architectural Component:** Edge Equipment **Performance Metrics:** Integration with at least 3 IoT sensors

4 ODTF Specifications

In this chapter each architectural component of the proposed architecture is related to specific functional and non-functional requirements and the set of relevant use cases; within the context of each use case, it is also identified the actor, the entity that interacts with each component, as well as the description of the interaction between the actor and the component.

4.1 Overview of ODTF and Architecture

The generic Digital Twin overall architecture is presented in Figure 2. The architectural diagram is high level and depicts in a layered approach the components of the METACITIES digital architecture that can support the specific DTs and Metaverses that lie at the core of the R&I Strategies.

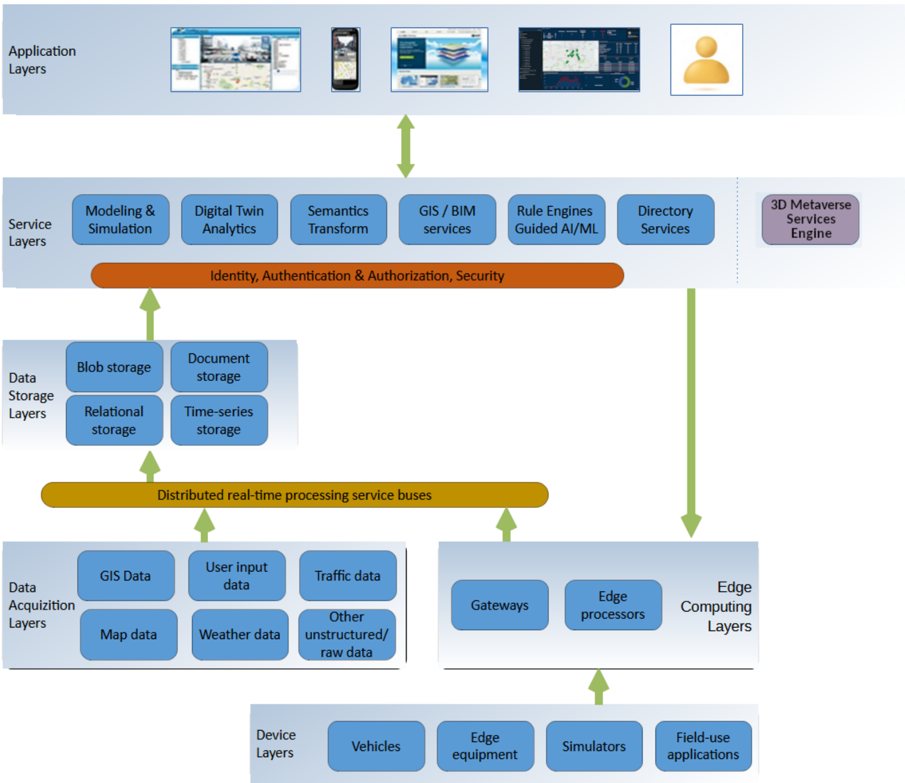


FIGURE 2: ODTF ARCHITECTURE

Layers are clearly separated with each serving specific purposes.

- The Device Layer includes physical devices and equipment as well as essential simulators and field-use applications, such as mobile apps for reporting issues, configuration, and similar tasks. Devices communicate with API Gateways or Edge Processors, which manage data forwarding, particularly for non-IP-capable devices like IoT sensors.
- The Edge Computing Layer facilitates device actuation, ensuring that the devices execute decisions made at the Service Layer reliably. This layer also processes data closer to the source, optimizing real-time decision-making.
- The Data Acquisition Layer is responsible for receiving data from third-party services, including cloud-based sources such as weather services, GIS, BIM, or raw text/CSV files. Data from various sources is processed through distributed real-time service buses (e.g., Kafka clusters),

which perform tasks like filtering, routing, shaping, and pre-processing before transferring it to the Storage Layer.
- The Storage Layer manages all persistent data needs using specialized database management systems tailored for various purposes: relational databases for structured data, time-series databases for sensor readings, document databases, and BLOB (Binary Large Object) storage for handling unstructured data.
- The Service Layer comprises interconnected microservices, either tightly coupled via IPC or loosely connected through cloud APIs. This layer represents the system's intelligence, housing the Digital Twin framework, AI/ML algorithms, rule execution engines, and decision-making mechanisms. It leverages the data processed in previous layers to generate insights, patterns, and actionable outcomes. These services implement advanced analytics, statistical models, machine learning algorithms, and other techniques to extract valuable information, while also interacting with the Edge Computing layer to execute decisions via its API endpoints. The Digital Twin Architecture within the Service Layer includes models and simulations that replicate the behavior of physical and logical real-world objects. These models enable the system to predict future states, analyze "what-if" scenarios, provide recommendations, and take action by directly interacting with devices or third-party services. They also generate alerts when necessary.
- Lastly, the Application Layer consists of user-facing applications (web, mobile, etc.) that provide interfaces for accessing analytics, executing guided "what-if" scenarios, and supporting all user interactions with the system.

4.2 ODTF Components

The present section provides a list of the METACITIES technical components tables. Each table includes along with short descriptions, architectural blocks, state-of-the-art, and requirements. In the list, information is encoded using appropriate prefixes/suffixes and color codes to facilitate browsing and search. More specifically, the table contains the following columns:

- Code: A unique identifier assigned to the technical component
- Component name: The name of the technical component.
- Author: The partner describing the component.
- Reviewers: The partner(s) contributing to the description of the component
- Type: Indicates whether this is software, hardware, or both.
- Description: A textual description of the scope, functionality, and objectives of the component.
- Layer: A set of architectural blocks has been identified in the presentation of the ODTF Architecture. This field allows the selection from a pre-defined list of values [Device Layer, Data Layer...]. This classification of components enables the conceptualization of the architecture.
- Architectural sub-block:
- Functional requirements: A set of technical/functional requirements that characterize the component as a standalone module. The requirements are encoded using the component’s code, along with the suffix .F and an incrementing integer (e.g. F-RQ-E-11) to enable unambiguous references to requirements.
- Non-functional requirements: Just like above, non-functional requirements are listed and encoded using the suffix .NF and an incrementing integer.
- Use cases: The set of use cases for this technical component. Each use case is assigned a code combining the component code with the suffix _UC and an incrementing integer. In case there are multiple types of components per use case, a descriptive title is used in addition.

- Actor: The entity that interacts with the component within the context of the specific use case. An actor, which assumes a role, can be a human that interfaces with the component or another software/hardware. System-compatible roles are extensively described on a dedicated table.
- Role's interaction: A textual description of the interaction between the actor and the component within the context of this use case.

Roles indicate the types of actors that interact with the METACITIES system and its technical components. These actors may be other system components, external systems or humans participating in use cases. The identification of the METACITIES -compatible roles, along with their potential interactions with METACITIES, is crucial for the definition of precise use cases and meaningful architecture designs. Defining roles is a continuous process, highly affected by the ongoing design of pilot use cases, therefore it is performed on an iterative basis. Table presents the currently defined actor types.

To represent the interactions and functions among the architectural component across the various use cases we selected to design a series of diagrams, placed in the Appendix, illustrating a combination of a layered architecture diagram, which provides a clear overview of each system component (e.g., Device Layer, Edge Computing Layer) and how they interact in sequence, and a data flow diagram, which maps how data flows through the system from acquisition to processing to storage and analytics and leads to outcomes.

TABLE 7: METACITIES COMPATIBLE ROLES

Actor	Interaction
Analyst	Uses data-driven processes to gain insights about required actions and potential improvements
Designer	Designs the models for simulations, communication, and deployment.
End-user	Provides specifications, requirements and preferences for the modelling and system design
HW/SW component	Provides raw data or processed data

TABLE 7: COMPONENT - 01 – SMART VEHICLES

Code: 01 **Component name: Smart Vehicles** **Layer: Device Layer**		**Author: UOP** **Reviewer: UPAT** **Type: Hardware**
Input Layer: Device Layer		**Output Layer:** Edge computing Layers
Devices in vehicles		Structured data per vehicle
Description: **Provider of detailed preprocessed data derived from built-in IoT devices in different types of vehicles**		
Functional requirements		**Non-functional requirements**
F-RQ-T-20, F-RQ-T-22, F-RQ-T-23, F-RQ-T-24		NF-RQ-T-1, NF-RQ-T-3
Component-level Use Cases		
Use Case/Cluster	**Actor type**	**Interaction**

GR: UC1	HW/SW component	Provide values from sensors and IoT devices on vehicles to define their position. Vehicles equipped with sensors and IoT devices provide critical data about their real-time position, speed, and behavior.
GR: UC3	HW/SW component	Provide values from sensors and IoT devices on emergency vehicles. Emergency vehicles transmit their real-time location and status through IoT sensors. Data may include their speed, proximity to the incident, and navigation routes.

TABLE 8: COMPONENT - 02 – EDGE EQUIPMENT

Code: 02 **Component Name: Edge Equipment** **Layer: Device Layer**		**Author: UoP** **Reviewer: UPAT, MPAT, YDW, CYENS, CCA** **Type: HW**
Input Layer: Edge equipment		**Output Layer:** Edge computing Layer -Edge processors, gateways
Sensors, data logger based on machine learning on device		Machine processed data
Description: Gets raw data, stores and catalogs it into machine format		
Functional requirements		**Non-functional requirements**
F-RQ-T-1, F-RQ-T-3, F-RQ-T-4, F-RQ-T-6, F-RQ-T-13, F-RQ-T-25, F-RQ-T-26, NF-RQ-E-3		NF-RQ-T-4, NF-RQ-T-7
Component-level Use Cases (or Pilot level)		
Use Case/Cluster	**Actor type**	**Interaction**
GR: UC1	HW/SW	Provides values, e.g. from IoT parking sensors, road cameras, about parking availability, illegal parking or congestion and transmit real-time traffic data.
GR: UC2	HW/SW	Provides values, e.g. from sensors placed around the city that monitor environmental factors such as air quality, noise levels, and temperature, about environmental issues.
GR: UC3	HW/SW	Provides values and real-time traffic data, detecting congestion or accidents and information about emergency car position.
BG: UC1	HW/SW	Provides raw data or processed data related to energy and environmental conditions

BG: UC2	HW/SW	Provides raw data or processed data related to energy and environmental conditions
CY: UC 1	HW/SW	Provide values from IoT Devices (Traffic Data) for near to real time tracking of traffic and types of vehicles passing through an area. The data provided by these types of IoT Devices will be used for analytics for the Smart Parking Use Case.

TABLE 9: COMPONENT - 03 – SIMULATORS

Code: 03 **Component Name: Simulators** **Layer: Device Layer**		**Author: UPAT** **Reviewer: UOP, CCA, ISBUR** **Type: Software**
Input Layer: Device Layer		**Output Layer:** Data Acquisition Layer
Simulated Device Configuration Parameters, Scenario Control Commands, Simulation Feedback		Simulated Device DataStream
Description: **Software based simulator or custom hardware designed to simulate/emulate equipment or conditions. Input data from simulated device and scenarios with output data stream for configured input parameters**		
Functional requirements		**Non-functional requirements**
F-RQ-T-2,F-RQ-T-27,F-RQ-U-2		
Component-level Use Cases		
Use Case/Cluster	**Actor type**	**Interaction**
CY: UC 1	SW	Model the impact of different interventions (e.g., tree planting, green roofs) on reducing UHI.
CY: UC 2	SW	Simulations may include real-time parking spot availability, predictive parking demand based on traffic patterns, vehicle arrival rates, dynamic pricing models, and optimal route guidance. Additionally, simulations can test IoT sensor integration, evaluate system response to

		peak demand, and analyse environmental impact through reduced congestion.

TABLE 10: COMPONENT - 04 – FIELD-USE APPS

Code: 04 **Component Name: Field-use apps** **Layer: Device Layer**		**Author: UPAT** **Reviewer: MPAT, CCA, ISBUR** **Type: Software**
Input Layer: Device Layer		**Output Layer:** Data acquisition Layer
User Input, OS APIs (for GPS, Camera, Connectivity etc.)		Control Commands/Requests, User-based Feedback, Sensor DataStream, Media, Metadata
Description: **Field-Use Apps are application clients that run on user devices and provide useful information about the state of a metacity through either crowdsourced feedback or sensor information provided by the device's operating system. They can also give users control over aspects of the city or equipment.**		
Functional requirements		**Non-functional requirements**
F-RQ-T-2, F**-RQ-T-7, F-RQ-T-8, F-RQ-T-15, F-RQ-T-27,F-RQ-U-1**		NF-RQ-T-1, NF-RQ-T-2, NF-RQ-T-6, NF-RQ-T-7, NF-RQ-T-8 ,NF-RQ-T-9, NF-RQ-T-10
Component-level Use Cases		
Use Case/Cluster	**Actor type**	**Interaction**
GR: UC3	Civilian user	By applying anonymized soft GPS tracking on a mobile application, traffic data regarding both city streets and places of interest can be acquired. These applications can be used by municipal authorities/field personnel/municipal workers/emergency responders/citizens to manually report incidents and updates on the scene.

TABLE 11: COMPONENT - 05 – GATEWAYS

Code: 05 **Component Name: Gateways** **Layer: Edge Computing Layer**		**Author: CYENS** **Reviewer: UPAT, UOP, CCA, ISBUR, PNET** **Type: Hardware**
Input Layer: Device Layer		**Output Layer:** Data Storage Layer
Data from sensors and devices		Processed and forwarded data to service layers
Description: **Gateways act as the intermediary between the device layer and the upper layers of the architecture. They forward data collected from the device layer to higher system levels for further processing and analysis, while also channeling commands and configuration settings from the data centers back to the devices. This ensures that the data collection aligns with the overarching system objectives and that devices operate coherently with system updates and directives.**		
Functional requirements		**Non-functional requirements**
F-RQ-T-16, NF-RQ-U-4		NF-RQ-T-8
Component-level Use Cases		
Use Case/Cluster	**Actor type**	**Interaction**
GR: UC1	HW/SW	Forwards data from smart parking sensors, Bluetooth devices and bus traffic data, about parking violations and traffic jams to the data storage layer.
GR: UC2	HW/SW	Forwards data from various environmental sensors about air quality and noise levels to the data storage layer.
GR: UC3	HW/SW	Forwards data from sensors and vehicles about traffic flow, road incidents, and emergency vehicle routes to the data storage layer.
CY: UC1	HW/SW	Forwards data from the device layer Environmental Data) to the Data Storage layer for further processing and analysis.
CY: UC2	HW/SW	Forwards data from the device layer (Smart Parking IoT Sensors) to the Data Storage layer for further processing and analysis.
BG: UC2	HW/SW	Collects data from multiple measuring devices and sensors installed in the buildings and send it to the Data storage Layer

TABLE 12: COMPONENT - 06 – EDGE PROCESSORS

Code: 06 **Component Name: Edge Processors** **Layer: Edge Computing Layer**		**Author: UOP** **Reviewer: UPAT, YDW, CYENS, ISBUR, PNET** **Type: Hardware**
Input Layer: Edge computing Layer		**Output Layer:** Data storage Layer
Data from sensors and devices (Edge equipment) **Data from service layers (when applicable)**		Processed and forwarded data to data storage layers and service layers State-of-the-Art / Innovation: Implements advanced routing and filtering algorithms to optimize data flow and ensure timely delivery.
Description: **Implements i) real-time analytics to support quick responses, ii) reduced latency by processing the data at the edge, iii) improved bandwidth efficiency by filtering and pre-processing data locally, iv) enhanced security by processing sensitive data processing at the edge and v) offline operation ensuring applications continue to operate seamlessly.**		
Functional requirements		**Non-functional requirements**
F-RQ-T-1, F-RQ-T-14, F-RQ-T-24,F-RQ-U-10, NF-RQ-U-4		NF-RQ-T-7, NF-RQ-T-8, NF-RQ-U-4
Component-level Use Cases		
Use Case/Cluster	Actor type	Interaction
GR: UC1	HW/SW	Data processing from sensors and edge devices, pre-processing and filtering of data, feature extraction and local decisions and data transmission to other system layers and components. Perform real-time analysis of data and immediate computations to reduce response times, e.g. trigger real-time alerts for illegal parking behaviors or traffic incidents.
GR: UC2	HW/SW	Data processing from sensors and edge devices, pre-processing and filtering of data, feature extraction and local decisions and data transmission to other system layers and components. Perform real-time analysis of environmental and traffic incident data, e.g. to immediately

		compute the environmental effects such as localized pollution spikes or noise increases.
GR: UC3	HW/SW	Data processing from sensors and edge devices, pre-processing and filtering of data, feature extraction and local decisions and data transmission to other system layers and components. Perform real-time analysis of traffic patterns and congestion to facilitate immediate decisions such as re-routing emergency vehicles or altering traffic light timings to clear a path for first responders.
BG: UC1	HW/SW	Data processing from sensors and edge devices, pre-processing and filtering of data, feature extraction and data transmission to other system layers and components.
BG: UC2	HW/SW	Data processing from sensors and edge devices, pre-processing and filtering of data, feature extraction and data transmission to other system layers and components.
BG: UC3	HW/SW	Data processing from sensors and edge devices, pre-processing and filtering of data, feature extraction and data transmission to other system layers and components.
CY: UC2	HW/SW	Data processing from sensors and edge devices, pre-processing and filtering of data, feature extraction and data transmission to other system layers and components.

TABLE 13: COMPONENT - 07 – GIS DATA

Code: 07 **Component Name: GIS Data** **Layer: Data Acquisition Layer**		**Author: YDW** **Reviewer: MPAT, CCA, BUR, ISBUR** **Type: Software**
Input Layer: Data Acquisition Layer		**Output Layer:** Data Storage Layer
Geo-located data from field-use app or edge equipment. **Data from service layers (when applicable)**		Presents GIS data to a map, integrating location data with all types of descriptive information.
Description: **Implements the GIS data that provides a foundation for mapping and analysis that is used for users to visualize information, understand patterns, relationships, and geographic context. The goal is to provide improved communication, efficiency, management, and decision-making and 3D mapping when applicable**		
Functional requirements		**Non-functional requirements**
F-RQ-T-8, F-RQ-U-2, F-RQ-E-7		NF-RQ-E-2
Component-level Use Cases		
Use Case/Cluster	Actor type	Interaction
GR: UC1	HW/SW	Provides geospatial data for mapping and analysis, enabling the visualization of parking positions and real-time parking availability and traffic conditions, identify congestion patterns, and assess their geographic context to support decision-making and traffic management.
GR: UC2	HW/SW	Provides geospatial environmental data layers, including air quality, noise pollution, and temperature distribution maps, allowing understanding spatial relationships along with traffic incidents and environmental patterns.
GR: UC3	HW/SW	Provides geospatial data for mapping and analysis, enabling the visualization of real-time traffic incidents and traffic conditions, identify congestion patterns, and assess the geographic context of emergency car to support rerouting.
BG: UC1	HW/SW	Implements the GIS data that provides a foundation for mapping and analysis that are energy related and used for Green and Climate adaptive resource management to visualize information, to understand patterns and relationships and 3D mapping when applicable.

BG: UC2	HW/SW	Implements the GIS data that provides a foundation for mapping and analysis that are energy related and used for Green and Climate adaptive resource management to visualize information, to understand patterns and relationships and 3D mapping when applicable.
CY: UC1	SW	Implements the GIS Data that provides the mapping of temperature variations, land use, vegetation cover, and building density. GIS will help visualize heat distribution and support targeted interventions like green infrastructure to mitigate excessive heat in specific areas.
CY: UC2	SW	Integrates with map data to provide special context for parking spaces and analytics. GIS layer will help in analysis of parking availability, optimization of routes, analysis of special trends, improve decision making in efficient parking management and traffic flow.

TABLE 14: COMPONENT - 08 – USER INPUT DATA

Code: 08 **Component Name: User Input Data** **Layer: Data Acquisition Layer**		**Author: CYENS** **Reviewer: UOP, BUR, ISBUR** **Type: Software**
Input Layer: Data acquisition Layer		**Output Layer:** Data Storage Layer
User inputs and system prompts		(User data processed and stored for system use)
Description: **User Input Data involves gathering data inputs directly from system users, which are not merely passive but can actively influence the system's functionality. This layer is capable of issuing system-generated queries and prompts to users to obtain specific data when needed. This interactive component ensures that user-contributed data is timely and relevant, and it helps in refining the data acquisition strategies based on user engagement and feedback.** **Dynamic user interaction platform that adapts to real-time system needs.**		
Functional requirements		**Non-functional requirements**
F-RQ-T-8		NF-RQ-T-3
Component-level Use Cases		
Use Case/Cluster	**Actor type**	**Interaction**
GR: UC2	End-user	Collects real-time feedback and data from users. For example, data from citizens to report environmental issues, like smoke from an accident.
GR: UC3	End-user	Collects real-time feedback and data from users. For example, data from citizens to report accidents, injuries, or dangerous situations and emergency services personnel to update data during incident management.
CY: UC1	End User	Collects real-time feedback and data from users
CY: UC2	End User	Collects real-time feedback and data from users
BG: UC1	End User	Collects real-time feedback and data from users
BG: UC2	End User	Collects real-time feedback and data from users
BG: UC3	End User	Collects real-time feedback and data from users

TABLE 15: COMPONENT - 09 – TRAFFIC DATA

Code: 09 Component Name : Traffic Data Layer: Data Acquisition Layer		Author: UOP Reviewer: MPAT Type: Software
Input Layer: Data Acquisition Layer		**Output Layer:** Data storage Layer
Data from 3d traffic management systems		Structured data based on time period with mapping ability
Description : This component is responsible for the recording and monitoring of traffic data. It also assists traffic controllers to optimally reroute traffic to minimise disruption		
Functional requirements		**Non-functional requirements**
F-RQ-T-1, F-RQ-T-23, F-RQ-T-24 , F-RQ-T-27, F-RQ-T-28		NF-RQ-T-6, NF-RQ-T-7
Component-level Use Cases		
Use Case/Cluster	**Actor type**	**Interaction**
GR: UC1	HW/SW	Collects real-time data from sensors regarding traffic, e.g. speed, congestion, vehicle positions and historical data about traffic patterns.
GR: UC2	HW/SW	Collects real-time data from sensors focusing on gathering data related to traffic incidents, vehicle density, and speed in various areas of the city, which affects the environmental parameters
GR: UC3	HW/SW	Collects real-time data from sensors regarding traffic, e.g. speed, congestion, vehicle positions focusing on gathering data that depict traffic density, blockages and emergency incidents in order to reroute traffic.
CY: UC2	SW	Monitor and factor traffic patterns into parking recommendations

TABLE 16: COMPONENT - 10 – MAP DATA

Code: 10 **Component Name: Map Data** **Layer: Data Acquisition Layer**		**Author: YDW** **Reviewer: UOP, CYENS, BUR, ISBUR** **Type: Software**
Input Layer: Data Acquisition Layer		**Output Layer: Data storage Layer**
Gets aggregated data from 3d systems		Provides structured massive of information layers based on specific needs for further processing
Description: **This component-supports the visualization of the position and status of devices and sensors on to a map widget, different type of thematic maps /2D, 3D, etc./, orthophoto or termo maps etc.**		
Functional requirements		**Non-functional requirements**
F-RQ-T-8, F-RQ-U-2, F-RQ-E-7		NF-RQ-E-2
Component-level Use Cases		
Use Case/Cluster	**Actor type**	**Interaction**
BG: UC1	Designer	This component supports the visualization of the position and status of devices and sensors on to a map widget based on the needs of the use cases.
BG: UC2	Designer	This component supports the visualization of the position and status of devices and sensors on to a map widget based on the needs of the use cases.
BG: UC3	Designer	This component supports the visualization of the position and status of devices and sensors on to a map widget based on the needs of the use cases.
CY: UC1	Designer	Map Data Component visualizes spatial data related to heat stress across the city. It layers environmental and urban data, such as temperature gradients, green space locations, building density, and land surface materials, onto a geospatial map.
CY: UC2	Designer	Map Data Component provides a spatial visualization of parking infrastructure and availability throughout the city. This component overlays real-time parking occupancy data, traffic flow, and points of interest on a

		geospatial map, enabling drivers, city planners, and parking authorities to quickly view parking availability and predict congestion points.

TABLE 17: COMPONENT - 11 – WEATHER DATA

Code: 11 **Component Name: Weather data** **Layer: Data Acquisition Layer**		**Author: YDW** **Reviewer: CYENS, ISBUR** **Type: Software**
Input Layer: Data Acquisition Layer		**Output Layer: Data storage Layer**
Meteorological and Environmental data received from third-party weather services or locally installed sensors		Semantic data information to upper service layers
Description: **This component gathers information about meteorological and environmental conditions, process it and delivers semantic data information to upper service layers**		
Functional requirements		**Non-functional requirements**
F-RQ-U-1, F-RQ-E-3, F-RQ-E-6		
Component-level Use Cases		
Use Case/Cluster	**Actor type**	**Interaction**
GR: UC2	HW/SW	Collects real-time meteorological and environmental data. Correlates traffic conditions with environmental factors and determines how external conditions like rain or fog may exacerbate traffic incidents, increase congestion, or affect air quality and noise pollution. Annotates semantically weather data in order to be used in upper service layers.
BG: UC2	HW/SW	Semantic data information to be used for analytical purposes in upper service layers
CY: UC1	HW/SW	Collects near to real time environmental data from IoT Sensors for analysis.

TABLE 18: COMPONENT - 12 – BLOB STORAGE

Code: 12 **Component Name: Blob storage** **Layer: Data Storage Layer**		**Author: ISBUR Type: Software** **Reviewer: UOP, CYENS**
Input Layer: Data storage Layer		**Output Layer:** Service Layer
Storing of combined data from 3d systems or other locally installed devices or applications		Forwarding of structured and optimized search data with fast speed and back-up to further analysis or applications
Description: **Clustering process for structured input data with API to service applications, with necessary access speed of big data and with automated back-up.**		
Functional requirements		**Non-functional requirements**
F-RQ-U-6, F-RQ-U-8, F-RQ-U-9		NF-RQ-U-2
Component-level Use Cases (or Pilot level)		
Use Case/Cluster	**Actor type**	**Interaction**
GR UC2:	HW/SW	Stores large datasets, such as video footage from cameras monitoring traffic incidents or environmental data logs from air quality monitors and photos that civilians upload.
BG: UC1	Analysis	Getting data using AI recognition for optimal use of solar energy and comparison to already installed solar panels. Clusterisation of various building energy efficiency data form BMS systems in different buildings.
BG: UC2	Analysis	Clusterisation of different building energy efficiency data form BMS systems in different buildings.
BG: UC3	Analysis	
CY: UC1	Analysis	Stores large datasets, satellite imagery, IoT Sensor Data and GIS Layers.
CY: UC2	Analysis	Store large volumes of unstructured data such as real-time IoT sensor data and historical parking usage records. It allows scalable storage of data, enabling efficient retrieval and analysis for tasks like parking spot detection, demand forecasting, and optimizing parking availability.

TABLE 19: COMPONENT - 13 – DOCUMENT STORAGE

Code: 13 Component Name: Document Storage Layer: Data Storage Layer		Author: ISBUR Type: Software Reviewer: UOP, YDW, BUR
Input Layer: Data Storage Layer		**Output Layer:** Service Layer
Getting combined data from Data acquisition Layer to be formed in document reading format.		Processed data to especially formed in document reading format /Word, Excel, CSV, IFC etc./ for future DT analysis.
Description: **Processing information from already structured data from gateways, edge equipment or 3-rd platforms and applications to be formed in detailed documents based on needs of information from service layers.**		
Functional requirements		**Non-functional requirements**
F-RQ-E-7, F-RQ-E-8		NF-RQ-E-2
Component-level Use Cases (or Pilot level)		
Use Case/Cluster	**Actor type**	**Interaction**
GR: UC2	Analysis	Processing information and stores reports, documentation of incidents, and metadata about sensors and models.
GR: UC3	Analysis	Processing information and stores reports and incident records, including historical data about past traffic incidents and emergency responses.

TABLE 20: COMPONENT - 14 – RELATIONAL STORAGE

Code: 14 Component Name: Relational Storage Layer: Data Storage Layer		Author: UOP Reviewer: YDW, CYENS, CCA Type: Software
Input Layer: **Data Acquisition Layers and Edge Computing Layers**		**Output Layer:** Service Layers
Processing of data from Data Acquisition Layers and Edge Computing Layers		Sending of combined data to service layer in database formats such as POSTGRE, SQL databases or similar
Description: **Databases that combine the guarantees of traditional relational databases. Offers native JSON support and graph extensions. Supports distributed architecture, AI features and security enhancements.**		
Functional requirements		**Non-functional requirements**
F-RQ-T-8, F-RQ-U-2, F-RQ-U-4, F-RQ-E-13, F-RQ-E-14, F-RQ-U-14, F-RQ-U-11		NF-RQ-T-2, NF-RQ-T-6, NF-RQ-T-7, NF-RQ-U-2, NF-RQ-U-3, NF-RQ-U-5
Component-level Use Cases		
Use Case/Cluster	**Actor type**	**Interaction**
GR: UC1	HW/SW	Stores structured data, such as records of parking slots, parking violations, vehicle IDs, and traffic patterns.
GR: UC2	HW/SW	Stores structured data, such as historical traffic incident records, environmental data, and sensor readings.
GR: UC3	HW/SW	Stores structured data on traffic conditions, emergency incidents, emergency vehicle movements, and response times.
BG: UC1	Analysis	Storing structured historical data from building energy devices and processing data from lidar and satellite sources.
BG: UC2	Analysis	Storing structured historical data from building energy devices and processing data from lidar and satellite sources.
BG: UC3	Analysis	Storing structured historical data from building energy devices and processing data from lidar and satellite sources.
CY: UC1	SW	Storing structured historical data from satellite sources.
CY: UC2	SW	Stores structured data, such as records of parking slots and traffic patterns.

TABLE 21: COMPONENT - 15 – TIME-SERIES STORAGE

Code: 15 **Component Name: Time-series Storage** **Layer: Data storage Layer**		**Author: UOP** **Reviewer: YDW, CYENS, CCA, BUR, ISBUR** **Type: Software**
Input Layer: Edge Computing Layers		**Output Layer:** Service Layers
Description: **Optimization for time-based queries and fast data retrieval. Efficient data compression and scalability for large volumes of data. Real time analysis of data and AI and machine learning integrated features as time series forecasting.** **It may support advanced compression techniques and adaptive encoding, improved query performance and integration with stream processing.**		
Functional requirements		**Non-functional requirements**
F-RQ-T-1, F-RQ-T-27, F-RQ-U-1, F-RQ-U-13, F-RQ-E-1, F-RQ-E-2, F-RQ-E-3, F-RQ-E-6, F-RQ-E-12		NF-RQ-T-2, NF-RQ-T-6, NF-RQ-T-7, NF-RQ-U-2, NF-RQ-U-3, NF-RQ-U-5
Component-level Use Cases		
Use Case/Cluster	**Actor type**	**Interaction**
GR: UC1	Analysis	Stores sequential data, such as the evolution of traffic over time or parking occupancy rates (overall number of available spots). Supports optimization for time-based queries and fast parking data retrieval and predictive analysis for parking availability.
GR: UC2	Analysis	Logs sequential data, such as the minute-by-minute air quality index, noise levels over time, and pollution measurements (this is in order to correlate patterns and spikes with traffic incidents at the service layer).
GR: UC3	Analysis	Logs data over time (in order to track incidents), traffic conditions to assess how traffic evolves during emergencies. Supports optimization for time-based queries and fast data retrieval and predictive analysis for traffic congestion affecting future emergency responses.
CY: UC1	Analysis	Captures environmental metrics over time, such as temperature and humidity levels, to monitor urban heat stress patterns. It also includes data on green space distribution and land use to evaluate how these factors influence heat retention in different areas.
CY: UC2	Analysis	Tracks parking space availability over time, capturing data on occupancy rates and duration of vehicle stays. This information helps assess how parking patterns evolve throughout the day and during special events. The system supports optimization for time-based queries and fast data

		retrieval, enabling predictive analysis of parking demand and trends.

TABLE 22: COMPONENT - 16 – MODELING & SIMULATION

Code: 16 **Component Name: Modeling & Simulation** **Layer: Service Layer**		**Author: UPAT** **Reviewer: UOP, MPAT, CCA, BUR, ISBUR** **Type: Software**
Input Layer: Data storage Layer		**Output Layer:** Application Layers
GIS Data, Map Data, Weather Data, Traffic Data, Vehicles, Edge Equipment, Simulators, Field-Use Applications, User Input Data		Thematic models
Description: **Modeling & Simulation Services allow for the creation of parameterized models of structures, traffic, natural phenomena and other dynamic processes using GIS Data & Maps or 3D environment. End Users or application software can then load these models with up-to-date information from the Input Layer along with artificial devices, measurements or scenarios and make predictions to provide meaningful feedback on relevant applications or decision making.**		
Functional requirements		**Non-functional requirements**
F-RQ-T-18, F-RQ-T-19,F-RQ-T-20,F-RQ-T-21,F-RQ-T-22,F-RQ-T-23,F-RQ-T-28,F-RQ-U-3, F-RQ-U-5, F-RQ-U-15, F-RQ-E-9		NF-RQ-T-1,NF-RQ-T-11
Component-level Use Cases		
Use Case/Cluster	Actor type	Interaction
GR: UC1	Designer	It simulates various traffic scenarios, including changes in traffic flows based on driver behaviors, parking policy adjustments, and enforcement actions. Supports designing predictive models for analyzing how illegal parking behaviors (e.g., double parking, violation of time limits) affect overall traffic congestion.
GR: UC2	Designer	It simulates how traffic incidents (e.g., accidents, blockages) impact environmental parameters such as air quality and noise levels. Using traffic and environmental data (including weather data), it models the spread of pollutants like CO2 or noise pollution after an incident.
GR: UC3	Designer	In order to simulate near-future traffic status and optimize for the niche routing scenario of emergency vehicle response, a continuous simulation of the urban grid is deployed drawing static assets for the model creation from GIS DATA & Maps while progressive information from the

		Input Layer updates the model with the current weather, equipment status and traffic conditions.
BG: UC1	Designer	Based on different input data making of simulation for energy efficiency and energy consumption predictions.
BG: UC2	Designer	Based on different input data making of simulation for energy efficiency and energy consumption predictions.
BG:UC3	Designer	Based on different input data making of simulation for energy efficiency and energy consumption predictions.
CY: UC1	Designer	Leverages environmental data to create predictive models of urban heat stress dynamics. By integrating variables such as temperature, humidity, vegetation cover, and urban infrastructure, the component simulates how different factors contribute to heat retention in urban areas.
CY: UC2	Designer	Analyzes parking behavior and demand patterns in urban environments. By utilizing historical occupancy data, traffic conditions, and event schedules, the component creates models to predict parking space availability and optimize resource allocation.

TABLE 23: COMPONENT - 17 – DIGITAL TWIN ANALYTICS

Code: 17 **Component Name: Digital Twin Analytics** **Layer: Service Layer**		**Author: ISBUR Type: Software** **Reviewer: BUR, UPAT**
Input Layer: Data storage layers		**Output-Layer:** application layers
Getting integrated and interrelated data to visualize digitally real objects or processes		Analyzing the behavior of digital objects or processes by using pattern models
Description: **Analytics of collected data in order to extract information for further usage**		
Functional requirements		**Non-functional requirements**
F-RQ-T-10, F-RQ-T-12, F-RQ-T-17, F-RQ-T-24, F-RQ-E-5		
Component-level Use Cases (or Pilot level)		
Use Case/Cluster	**Actor type**	**Interaction**
GR: UC1	Designer	Analyzes traffic data, parking behavior, and congestion patterns.
GR: UC2	Designer	Analyzes correlations between traffic incidents and environmental factors like air quality and noise.
GR: UC3	Designer	Analyzes correlations between real-time traffic data with emergency vehicle routes and other relevant factors to optimize response times.
BG: UC2	Designer	Analyzing the behavior of parameters of the building environment by using pattern models and variable input data.
CY: UC1	Designer	Analyzes real-time, data-driven model of the urban environment. By continuously integrating sensor data, such as temperature, humidity, wind speed the component provides a dynamic digital representation of the city’s microclimate.
CY: UC2	Designer	Builds a live digital representation of parking infrastructure and usage across the city.

TABLE 24: COMPONENT - 18 – SEMANTICS TRANSFORM

Code: 18 **Component Name: Semantics Transform** **Layer: Service Layer**		**Author: ISBUR Type: Software** **Reviewer: CCA**
Input Layer: Data storage layers		**Output Layer:** Application layers
Getting data in text format in different human languages from document storage		Processing and machine interpretation of human languages on different topics
Description: **Machine transformation of human language raw data to be used for analytics and KPIs evaluation.**		
Functional requirements		**Non-functional requirements**
F-RQ-T-5, F-RQ-T-6, F-RQ-T-10, F-RQ-E-10, F-RQ-E-15		
Component-level Use Cases (or Pilot level)		
Use Case/Cluster	**Actor type**	**Interaction**
GR: UC1	Designer	Semantically annotates and transforms data from parking reports, enforcement logs, driver behavior descriptions, and public feedback (e.g., social media, city apps) into machine-readable formats to identify trends in illegal parking.
GR: UC2	Designer	Semantically annotates and transforms data from environmental reports, incident descriptions, and citizen complaints related to pollution, noise, or traffic incidents into machine-readable format and meaningful insights how traffic incidents affect environmental factors and contributes to KPIs for air quality and noise levels.
GR: UC3	Designer	Semantically annotates and transforms data from accidents reports, public incident descriptions and emergency response feedback into machine-readable format and meaningful insights to facilitate emergency management.
CY: UC1	Designer	Translate raw temperature data and satellite imagery into actionable insights.
CY: UC2	Designer	Transform raw sensor data into understandable insights (e.g., parking space availability).

TABLE 25: COMPONENT - 19 – GIS/BIM SERVICES

Code: 19 **Component Name: GIS/BIM services** **Layer: Service Layer**		**Author: YDW** **Reviewer: CCA, BUR, ISBUR** **Type: Software**
Input Layer: Data storage layers		Output Layer: Application Layers
3d party services from Data storage Layers which are geo and maps reference		Providing of combined API services which can be used directly by end-user applications
Description: **This component is responsible for providing a digital model that incorporates information and parameters related to the form, structure, and systems of the actual infrastructure gathering information from and provide a working environment for all the 3-rd systems involved, from the design stage to the construction and finally to the project lifecycle, in terms of maintenance.**		
Functional requirements		**Non-functional requirements**
F-RQ-T-6, F-RQ-T-8, F-RQ-T-10, F-RQ-U-2, F-RQ-E-7, F-RQ-U-12		NF-RQ-E-2
Component-level Use Cases		
Use Case/Cluster	Actor type	Interaction
GR: UC1	Designer	Visualizes roads and parking infrastructure using 3D models. It maps illegal parking behavior, traffic congestion, and other mobility-related issues.
GR: UC2	Designer	Visualizes environmental sensors located around the city. It maps spatial correlation between traffic incidents and environmental factors such as air quality, noise pollution, and smoke.
GR: UC3	Designer	Visualizes the emergency vehicles position and incident locations.
BG: UC2	Designer	Visualization of real building using 3D models and detailed information from sensors included in the building.
BG: UC3	Designer	Visualization of real building using 3D models and detailed information from sensors included in the building.
CY: UC1	Designer	Provide geospatial analysis to identify UHI hot spots and evaluate intervention effects.
CY: UC2	Designer	Integrate with map data to provide spatial context for parking spaces and navigation.

TABLE 26: COMPONENT - 20 – RULE ENGINES GUIDED AI/ML

Code: 20 **Component Name: Rule Engines Guided AI/ML** **Layer: Service Layer**		**Author: CYENS** **Reviewer: CCA, ISBUR, UOP** **Type: Software**
Input Layer: Data storage Layer		**Output Layer:** Application Layer
Data from various sources		Insights and decision support
Description: Rule Engine Guided AI/ML is a sophisticated component that processes data and refines its algorithms continually based on the outcomes and directives received from the application and data storage layer. These component leverages artificial intelligence and machine learning to enhance decision-making processes within the system, ensuring that data analysis is not only reactive but also predictive, adapting to new patterns and insights for improved accuracy and operational efficiency.		
Functional requirements		**Non-functional requirements**
F-RQ-T-4, F-RQ-T-9, F-RQ-T-10		NF-RQ-T-5
Component-level Use Cases		
Use Case/Cluster	**Actor type**	**Interaction**
GR: UC1	Analyst	Predicts traffic and parking behavior and suggests optimized solutions (e.g., dynamic traffic light adjustments or recommended routes).
GR: UC2	Analyst	Predicts future environmental conditions based on historical traffic data and sensor readings and proposes restrictions to traffic access and traffic reroutes in order to improve air quality.
GR: UC3	Analyst	Predicts traffic patterns and congestion in order to optimize emergency response routes and train models to anticipate potential future incidents.
CY: UC1	Analyst	Use machine learning to predict how green initiatives will reduce UHI and enhance urban climate resilience.
CY: UC2	Analyst	Optimize parking management using AI-driven algorithms for dynamic pricing or predictive parking space recommendations.

TABLE 27: COMPONENT - 21 – DIRECTORY SERVICES

Code: 21 **Component Name: Directory Services** **Layer: Service Layer**		**Author: CYENS** **Reviewer: CCA, BUR** **Type: Software**
Input Layer: Data storage Layer		**Output Layer:** Application Layer/ Edge Computing Layer
User access requests		Authorization tokens and access logs
Description: **Directory Services manage and optimize system resources by dynamically responding to changing access patterns and usage. This component ensures efficient performance and security within the system by regulating access to data and resources, adjusting to system demands, and handling authentication and authorization processes. It plays a crucial role in maintaining the integrity and accessibility of the system's infrastructure.**		
Functional requirements		**Non-functional requirements**
F-RQ-T-11, NF-RQ-E-1		NF-RQ-T-10, NF-RQ-T-11
Component-level Use Cases		
Use Case/Cluster	**Actor type**	**Interaction**
GR: UC1	End User	Manages and authenticates user access to various system resources.
GR: UC2	End User	Manages and authenticates user access to various system resources.
GR: UC3	End User	Manages and authenticates user access to various system resources.
CY: UC1	End User	Manages and authenticates user access to various system resources.
CY: UC2	End User	Manages and authenticates user access to various system resources.

5 Transition to Metaverse Technologies and 3D Representation

This section includes information on 3D Reconstruction and a high-level description of ways to link the proposed ODTF to the Metaverse.

5.1 3D Services / 3D Urban Reconstruction

Three-dimensional (3D) urban reconstruction is a sophisticated process that involves transforming diverse input data into realistic and functional 3D representations of urban spaces. These models serve as essential tools in urban planning, architectural visualization, and simulation environments, offering stakeholders detailed insights into spatial structures and environments. This Section provides a high-level discussion of the concept of 3D reconstruction and elaborates on the core steps involved, emphasizing the blend of technology, data processing, and visualization required to create comprehensive urban models, Figure 3.

At its core, 3D reconstruction involves generating three-dimensional digital models that replicate the geometry, textures, and features of real-world environments. Urban 3D models capture the intricacies of cities, including buildings, roads, vegetation, and other elements, allowing a detailed representation that is both accurate and versatile. These models are constructed by integrating diverse datasets collected from multiple perspectives, including ground-level and aerial views.

5.1.1 The Four Core Steps in 3D Urban Reconstruction

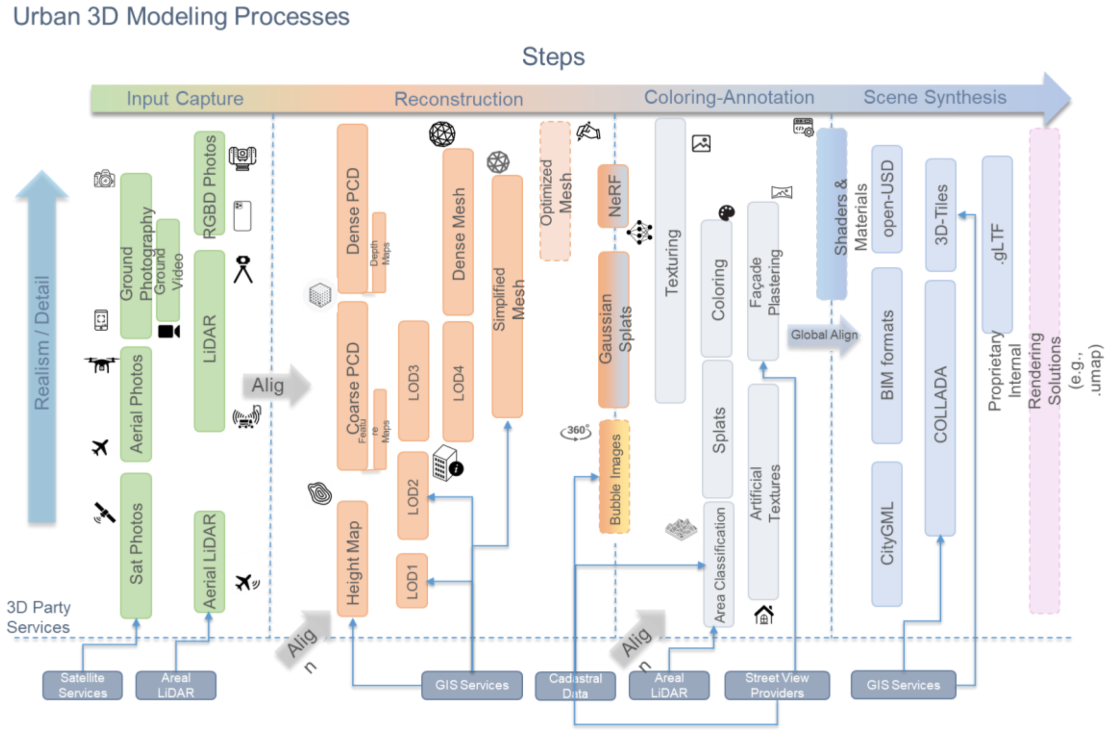


FIGURE 3: URBAN 3D MODELING PROCESSES – THE 4 CORE STEPS

5.1.1.1 Input Capture: Laying the Foundations

The journey of 3D urban reconstruction begins with data collection, which serves as the backbone of the entire process. Diverse input sources are employed to ensure comprehensive and detailed coverage of the target area.

Ground-based capture, such as ground-level photography and video, provides detailed views of streetscapes, facades, and human-scale environments, offering vital data for accurately reconstructing intricate details of building exteriors and urban textures. Aerial and satellite imagery, obtained from high-resolution aerial drones and satellites, captures the broader urban context, providing large-scale data for mapping spatial relationships between structures. LiDAR technology, through both ground-based and aerial systems, scans urban spaces with precision, capturing depth and spatial dimensions crucial for creating detailed 3D representations. Additionally, multispectral and RGBD imaging enhances the visual fidelity and accuracy of the model by adding layers of depth and color. By integrating these sources, a holistic dataset is created, enabling the reconstruction of urban environments with a balance of micro and macro perspectives.

5.1.1.2 Alignment and Reconstruction: Building the Structure

Once the input data is collected, it undergoes alignment and reconstruction processes to create cohesive 3D structures. The data from multiple sources is processed and aligned to a common spatial reference frame, ensuring that ground-level, aerial, and satellite data correspond accurately to one another. Foundational elements such as height maps, feature maps, and point clouds (both coarse and dense) are then generated to define the geometric structure of the urban space. Detailed 3D meshes are created to represent the physical surfaces of buildings and landscapes, often developed at multiple Levels of Detail (LOD) to range from simplified representations for large-scale analyses to intricate models for close-up visualization. Advanced techniques such as Neural Radiance Fields (NeRF), Gaussian Splats, and bubble imaging are employed to enhance realism and depth perception, pushing the boundaries of traditional reconstruction methods.

This stage converts raw input data into structured and scalable 3D models, forming the architectural backbone of the reconstruction process.

5.1.1.3 Coloring and Annotation: Enhancing Realism

With the structural foundation in place, the models undergo coloring and annotation to improve their visual and functional qualities.

High-resolution textures are applied to the meshes to mimic real-world appearances, creating visually compelling models, while accurate color mapping ensures realistic differentiation between materials and surfaces. Beyond visual appeal, semantic information is added by classifying and annotating various elements of the model, such as roads, buildings, vegetation, and water bodies, enhancing the model's utility in analytical and simulation contexts. Where raw data lacks sufficient detail, artificial textures such as facade plastering or generic building and environmental texture assets are applied to ensure a polished and professional finish.

These enhancements make the models not only visually appealing but also informative and functional for various applications.

5.1.1.4 Scene Synthesis: Preparing for Real-World Application

The final step in 3D reconstruction involves synthesizing the scene for practical use in diverse domains, ranging from urban planning to virtual reality. The model is enriched with data from external sources such as GIS services, cadastral data, and third-party providers like satellite services and street-view platforms. To ensure broad usability, models are converted into various formats, such as open-USD, CityGML, and proprietary formats compatible with rendering software, facilitating integration into simulation systems and rendering pipelines. The final models are then optimized for high-quality rendering, incorporating shaders, materials, and lighting effects to create lifelike simulations for visualization or analytical purposes. This step ensures the resulting models are versatile, integrable, and tailored to meet the needs of diverse stakeholders and industries.

5.2 Transitioning to the Metaverse

Transforming a **digital twin** into a **Metaverse-based solution** involves integrating advanced technologies to create immersive, interactive, and scalable digital environments. These technologies bridge the gap between static digital twins and dynamic, real-time Metaverse applications.

5.2.1 Metaverse-enabling Technologies

Here are the key available technologies enabling this transformation:

- **3D modeling and simulation software**, such as Unity, Unreal Engine, and Blender, are critical for creating realistic 3D models of physical assets and environments. These software platforms support high-fidelity graphics and complex simulations essential for building Metaverse environments.
- **Existing platforms** provide the base for deploying digital twins in a Metaverse ecosystem, including **Decentraland**, a blockchain-based Metaverse platform allowing user interaction with digital assets; **NVIDIA Omniverse**, which supports collaborative development and real-time simulation of digital twins in virtual spaces; and **Meta's Horizon Worlds**, a VR social platform enabling immersive interactions.
- The **Internet of Things (IoT)** plays a crucial role by collecting real-time data from physical assets that can be integrated into the digital twin within the Metaverse, enabling real-time monitoring and control of physical environments from within the virtual space.
- **Augmented Reality (AR) and Virtual Reality (VR) technologies** are fundamental to the Metaverse, offering immersive experiences that allow users to interact with digital twins as if they were physically present.
- **Devices** like Oculus, HTC Vive, and Microsoft HoloLens are popular choices for experiencing the Metaverse.
- **Artificial Intelligence (AI) and Machine Learning (ML)** analyze data from IoT devices and sensors to predict maintenance needs, optimize operations, and enhance decision-making processes within the Metaverse, while also driving automation in the digital twin environment.
- **Blockchain and Distributed Ledger Technology (DLT)** secure transactions, manage identities, and ensure data integrity within the Metaverse, proving particularly useful for handling ownership, intellectual property rights, and transactions in the virtual environment.
- **Cloud and edge computing** manage the vast amount of data generated by IoT devices and ensure low-latency interactions in the Metaverse, providing the computational power and storage needed for complex simulations and real-time data processing.
- **Advanced networking technologies**, including 5G and beyond, are essential for delivering the low latency and high bandwidth required for seamless and responsive Metaverse experiences.
- **Robust cybersecurity measures** are indispensable to protect data privacy and prevent unauthorized access, given the extensive data sharing and user interactions in the Metaverse. Interoperability standards are also critical for digital twins to function effectively within the

Metaverse, ensuring interaction across different systems and platforms through standards and protocols like USD, OPENXR, and CityGML.

Together, these technologies create a comprehensive Metaverse-based digital twin solution, extending the utility of traditional digital twins by adding layers of interaction, immersion, and real-time data integration.

- **Augmented Reality (AR) and Virtual Reality (VR)**: AR and VR technologies are fundamental to the Metaverse, providing immersive experiences that allow users to interact with digital twins as if they were physically present. Devices like Oculus, HTC Vive, and Microsoft HoloLens are popular choices for experiencing the Metaverse.
- **Network Infrastructure**: Advanced networking technologies, including 5G and beyond, are crucial for delivering the low latency and high bandwidth necessary for seamless and responsive Metaverse experiences.

These technologies can be combined to create a comprehensive Metaverse-based digital twin solution that extends the utility of traditional digital twins by adding layers of interaction, immersion, and real-time data integration.

5.2.2 Integration Workflow

The integration workflow involves several key steps to ensure a seamless and functional connection between digital twin models and the Metaverse. First, digital twin models are enhanced for Metaverse compatibility through optimization techniques like Levels of Detail (LOD) and the use of formats such as GLTF or USDZ. Next, a suitable Metaverse platform or a custom development path is selected based on the intended application, whether for urban planning, industrial simulations, or other use cases. Real-time data integration is achieved using IoT and edge computing to synchronize virtual models with real-world conditions. User interactions are then enhanced by implementing AI-driven interactivity and immersive AR/VR experiences. Finally, the deployment and maintenance processes utilize cloud resources to ensure scalability and blockchain technology to provide robust security.

5.2.3 User Interactions

User interactions in the Metaverse and virtual worlds are fundamental to their functionality and appeal, transforming them from static environments into dynamic and engaging platforms. Effective user interactions in the Metaverse ensure a sense of presence, participation, and personalization, which are critical for fostering meaningful virtual experiences. Below are the core categories and technologies enabling user interactions in the Metaverse [4]:

- **Immersive interaction technologies** play a pivotal role in creating a feeling of "being there," a critical characteristic of virtual worlds. Virtual Reality (VR) and Augmented Reality (AR) are at the heart of these interactions, with VR headsets fully immersing users in digital environments and AR overlaying digital information onto the real world to blend real and virtual elements seamlessly.
- **Metaverse platforms** are inherently social, enabling multiple users to interact simultaneously in shared spaces. Robust server technologies and network infrastructure support these multiuser environments, ensuring smooth, lag-free synchronous activities. The ability to maintain persistent states within the Metaverse ensures that actions and changes have lasting impacts, while scalability allows the experience to remain stable and enjoyable as more users join and interact.

- **Multi-sensory interaction** further enhances engagement and realism by incorporating inputs beyond visuals and sound. Real-time voice and text communication, supported by technologies like spatial audio, mimic real-world sound behavior to create realistic and immersive conversations. Gesture and expression tracking, facilitated by motion capture and facial recognition, captures and replicates user gestures and facial expressions, enhancing non-verbal communication. Haptic feedback devices, such as gloves, suits, and other wearables, simulate touch, pressure, and texture, providing tactile sensations that deepen the immersive experience.
- **User embodiment and social presence** are key aspects of Metaverse interaction. Personalized avatars allow users to express their identity, with advanced tools enabling detailed customization of appearance, clothing, and gestures. **Social and collaborative tools**, such as shared virtual spaces, collaborative functionalities, and social networking features, foster community and collaboration. Users also expect to interact with virtual objects as they would in the real world, requiring sophisticated physics engines and interaction models to simulate realistic behaviors and responses from these objects.
- **Economic transactions** form an integral part of many Metaverse environments, where users can buy, sell, or trade items. Secure transaction systems, often underpinned by blockchain technology, ensure reliable and transparent exchanges, further enriching the interactive and participatory nature of the Metaverse.

6 Enabling Technologies

The present section provides in a concise but comprehensive way blockchain, blockchain architecture and how this technology can interact with the METACITIES digital twin. Additionally, this section describes the network technologies that are instrumental for the implementation of Digital Twins and presents the main network protocols and how they can generally be utilized in a smart city environment.

6.1 Blockchain

Integration of blockchain technology with rule engines and digital twin analytics in a cohesive architecture would enhance transparency, security, and trust, while ensuring data integrity in decentralized environments [5]], [6][7]. This architecture involves several layers and components that interact seamlessly to provide a more robust system.

The rule engine layer, [7]guided by AI and machine learning models, relies on blockchain smart contracts to enforce business rules and logic. These smart contracts are decentralized, ensuring immutability and trust in the decision-making processes. The rule engine processes events triggered by data inputs, such as sensor readings or user actions. Blockchain records the outcomes and decisions made by the AI models, making them auditable and traceable. This layer also benefits from the decentralized validation of rules, where business logic is autonomously executed when predefined conditions are met [8] [9],

In the digital twin analytics layer, the system leverages blockchain to store critical data streams from real-world objects, like IoT devices, as well as simulation outputs [10]. The digital twin, a virtual representation of a physical asset, uses real-time data to mirror and predict the behavior of its physical counterpart. Blockchain ensures the integrity of these data inputs and outputs, recording key state changes and analytics results. This enables organizations to audit any changes or anomalies, improving trust and reliability when collaborating with third parties.

The blockchain layer underpins these interactions by providing a decentralized infrastructure. Smart contracts store business rules and enforce logic immutably. This ensures that decisions or actions triggered by data from the digital twin or rule engines are recorded transparently. The consensus mechanism inherent to blockchain verifies each transaction and decision across the network, making sure that all participants trust the shared data and outcomes.

Real-time data acquisition from IoT devices and external sources, such as weather data, is critical in this system. Blockchain captures and verifies the raw data from these sources, ensuring no tampering has occurred. For example, sensor readings from traffic data in smart city infrastructures are hashed and stored on-chain, allowing stakeholders to verify the authenticity of these data points. The digital twin, in turn, uses this verified data to run simulations, while the rule engine uses it to apply business logic.

Data integrity is critical to AI/ML models that guide the rule engines and digital twin analytics. Blockchain plays a key role by ensuring that the training data used by these models is authentic and unchanged. By hashing and storing these data on-chain, the system can detect any manipulation attempts, ensuring that AI/ML outputs are trustworthy. Moreover, every decision made by AI models is logged on to the blockchain, providing transparency and traceability. This ensures that decisions, such as those made in predictive maintenance or anomaly detection, can be reviewed, verified, and explained later.

AI explainability is another key benefit of integrating blockchain into this architecture. As models generate decisions based on inputs, the blockchain stores these decisions alongside the factors that contributed to them, such as input data, model weights, and logic applied by the rule engine. This creates an audit trail that can explain how a decision was reached, which is particularly useful in regulated industries such as finance or healthcare.

The digital twin layer also benefits from blockchain by enabling multi-party trust in environments where different organizations need to share data. For example, in a supply chain context, various stakeholders might need to share data from their digital twins. Blockchain ensures that this shared data is verified, secure, and trustworthy. By recording key metrics, events, and predictions on the blockchain, all parties can rely on the accuracy of the data without needing a centralized authority.

In a typical workflow, data from IoT devices flows into the rule engine and the digital twin [8]. If the AI model detects an anomaly, such as an off-limits CO2 measurement, a smart contract in the rule engine triggers an action, such as giving an alert or notifying the relevant personnel. This decision, as well as the data that triggered it, is recorded on the blockchain, creating a verifiable record. The digital twin, in parallel, receives continuous updates from its physical counterpart. Blockchain ensures that these updates are immutable, so any changes in the physical asset's state are securely recorded and can be traced back to the source in case of future issues.

In summary, blockchain enhances the overall architecture by providing immutability, auditability, and decentralized trust. The rule engines benefit from transparent, verifiable decision-making, while digital twin analytics leverage blockchain to ensure the integrity and reliability of their data streams and simulations. This architecture creates a resilient, transparent system capable of supporting decentralized decision-making, collaborative environments, and secure, auditable AI-driven processes.

6.1.1 Blockchain Architecture

The architecture can be broken down into several layers and components that interact with each other in a decentralized manner. The core idea is to use blockchain to manage rule executions, decision logging, data validation, and trust between multiple entities interacting with the digital twins and the rule engines [9][10].

6.1.1.1 Blockchain Network Layer

The blockchain nodes are the backbone of the decentralized system. These nodes are distributed across various participants in the system, such as organizations using digital twin models or entities that rely on the rule engines for decision-making. Each node maintains a copy of the distributed ledger and participates in consensus mechanisms.

The blockchain network can be based on Ethereum, Polygon, or any other high-performance blockchain network capable of supporting smart contracts. In scenarios where real-time data and fast decision-making are critical, Layer-2 scaling solutions (e.g., Polygon) or private/consortium blockchains (e.g., Hyperledger) may be used to ensure performance and scalability.

6.1.1.2 Smart Contract Layer

The smart contract layer is the core logic where business rules and conditions are defined and enforced in an autonomous, decentralized manner. Smart contracts are key for managing decisions within the rule engines and orchestrating interactions between entities using digital twins.

Rule Engine Smart Contracts define and execute the business rules or policies that guide operations. In this architecture, each rule engine or process is represented by a smart contract that performs the following:

- Data-Driven Rule Execution: Smart contracts automatically execute business rules based on data inputs. For example, data from IoT sensors (temperature, noise, etc.) is submitted to the smart contract, which evaluates the data against predefined conditions.
- Condition-Based Triggers: Rules can be defined for various events such as a parking slot being freed up, threshold breaches (e.g., CO2 exceeding a limit), or predicted outcomes from AI/ML models. These triggers are automatically executed when the conditions are met, and the action (e.g., sending alerts) is logged on the blockchain.
- Auditability of Decisions: Every decision made by the rule engine smart contract is stored immutably on the blockchain. This allows for future audits to ensure that decisions followed the rules, and any deviations are logged.

Smart contracts for digital twin analytics serve as the intermediary between real-world assets and their virtual counterparts. These contracts handle the synchronization and validation of data flowing between the physical and virtual twins:

- Data Stream Validation: When real-time data (e.g., from IoT sensors on physical assets) is collected, it is hashed and submitted to the blockchain via a smart contract. This ensures that only validated data is used by the digital twin models. Smart contracts can also be used to manage and ensure that data shared across organizations is trustworthy and accurate.
- Simulation and State Change Logging: As the digital twin runs simulations or analytics, any significant state changes or predictions are logged on to the blockchain. This ensures that stakeholders can audit these simulations and track predictions, making the entire process transparent.
- Collaboration Between Multiple Stakeholders: In cases where multiple organizations need to interact with the digital twin (e.g., a supply chain scenario), smart contracts enforce the rules of collaboration and ensure that data shared between entities is consistent and verified. The blockchain provides trust between different organizations by recording each party's interactions and data submissions immutably.

6.1.2 Data Acquisition and Oracle Layer

Since rule engines and digital twins need to rely on off-chain data (such as IoT sensor readings, external APIs, etc.), the architecture must include oracles to bridge the gap between the blockchain and the external data sources.

Oracles serve as a bridge that fetches real-world data (such as sensor data, weather data, market prices, etc.) and brings it into the blockchain where the rule engine smart contracts can process it. The oracle network ensures that the off-chain data is verifiable and trustworthy by:

- Fetching data from IoT devices (real-time sensor readings) or other external sources.
- Verifying the authenticity of the data and hashing it before submitting it to the blockchain.
- Feeding real-time data into smart contracts that trigger actions based on predefined rules (e.g., send alerts if a CO2 threshold is crossed).

This ensures that both the rule engine and the digital twin receive verified, real-world data, preserving the trust and transparency that blockchain provides.

6.1.2.1 Data Integrity Layer

To maintain the integrity and transparency of the system, any decision, rule execution, or state change in the digital twin must be stored immutably on-chain. However, not all data (such as large sensor logs or detailed simulation results) can be stored directly on the blockchain due to size and cost constraints. Instead of storing entire datasets on-chain, cryptographic hashes of the data (such as IoT sensor readings or digital twin predictions) are recorded. This allows anyone to verify the integrity of the data without needing to store it directly on the blockchain. For larger datasets, external storage solutions like IPFS (InterPlanetary File System) or decentralized cloud storage (e.g., Filecoin) are used. Only references (hashes or pointers) to this external data are stored on the blockchain, ensuring tamper-proofing without burdening the network.

6.1.2.2 Monitoring and User Interface Layer

The architecture includes user interfaces for monitoring and visualizing the state of the system. For rule engines, this could be a dashboard that shows rule execution logs, recent decisions, and AI model outcomes. For digital twins, this would include real-time monitoring of physical asset states, simulations, and predictive analytics results. The UI interacts with the blockchain to retrieve the immutable history of decisions and actions taken by the smart contracts. It provides stakeholders with a transparent and verifiable view of the entire system, ensuring confidence in the decision-making processes.

6.1.3 End-to-End Workflow Example

1. Data Acquisition: IoT sensors send real-time data (temperature, CO2, etc.) to the oracle network. The oracle hashes the data and sends it to the blockchain, where the data is validated.
2. Smart Contract Execution (Rule Engine): A smart contract evaluates the sensor data against predefined rules (e.g., "If CO2> 5,000 ppm, alert "). If the condition is met, the rule is triggered, and the action is taken.
3. Digital Twin Update: The digital twin receives the validated data from the blockchain and updates its virtual model of the smart city. If necessary, the digital twin runs a simulation to predict the environmental status based on the current state. The result of the simulation is logged on to the chain.
4. Consensus and Validation: The decision to provide an alert and the state update in the digital twin are validated by network participants and recorded immutably on the blockchain.
5. Auditability: Later, stakeholders can audit the entire process, reviewing the raw sensor data, the rule engine’s decision, and the digital twin's simulation results, all of which are securely stored on the blockchain.

6.1.4 Rule Engine Decision Based on Real-Time IoT Data Scenario

This scenario consists of a sequence of events when IoT data triggers a decision in the rule engine, which is recorded on the blockchain for auditability. The actors that take part in the scenario are the IoT Devices, Oracle, the Rule Engine Smart Contract, the Blockchain Node and the Action System (e.g., alert). The Sequence Flow is presented in Figure 4. The IoT device collects sensor data (e.g., temperature, noise) and sends it to the Oracle. As a next step, Oracle hashes the IoT data and submits it to the blockchain. Then, the blockchain node verifies the validity of the transaction and stores the hashed IoT data on the ledger. The rule engine smart contract receives the IoT data from the blockchain and evaluates it against predefined rules. For example, "If CO2> 5.000bpm, take action."

Smart Contract Triggers Action: If the rule is triggered, the smart contract sends a request to the Action System to take the necessary action (e.g., sending an alert).

Action Executed: The Action System executes the predefined action based on the rule.

Store Decision on Blockchain: The decision made by the rule engine and the action taken is stored immutably on the blockchain for future auditing and traceability.

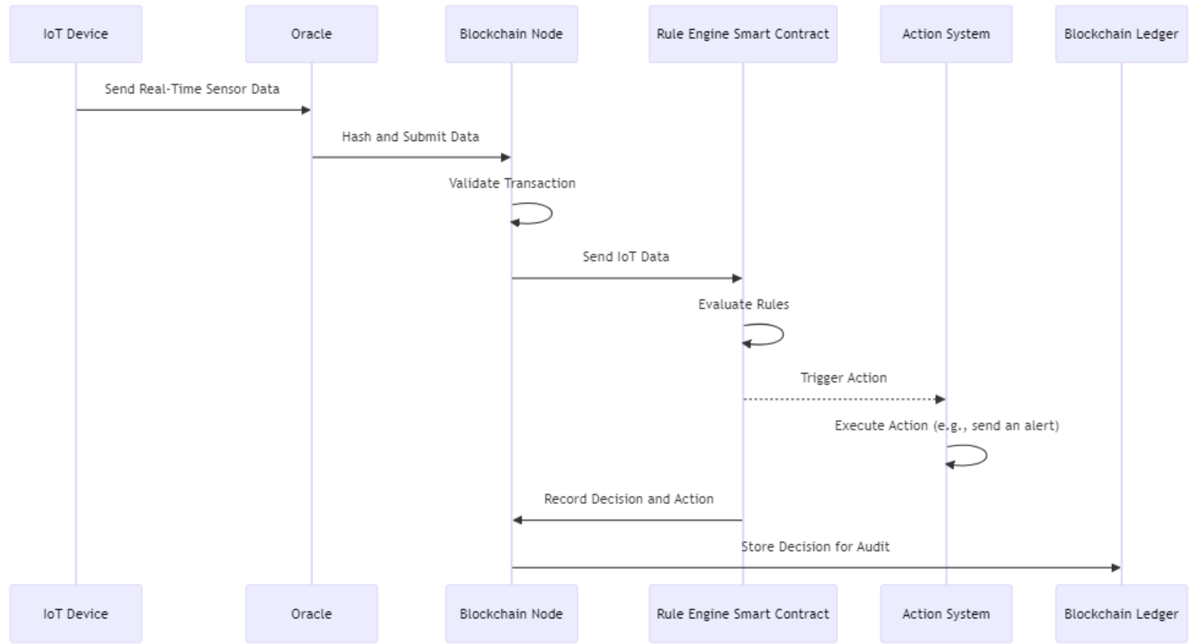


FIGURE 4. SEQUENCE FLOW OF A REAL TIME IOT DATA SCENARIO

6.1.5 Digital Twin Analytics with Blockchain Integration Scenario

This scenario regards the sequence of events when data from a digital twin is synchronized with real-time physical data and analytics results are recorded on the blockchain.

The actors that take part in the scenario are the IoT Devices (connected to a physical asset), Oracle, the Digital Twin Model, the Blockchain Node, the Simulation Engine and the Stakeholders (e.g., Public Sector).

The Sequence Flow is presented in Figure 5 Sequence Flow of a BLOCKCHAIN SCENARIO The IoT device collects real-time data (e.g., number of cars per minute in a specific crossroad) and sends it to the Oracle. Then, the Oracle hashes the data and submits it to the blockchain. The blockchain node verifies the validity of the transaction and stores the hashed data on the ledger and sends the validated real-time data to the digital twin model. The digital twin updates its virtual representation of the physical asset based on the real-time data received from the blockchain and runs simulations to predict the future state (e.g. predict traffic). The simulation results and state changes are recorded on the blockchain for auditability and traceability. Finally, the stakeholders (e.g., representatives from the public sector) access the blockchain to verify the integrity of the digital twin's data and simulation results.

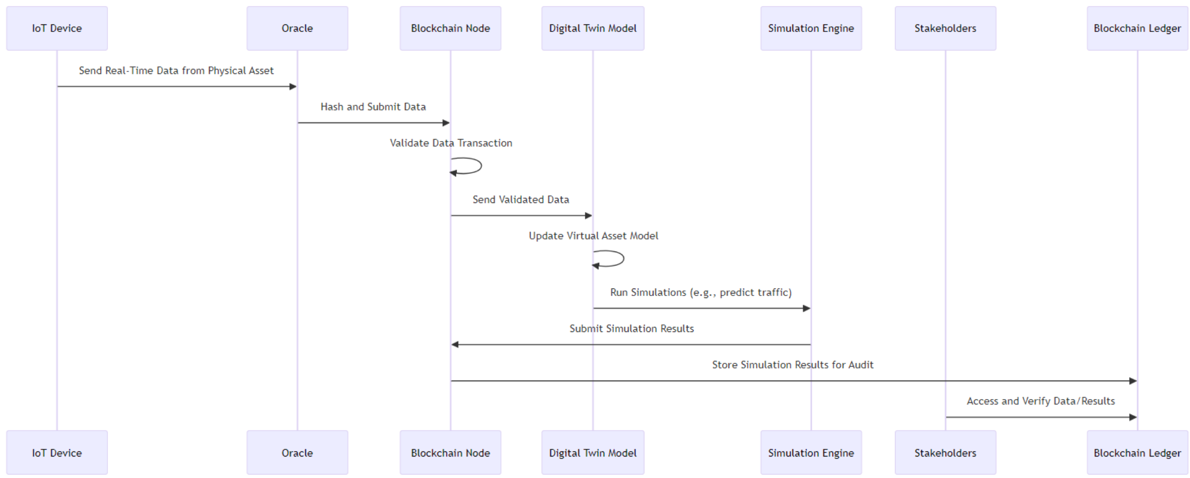


FIGURE 5 SEQUENCE FLOW OF A BLOCKCHAIN SCENARIO

6.2 Network Technologies

This Section will entail the most popular infrastructural elements for the interconnection of the devices to the edge computing layer, Figure 27, and the ones that are popular in the METACITIES ecosystem. Emphasis is given to unlicensed spectrum options although cellular solutions are discussed as well. We particularly investigate the network technologies that serve the specific layers as there is a variety of options that may affect the overall performance, cost and deployment aspects. Specifically, the choices will affect the flow of information, namely, control, monitoring and data, and the relevant functionalities involved.

The generic Digital Twin overall architecture can be implemented by a digital infrastructure that will consist of generic planes: one plane that stands for the physical world where humans, vehicles, sensors, and data sources infrastructures reside; the second plane represents the digital space where the digital replicas of those physical entities are found; and the space between the physical and the logical planes, the communication plane plays a crucial role in this framework to allow real-time and non-real-time data streaming, both upstream and downstream together with activation functions that may be automated as Actions.

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 analyzed. The network will also allow actuation of specific interconnected elements and all user interaction with the digital infrastructure along with visualization of data. To that respect in the next paragraph, we describe the networking technologies that are required for implementing the vision of METACITIES.

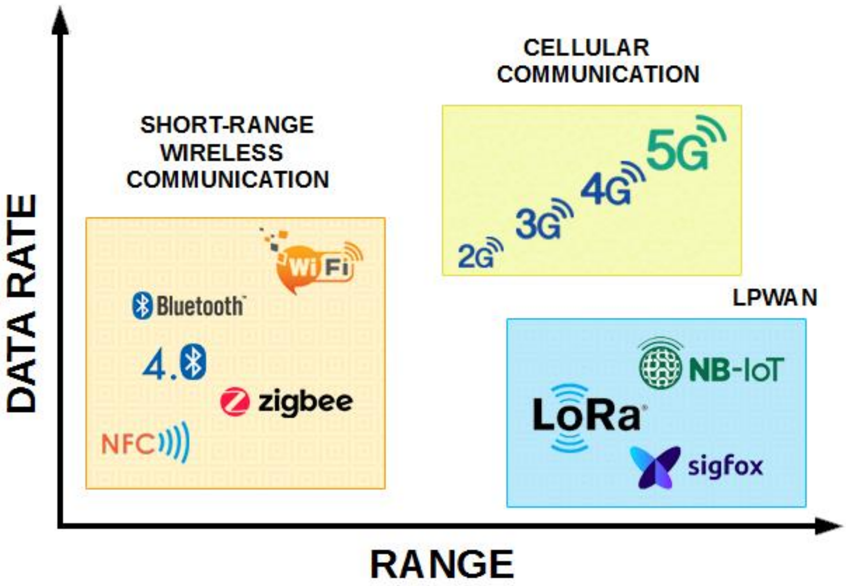


Figure 6. Range and Data Rate placement of various wireless technologies[1]

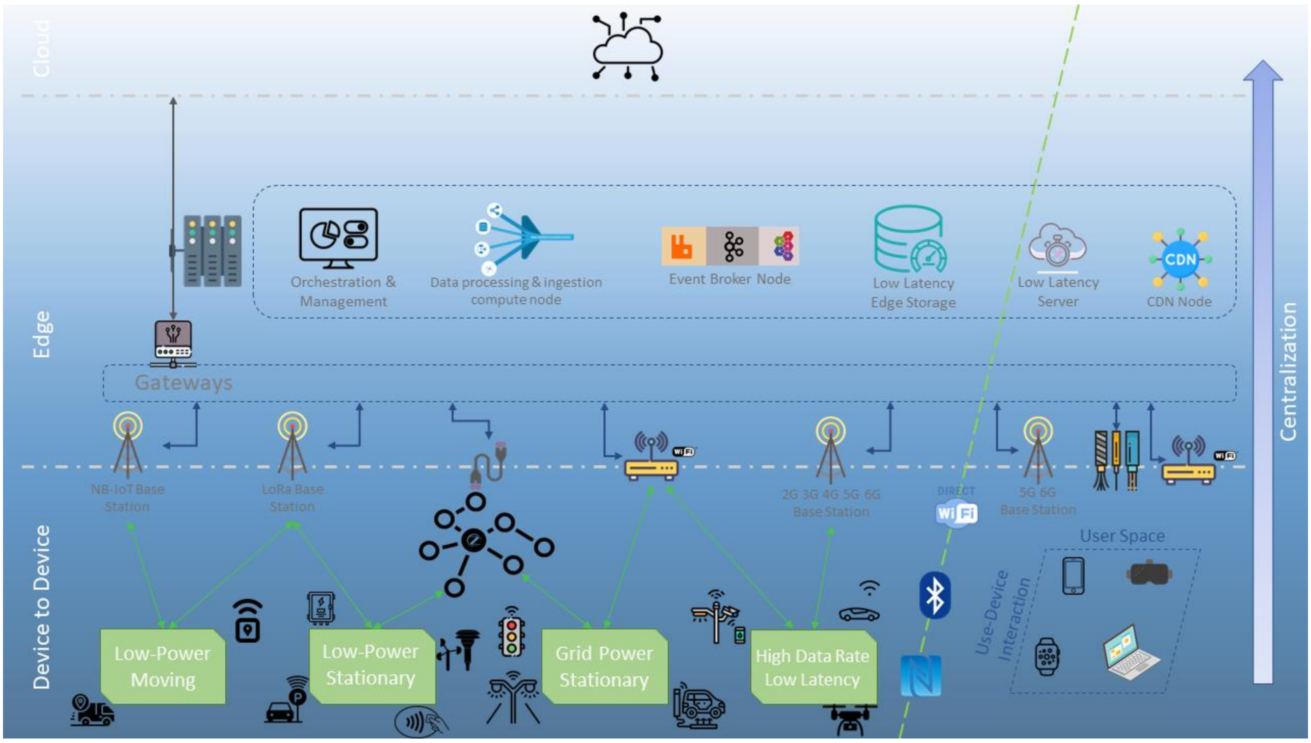


Figure 7. Overall Network Architecture for METACITIES[2]

6.2.1 5G technologies

In order to ensure that the METACITIES digital twins can be instantiated in each of the cities, there is a requirement for the existence of certain tools and an overall digital infrastructure architecture that

[1] https://www.embien.com/blog/introduction-to-lora-technology

[2] D3.1

captures the key architectural artifacts, the basic interactions with the 5G/6G system, the flow of information, namely, data, control, monitoring, and the relevant functionalities involved. This network architecture that structures the architectural elements may serve as the starting point for any Smart City project/pilot execution. However, architectural extensions may be identified for the 5G/6G as the project progresses that may benefit from the selected applications and specifications/requirements that are currently being solicitated 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).

Before explaining the flow of data and control/monitoring information in a system we describe briefly the 5G architectural and technology elements that are required for establishing a 5G/6G network in order to ensure the integration of the advanced network infrastructures with the METACITIES vision.

The paragraphs below have originated from the University of Patras Facility (Patras5G) intended to provide a platform for external parties, to test their proposed 5G use cases in an environment that is expected to be operational and stable for the delivery of good quality, 5G service.

RAN: 5G New Radio (NR) technology represents the latest advancement in wireless communications, offering high-speed data rates, ultra-low latency, and massive device connectivity. State-of-the-art developments in 5G NR have enabled more efficient spectrum utilization through dynamic spectrum sharing, millimeter-wave (mmWave) frequencies, and advanced antenna technologies like massive MIMO (Multiple Input Multiple Output). Radio Access Networks (RAN) in 5G are evolving towards a more flexible, software-defined architecture, known as Open RAN (O-RAN). This approach disaggregates hardware and software components, allowing operators to deploy RAN elements from different vendors, fostering innovation and cost efficiency. Major vendors in 5G NR and radio access networks (RAN) include Ericsson, Nokia, Huawei, Samsung, and Qualcomm, each advancing technologies to enhance 5G coverage and adaptability. These vendors focus on technologies like integrated access backhaul to replace or supplement traditional fiber backhaul, which simplifies deploying small cells in dense urban areas. Additionally, Open RAN is gaining traction, with companies like Juniper Networks and EdgeQ working with telecoms such as Vodafone to create more flexible RAN solutions using standardized hardware and software-defined elements. This flexibility enables operators to manage and optimize networks more effectively while reducing costs.

5G core: 5G core is a fundamental cornerstone of 5G networks establishing reliable connectivity for end users and providing access to its services. The core domain handles a range of essential functions in the mobile network, such as connectivity and mobility management, authentication and authorization, subscriber data management and policy management. The state-of-the-art in 5G Core Network technologies emphasizes standalone (SA) architecture, which operates independently of legacy LTE systems and is critical to unlocking the full capabilities of 5G. Core networks based on SA architecture also use cloud-native and containerized functions, which make the networks more flexible and scalable, supporting both public and private cloud deployments for broader enterprise integration.

The industry is also seeing efforts toward seamless integration with edge computing capabilities, which complement 5G Core to minimize latency by processing data closer to the source. While there are challenges, SA Core advancements have been instrumental in driving 5G's potential across various industries. Several leading vendors offer advanced 5G core solutions. These vendors are collectively advancing the 5G core market by adopting cloud-native, containerized architectures, and enhancing automation, which are essential for network slicing and managing complex, high-demand services in 5G networks with open-source solutions being available.

Transport network: The transport network technologies in 5G play a critical role in supporting the advanced capabilities required for high bandwidth, low latency, and extensive connectivity. As 5G infrastructure evolves, transport networks are focusing on xHaul (including fronthaul, midhaul, and backhaul) to manage the increased data demands across cellular networks. This involves high-capacity IP and Ethernet-based transport to support cloud-native deployments and enable network slicing, a key 5G feature that allows operators to dedicate resources to specific applications and user needs. In a city environment key advancements include programmable network technologies, enabling more efficient packet-switched architectures. Additionally, the shift toward software-defined networking (SDN) and network function virtualization (NFV) in transport networks enables cloud-ready and virtualized infrastructure, essential for supporting multi-cloud environments and improving operational efficiency. Furthermore, integration with non-terrestrial networks (NTN), such as low Earth orbit (LEO) satellites, is increasingly important to extend coverage and support high-quality services in remote areas. Operators are partnering with satellite providers to create a seamless blend of terrestrial and non-terrestrial network connectivity, addressing the global demand for robust and ubiquitous 5G coverage. In City environments however where assets and applications are typically placed in geographically close and diverse cloud compute centers, optimization of transport network technologies is an open issue.

6.2.1.1 5G-Network architecture in METACITIES

The 5G-Network architecture flavor proposed for METACITIES is in line with 3GPP TR 26.928, titled "Extended Reality (XR) in 5G"[3], 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 micro service 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 behavior in the data path. 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.

6.2.2 LoRa

LoRa (from "**Lo**ng **Ra**nge") is a low-power, long-range wireless communication technology designed specifically for Internet of Things (IoT) applications. Along with the LoRaWAN protocol it is a key enabler in the development of smart city infrastructure, providing connectivity for devices while requiring **extremely small energy consumption**, relative to options in similar range categories[4]. As of 2023, LoRa systems power **29%** of the total LowPowerWAN connections[5].

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

[4] https://kth.diva-portal.org/smash/get/diva2%3A1451892/FULLTEXT01.pdf

[5] https://iot-analytics.com/lpwan-market/

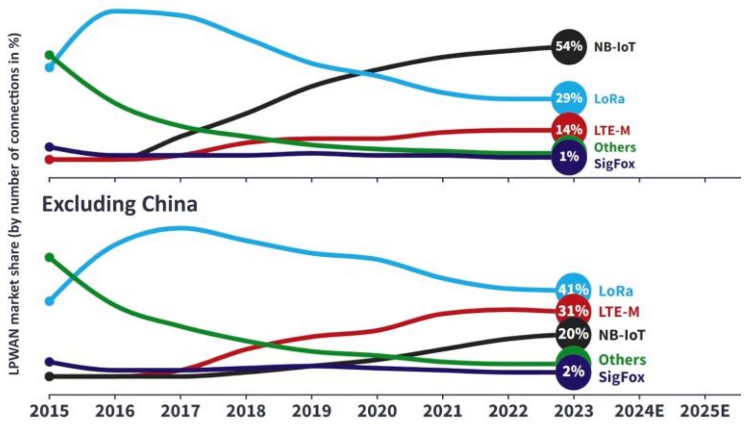


FIGURE 8. GLOBAL LPWAN MARKETSHARE[6]

	Europe	North America
Frequency band	867-869 MHz	902-928 MHz
Channels	10	64+8+8
Channel BW Up	125/250kHz	125/500kHz
Channel BW Dn	125kHz	500kHz
TX Power Up	+14 dBm	+20 dBm typ
TX Power Dn	+14 dBm	+27 dBm
SF Up	7-12	7-10
Data rate	250 bps-50 kbps	980 bps-21.9 kbps
Link Budget Up	155 dB	154 dB
Link Budget Dn	155 dB	157 dB

FIGURE 9. LORAWAN REGIONAL SPECIFICATION[7]

In an urban scenario, LoRa networks can connect various low-power devices like sensors, smart meters, environmental monitors, and public safety systems, allowing for efficient data exchange across citywide distances with neither substantial installation costs (relating to acquiring access to grid power) nor frequent maintenance. LoRa's characteristics make it ideal for urban environments where multiple devices must remain connected over extended ranges or while on the move with minimal power usage, facilitating applications in environmental monitoring, asset tracking, smart waste management, and more. LoRaWAN, the protocol layer for LoRa, enables **bidirectional communication**, end-to-end security, and adaptive data rates, making it highly scalable and suited to large-scale IoT deployments in diverse urban areas.

[6] [https://iot-analytics.com/lpwan-market/]

[7] https://resources.lora-alliance.org/document/what-is-lorawan

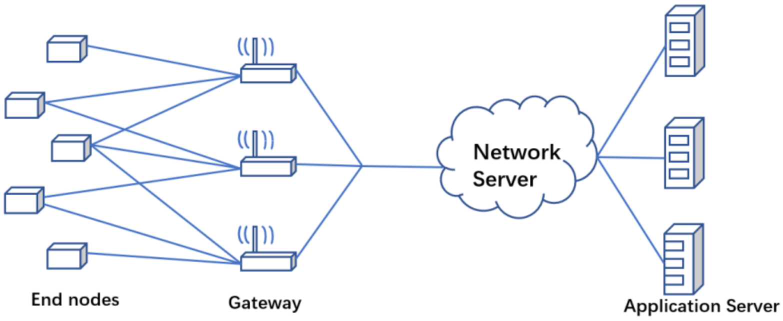
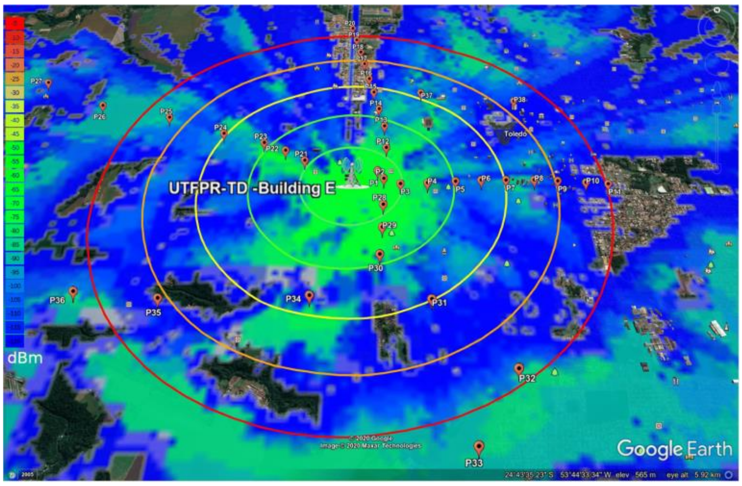


FIGURE 10 LORAWAN NETWORK TOPOLOGY[8]

However, LoRa devices, unlike cellular based ones that use existing consumer-oriented infrastructure, require the **installation of the corresponding LoRa base stations** in dense configurations in order to provide coverage in areas with strong occlusion characteristics. Those stations, often referred to as **"Gateways"** (although the gateway is only one part of a station), serves as a bridge between LoRa end devices and the LoRaWAN network server. It receives LoRa RF signals from end devices, converts them into IP packets, and forwards the data to the network server using backhaul networks such as Ethernet, Wi-Fi, or cellular[9]. The gateway performs demodulation and manages multi-channel and multi-device communication simultaneously. It operates as a pass-through device, handling no decision-making or storage of application-level data.

The communication range of LoRa varies based on environmental factors and device settings. In urban environments, where obstacles like buildings can attenuate signals, LoRa typically achieves ranges between 2 to **2.5 kilometers** [11]. In contrast, in rural or open areas with line-of-sight conditions, the range can extend up to 10 kilometers or more.



Values ranging from -120 dBm (blue shades) to -5 dBm (red).

FIGURE 11 DEPLOYMENT OF A LORAWAN NETWORK AND EVALUATION OF TRACKING DEVICES IN THE CONTEXT OF SMART CITIES [11]

[8] https://kth.diva-portal.org/smash/get/diva2%3A1451892/FULLTEXT01.pdf

[9] https://news.rakwireless.com/things-to-consider-when-picking-a-lorawan-gateway/#BackhaulConnectivity

Attempts have been made to enable wider signal coverage through the use of UAVs to create line of sight between base stations and devices[10], an effort made possible by the modular design of LoRa networks in how messages are intercepted and deduplicated, as discussed later. With regard to device installation, in LoRaWAN, Over-The-Air Activation (OTAA) and Activation By Personalization (ABP) are two methods for connecting devices to a network. OTAA is the preferred method, where a device joins the network dynamically through a "join request" that the network server accepts with a "join accept." During this process, session keys are generated securely, enabling end-to-end encryption and making it easier to update keys if needed. In contrast, ABP involves hardcoding the session keys and other parameters directly on the device before deployment. This makes ABP simpler to set up initially, but it lacks the flexibility and security advantages of OTAA, as session keys remain static and can't be updated remotely[15].

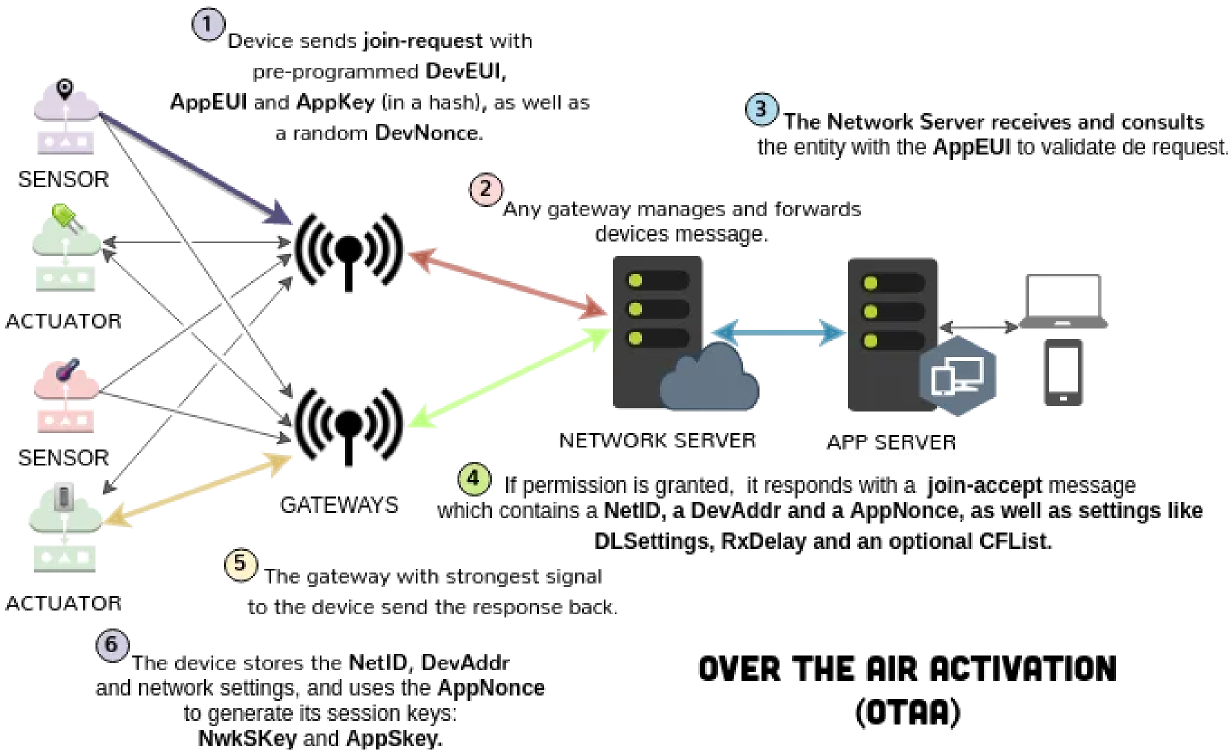


FIGURE 12 *LORAWAN ARCHITECTURE WITH OTAA CONNECTION MODE*[11]

Commonly used LoRa Network Servers include:

- The Things Stack *Integrations*[12]*:* AWS IoT, Azure IoT Hub, MQTT, Webhooks, HTTP integrations, and integrations with popular databases like PostgreSQL.
- ChirpStack *Integrations*[13]*:* Google Cloud, AWS IoT, MQTT, HTTP, PostgreSQL, InfluxDB, and Grafana for data visualization.

[10] https://arxiv.org/abs/1902.11243
[11] https://www.dusuniot.com/blog/build-lorawan-network-and-connect-to-server/
[12] https://www.thethingsindustries.com/docs/integrations/
[13] https://www.chirpstack.io/docs/chirpstack/integrations/index.html

- KONA Core by TEKTELIC *Integrations[14]:* AWS IoT, Azure IoT Hub, MQTT, and HTTP APIs for custom applications.
- LORIOT Integratio*ns[15]:* IBM Watson IoT, Microsoft Azure IoT Hub, AWS IoT, HTTP integrations, and MQTT.

A party may use gateways from another shareholder (e.g. a private company might use gateways operated by the municipality) and deploy its own LoRaWAN Server in order to decrypt messages and manage its devices without the other shareholder understanding what is being communicated through their infrastructure. This way the LoRaWAN Protocol achieves simplified multitenancy and care-free installations in spaces used by multiple parties.

6.2.3 Local IP Based Networks

High-bandwidth local short-range connectivity is still a key enabler in smart city equipment communication, ensuring reliable and fast communication for a variety of devices and systems. Wi-Fi and Ethernet have been traditionally the main pathways to establish reliable and multi-compatible connectivity in short range usage while previously mentioned protocols and technologies put their weight on wide area or mobility based connectivity [12].

Wi-Fi (Wireless Fidelity)

Wi-Fi is widely used in urban environments, both for public access and connecting stationary devices such as bandwidth-hungry sensors and cameras. It is particularly effective for scenarios requiring high data rates and flexible deployment. In modern cities, Wi-Fi networks often provide connectivity for citizens in public spaces and therefore the installation of Wi-Fi access points across a wide area is an infrastructure already present, making the installation of supported IoT equipment simpler and with lower overhead[16] cost.

Due to its relatively high-power consumption, Wi-Fi is primarily used for stationary devices with access to constant power or for public infrastructure supported by robust power sources, although newer standards have proposed functions aimed at evolving the protocol to reduce the dependence on stable power sources [13][14]. Its ubiquitous nature, due to high consumer adoption, and the standardization under the IEEE 802.11 family of protocols has also made it an important interoperability protocol since Wi-Fi networks can support a multitude of devices with different power, manufacturing cost and data-rate specifications in contrast to other protocols where proprietary protocols hinder manufacturer adoption and support.

A consideration growing in significance, however, is the stability of Wi-Fi networks in crowded environments such as cities, where multiple networks often operate in close proximity. The proliferation of overlapping Wi-Fi signals in dense urban areas can lead to increased interference, reduced performance, and connectivity challenges. This issue becomes more critical as cities grow smarter and more connected, relying heavily on robust wireless infrastructure to support everything from IoT devices to high-bandwidth applications. Effective spectrum management, the adoption of newer technologies like Wi-Fi 6E, and strategies to mitigate congestion are essential to ensure network reliability in these crowded spaces[17] .

[14] https://tektelic.com/expertise/lorawan-network-server-explained/

[15] https://loriot.io/community-server.html

[16] https://cloud4wi.com/resources/smart-cities-public-wifi-foundation-of-digital-transformation/

[17] https://technetworks.ca/effective-planning-of-wi-fi-networks-in-dense-urban-environments

Ethernet

Ethernet plays a vital role in smart city infrastructure, particularly for applications that demand high reliability and minimal latency. As a wired communication protocol governed by the IEEE 802.3 standards [18], Ethernet ensures robust and consistent performance, making it an ideal choice for many critical IoT systems in urban environments.

In the context of smart cities, Ethernet's reliability is a cornerstone for systems where uninterrupted communication is essential, such as traffic management networks, industrial IoT implementations, and emergency response systems. Its ability to deliver consistent high-speed connectivity is crucial for handling the vast amounts of data generated by IoT devices like high-definition cameras, environmental sensors, and smart meters.

Low latency is another significant advantage of Ethernet in these environments. Smart city applications, such as real-time video surveillance and autonomous systems, rely on instant data transmission, which Ethernet provides more effectively than wireless alternatives. This responsiveness enhances the efficiency and safety of urban systems, particularly those operating under tight time constraints.

Ethernet's scalability is invaluable for accommodating the growing data requirements of smart city devices. Cities can future-proof their networks to support evolving IoT needs with affordable yet highly scalable ethernet infrastructure. This capability ensures that the infrastructure remains resilient as cities adopt more bandwidth-intensive solutions.

In terms of deployment, Ethernet also supports Power over Ethernet (PoE), a feature that simplifies the installation of IoT devices [19]. PoE allows for the delivery of both power and data through a single cable, reducing the complexity and cost of connecting devices like smart cameras, weather sensors, and access control systems. This dual functionality is particularly beneficial in urban environments where efficient resource utilization is a priority.

Security and reliability are also critical factors in Ethernet's suitability for smart city IoT networks. The physical nature of wired connections makes them less susceptible to unauthorized access, providing an added layer of protection for sensitive systems and data. For applications such as public safety networks and utility monitoring, this inherent security is an essential consideration.

Although the initial installation of Ethernet networks can involve higher costs compared to wireless alternatives, the long-term reliability, low operational costs, and high performance make it a cost-effective solution for smart cities. Its ability to meet the rigorous demands of IoT devices ensures that Ethernet remains a foundational technology in the development of interconnected urban environments.

6.2.4 Device/User to Device

Device-to-device (D2D) communication refers to localized interactions between two devices, often within close physical proximity, to complement the functionalities provided by the broader communication grid. Oftentimes, one of the devices might serve as a proxy of the user in a scenario (such as an ID tag or a smart-phone), making the interaction of type “user to device”. This approach, in general, allows devices to share data, authentication information or commands efficiently and

[18] https://standards.ieee.org/ieee/802.3/10422/

[19] https://www.microchip.com/en-us/about/media-center/blog/2024/microchip-poe-powers-smart-cities

directly, minimizing latency and bandwidth usage on the primary network or more importantly, lowering installation costs, energy requirements and enhancing ease of use (in user to device scenarios) while maintaining a higher degree of reliability in situations where safety is critical (e.g. coordination of traffic lights in an intersection). These interactions play a crucial role in smart city initiatives, enabling diverse technologies to work together seamlessly to provide real-time, context-aware services while prioritizing security and energy efficiency.

A variety of short-range communication technologies facilitate localized device interactions, each suited to specific needs depending on range, energy efficiency, data throughput, and use-case complexity:

- Bluetooth technology, including both Classic and Low Energy (BLE) variants[20] , is widely used for direct device pairing and communication. BLE, in particular, is optimized for energy-efficient, intermittent data exchanges. Applications include device configuration, sensor updates, and short-range data sharing without substantial power drain.
- Wi-Fi Direct allows devices to establish a high-speed, peer-to-peer connection without requiring an intermediary access point. This is particularly useful for high-bandwidth tasks like firmware updates or media sharing. It provides greater throughput than Bluetooth, albeit with higher energy consumption, making it suitable for devices with robust power sources or short-duration tasks. However, ignoring the limitations in energy consumption, Wi-Fi direct has found use in User to Device interaction [16] thought the ubiquitous support of it in commercial smartphones. Scenarios such as device configuration, traffic detection [16] and vehicle to pedestrian communications [17] are common use cases.
- NFC operates at very short ranges (a few centimeters), enabling secure, instantaneous communication between devices. It is ideal for use cases requiring authentication or transaction-like interactions, such as:
  - Pairing devices for further interaction (e.g., connecting a smartphone to a smart sensor for setup).
  - Authentication for physical or digital access control.
  - Facilitating payments or data exchange with minimal user intervention.
- RFID is predominantly used for identification and data transmission in environments where devices or tags need to communicate passively. RFID systems consist of two main components:
  - Tags: Passive or active identifiers attached to objects or devices.
  - Readers: Devices that energize passive tags and retrieve their stored data.

  RFID applications relevant to D2D interactions include[21] :
  - Asset tracking: Smart devices logging RFID-tagged assets for inventory or operational purposes.
  - Authentication: Vehicles or users identified via RFID to interact with IoT-enabled infrastructure (e.g. wireless toll stations, smart charging facilities or equipment access management).
  - Maintenance: Using RFID-enabled tools to log work or access specific equipment.
- Other wireless protocols, technologies like Zigbee, Z-Wave [22], and proprietary short-range protocols also contribute to D2D interactions. These are particularly prominent in constrained IoT environments, such as smart homes, where low power consumption and interoperability are key.

[20] https://www.bluetooth.com/learn-about-bluetooth/tech-overview/

[21] https://www.rfidcard.com/rfid-and-smart-cities-building-the-urban-future/

[22] https://goodhomeautomation.com/smart-home/z-wave-vs-zigbee-smart-home-protocols/

- Wired technologies such as CAN (Controller Area Network) [23] or NEMA TS2 (specifically for traffic lights)[24] are also commonly deployed in short range device communication.

Device-to-Device (D2D) communication represents a critical advancement in IoT and smart city ecosystems by enabling direct interactions between devices, either independently or as an extension of the centralized communication grid. The integration of D2D into existing systems addresses numerous challenges while unlocking new capabilities that enhance functionality, efficiency, and reliability. Below are the key achievements facilitated by D2D communication, structured to reflect its multifaceted benefits:

- D2D communication reduces the reliance on centralized infrastructure for certain localized interactions. This achieves:
  - Bandwidth Conservation: By offloading localized data exchanges from the main communication grid, D2D minimizes the load on centralized networks, preserving bandwidth for critical operations. However, this is of minimal concern in device-to-device communications since they rarely incorporate transmissions of lengthy data.
  - Low Latency: Direct communication between devices reduces transmission time, which is essential for real-time applications such as traffic control or safety systems.
  - Energy Savings: Devices can communicate directly using small range energy-efficient protocols like Bluetooth Low Energy (BLE) or Near Field Communication (NFC), extending battery life and reducing operational costs.
- It also extends the capabilities of connected systems by enabling auxiliary interactions that enrich their core functions:
  - Localized Contextual Interactions: Multiple devices can exchange localized information (e.g., vehicle identification with parking sensors or wireless vehicle detection by traffic lights) that can be later uploaded to the cloud by only one device, driving down installation and maintenance costs.
  - Interoperability Across Protocols: D2D technologies like NFC, RFID, and Wi-Fi Direct facilitate seamless interactions across devices with diverse communication standards.
  - Flexibility for On-Site Adjustments: Maintenance crews or operators can directly connect to devices using short-range protocols to configure, monitor, or troubleshoot without requiring internet access.
- Furthermore, D2D communication can enhance the security of data exchanges by:
  - Local Data Isolation: Sensitive data remains within a localized context, reducing exposure to external threats and mitigating the risk of breaches.
  - Secure Protocols: Technologies like Bluetooth and NFC incorporate robust encryption and authentication mechanisms, ensuring secure interactions between devices.
  - Controlled Access: On-site connections for setup or maintenance often require physical proximity or specific access credentials, adding a layer of security.
- Finally, communication contributes to system robustness by ensuring continuity of service even when centralized components fail:
  - Fallback Communication: In scenarios where the main grid is unavailable (e.g., network outages), D2D enables devices to continue interacting locally to perform essential functions.

[23] https://www.ni.com/en/shop/seamlessly-connect-to-third-party-devices-and-supervisory-system/controller-area-network--can--overview.html

[24] https://www.nema.org/docs/default-source/standards-document-library/nema-ts-2-2021-contents-and-scopeb71294ae-eb9a-45e2-a501-e5c0672dbd6b.pdf?sfvrsn=ef98a362_3

- Redundancy: Devices can share critical information directly to bypass temporary disruptions in centralized communication.

Device-to-Device (D2D) communication provides a practical way for devices to interact directly, improving efficiency and reducing the need for centralized systems in localized operations. Using technologies like Bluetooth, NFC, Wi-Fi Direct, RFID, and other D2D communication solutions enables user friendly, efficient and low-latency interactions suited to various everyday applications, such as user authentication or traffic systems. While not a replacement for broader networks in any way, D2D offers a reliable and cost-effective solution for many short-range communication needs and enhances the existing web of devices without additional centralized connectivity infrastructure.

7 Conclusions

This deliverable presents the functional requirements and end-user needs, their specifications, as well as their relationship with the use cases and the main technologies that will be used in the ODTF. Through this analysis, we aimed to establish a comprehensive foundation that integrates the technical, functional, and user-centric aspects of the METACITIES Digital Twin framework. Additionally, the deliverable offers an in-depth presentation of the technological components, providing clarity on the architecture and its applications in real-world scenarios.

The work presented in this deliverable was carried out in four main steps. First, we defined the specifications of the requirements by conducting a thorough analysis of use case demands and stakeholder objectives. This ensured that all identified requirements were aligned with the overarching goals of the METACITIES initiative. Second, we meticulously detailed the technical components, outlining their capabilities, constraints, and relevance to the identified needs. Third, these components were matched with specific use cases, creating a clear linkage between the conceptual framework and practical implementation. Finally, we proposed the core technologies that will underpin the METACITIES Digital Twin, ensuring their scalability, interoperability, and efficiency in addressing urban challenges.

The primary outcome of this deliverable is a well-defined description of the technical components, enriched with information regarding their alignment with requirements and use cases. This alignment underscores the coherence of the proposed solutions and demonstrates how they cater to diverse urban scenarios, from smart mobility to green city initiatives. Combined with the innovative 3D representation technologies and transitioning to Metaverse approaches (Section 5), and enabling technologies outlined in Section 6, the deliverable provides a holistic view of the ODTF architecture. This integration not only facilitates a clear understanding of the framework but also establishes a robust foundation for future developments and applications within the METACITIES ecosystem.

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Appendix

A. Smart mobility

Use case 1

For the use case 1, smart mobility and parking behavior analysis, input data include car position, Bluetooth and sensors data as well as google map data, and supports decisions on parking behavior, parking density and parking violations.

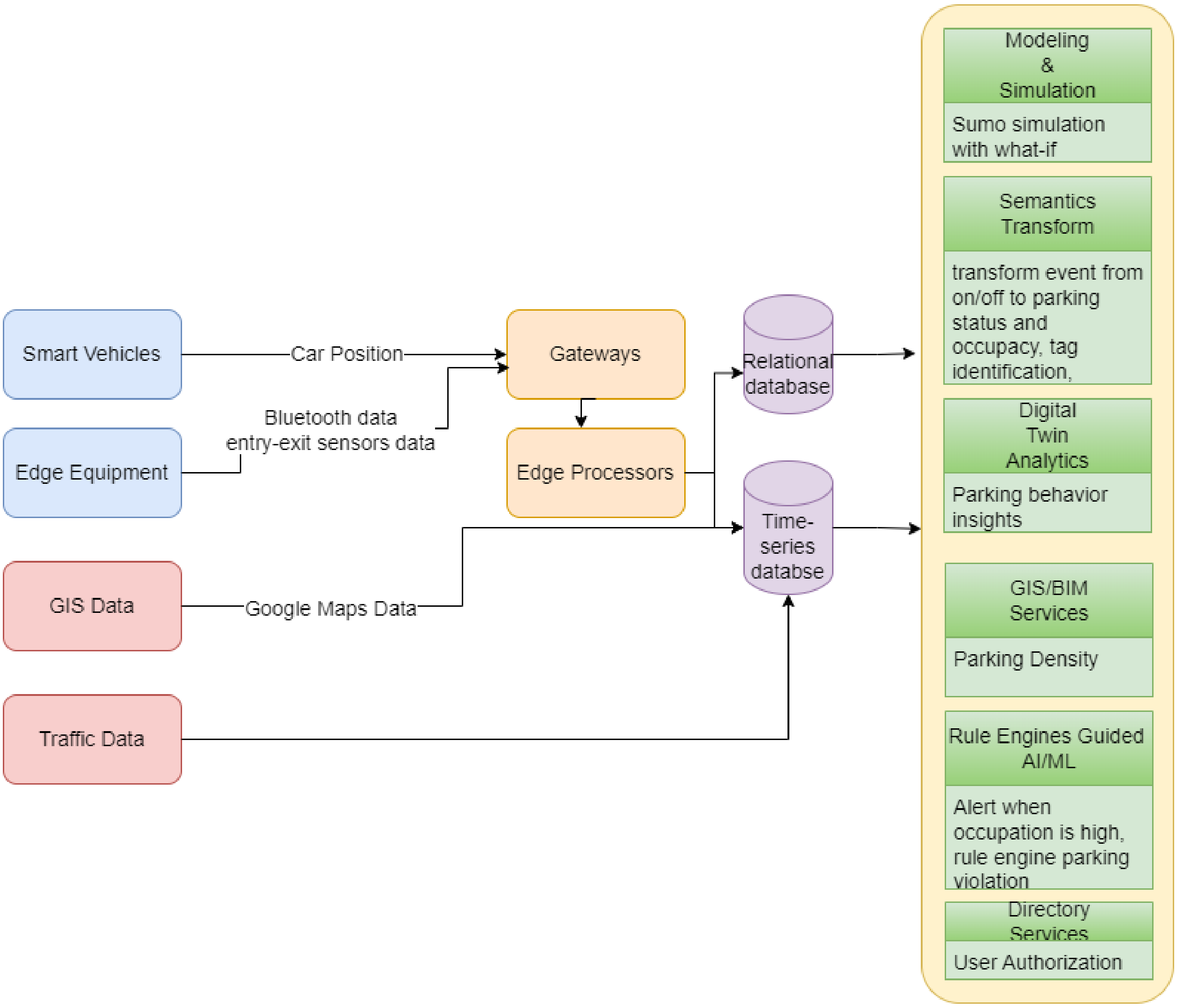

FIGURE 13. GR CLUSTER- USE CASE 1

Use case 2

For the use case 2, environmental patterns of traffic incidents, input data includes traffic monitoring and bus traffic data, maps, crowd sourcing incidents as well as flow and blocking events, and supports decisions on traffic obstruction and congestion estimation.

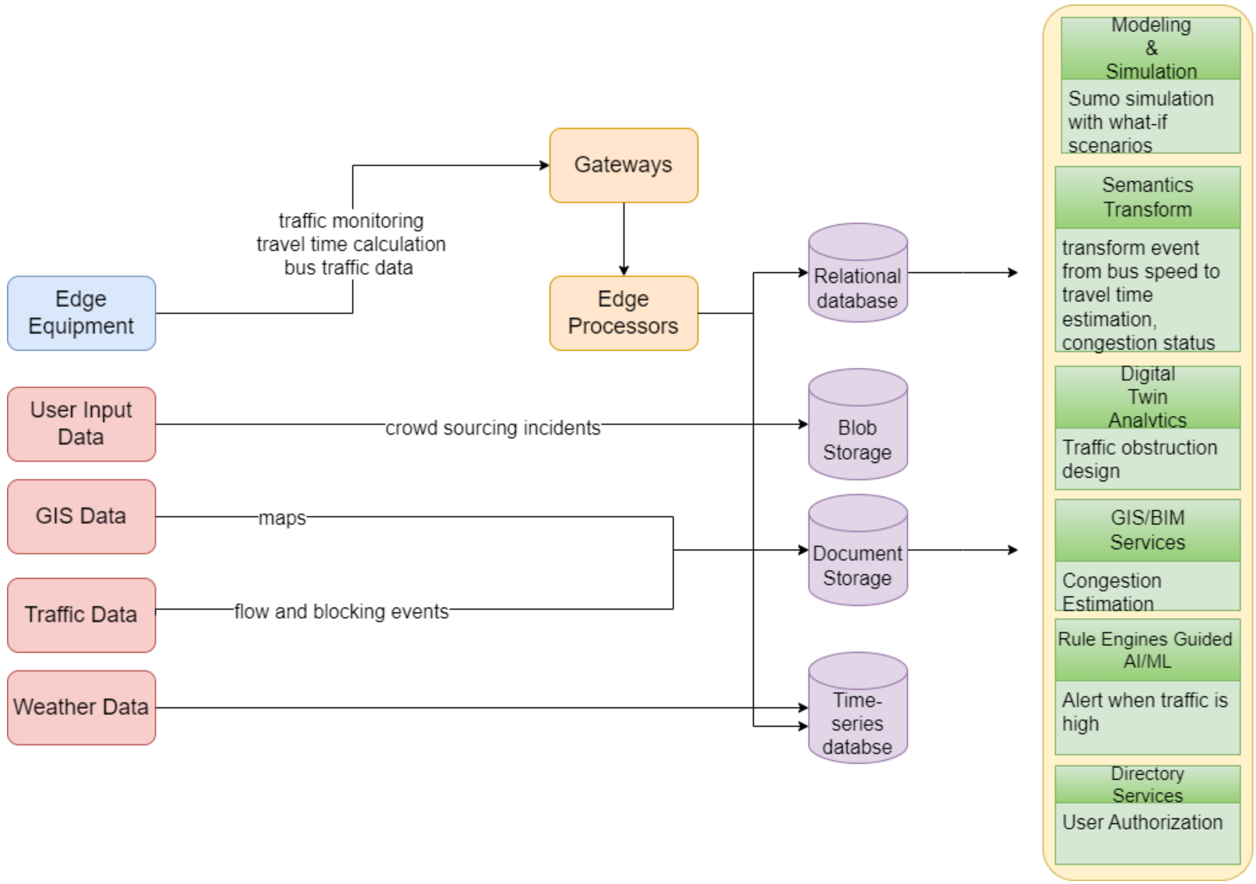

FIGURE 14. GR CLUSTER- USE CASE 2

Use case 3

For the use case 3, emergency management, input data includes traffic monitoring, air quality and noise intensity, and supports decisions on traffic density and traffic re-routes on emergency incidents.

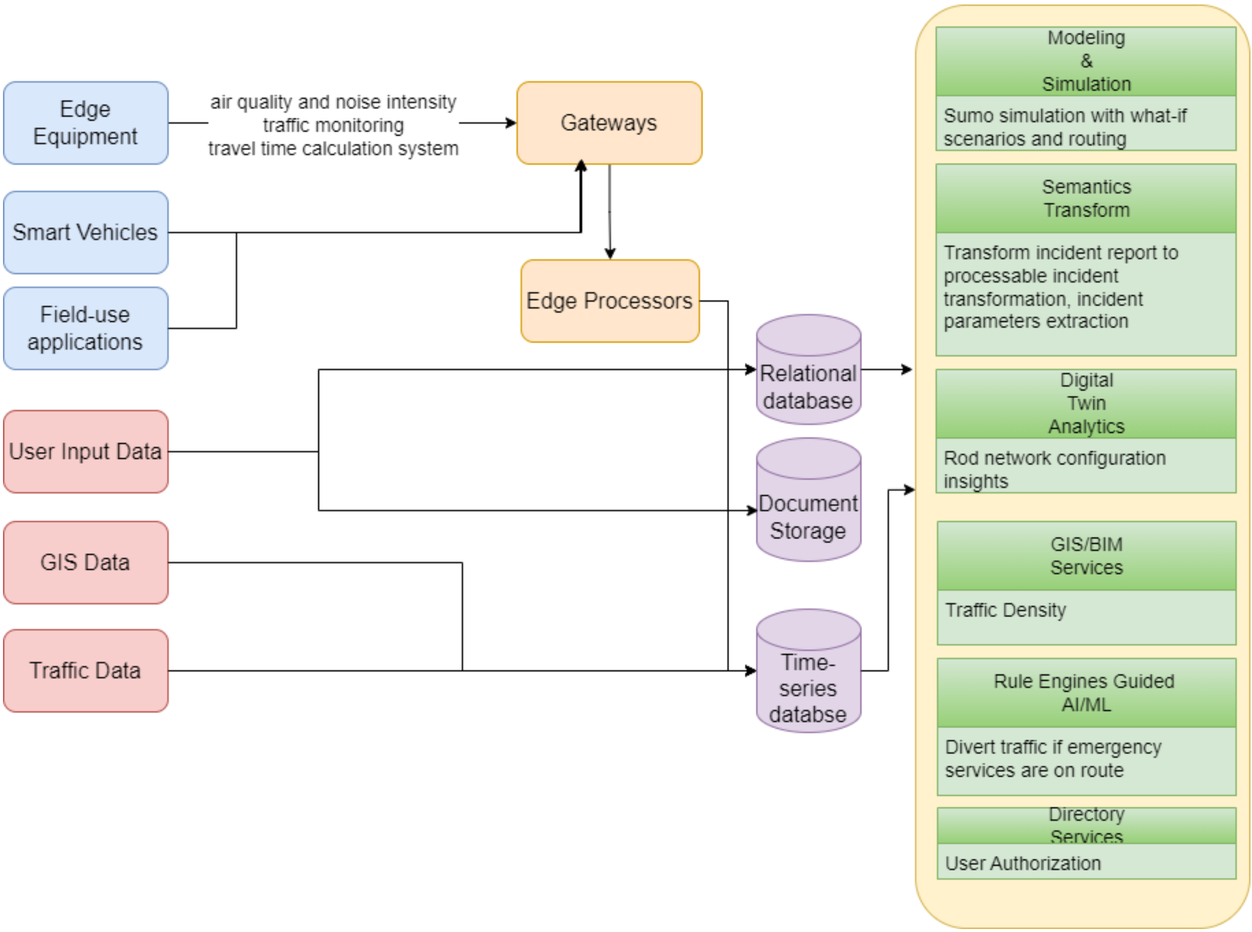

FIGURE 15. GR CLUSTER- USE CASE 3

B. Green City

Use case 1

For the use case 1, renewables (PV) potential and performance, input data includes GIS data and Lidar images, data from Burgas platform, google maps as well as manually corrected data, and supports decisions on the installation of PV systems and optimization of energy utilization.

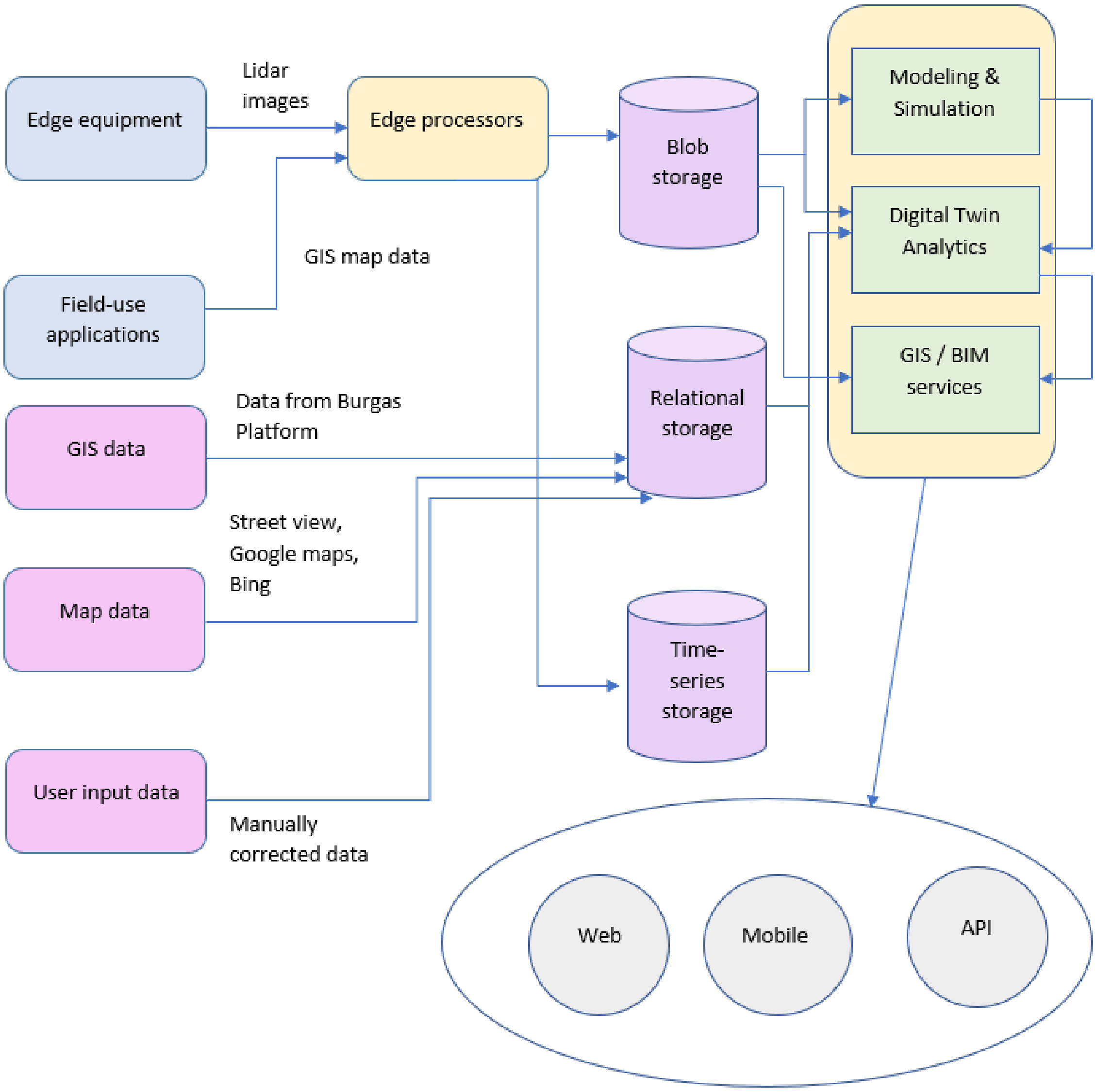

FIGURE 16. BG CLUSTER- USE CASE 1

Use case 2

For the use case 2, buildings energy performance, input data includes data from IoT devices, the 3D AutoCAD platform, google maps as well as manually corrected data, and supports decisions on energy consumption.

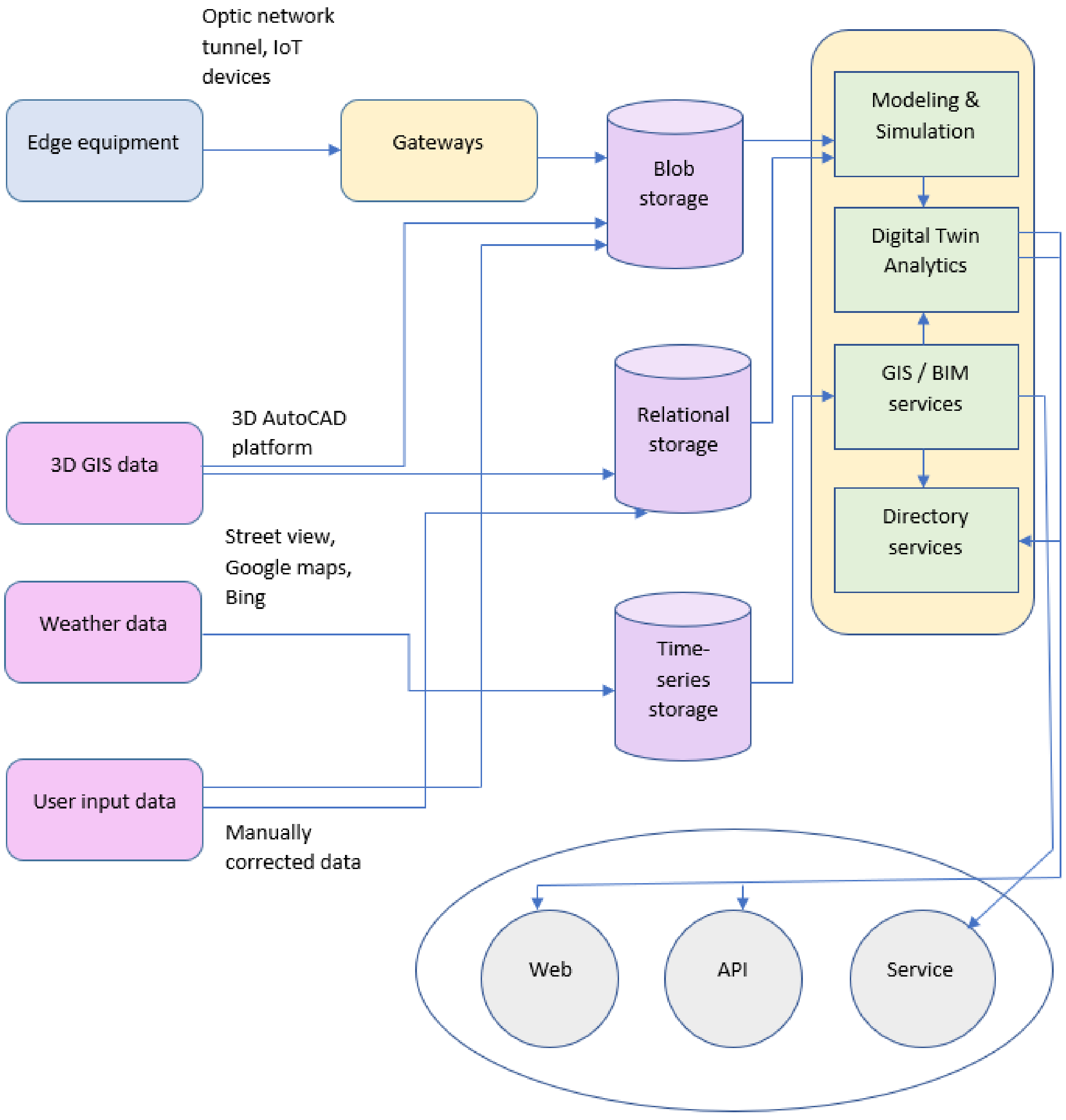

FIGURE 17. BG CLUSTER- USE CASE 2

Use case 3

For the use case 3, budget planning for energy usage, input data includes data from drone thermal images, GIS data, google maps as well as manually corrected data, and supports decisions on the economic viability of energy efficiency measures and PV energy systems.

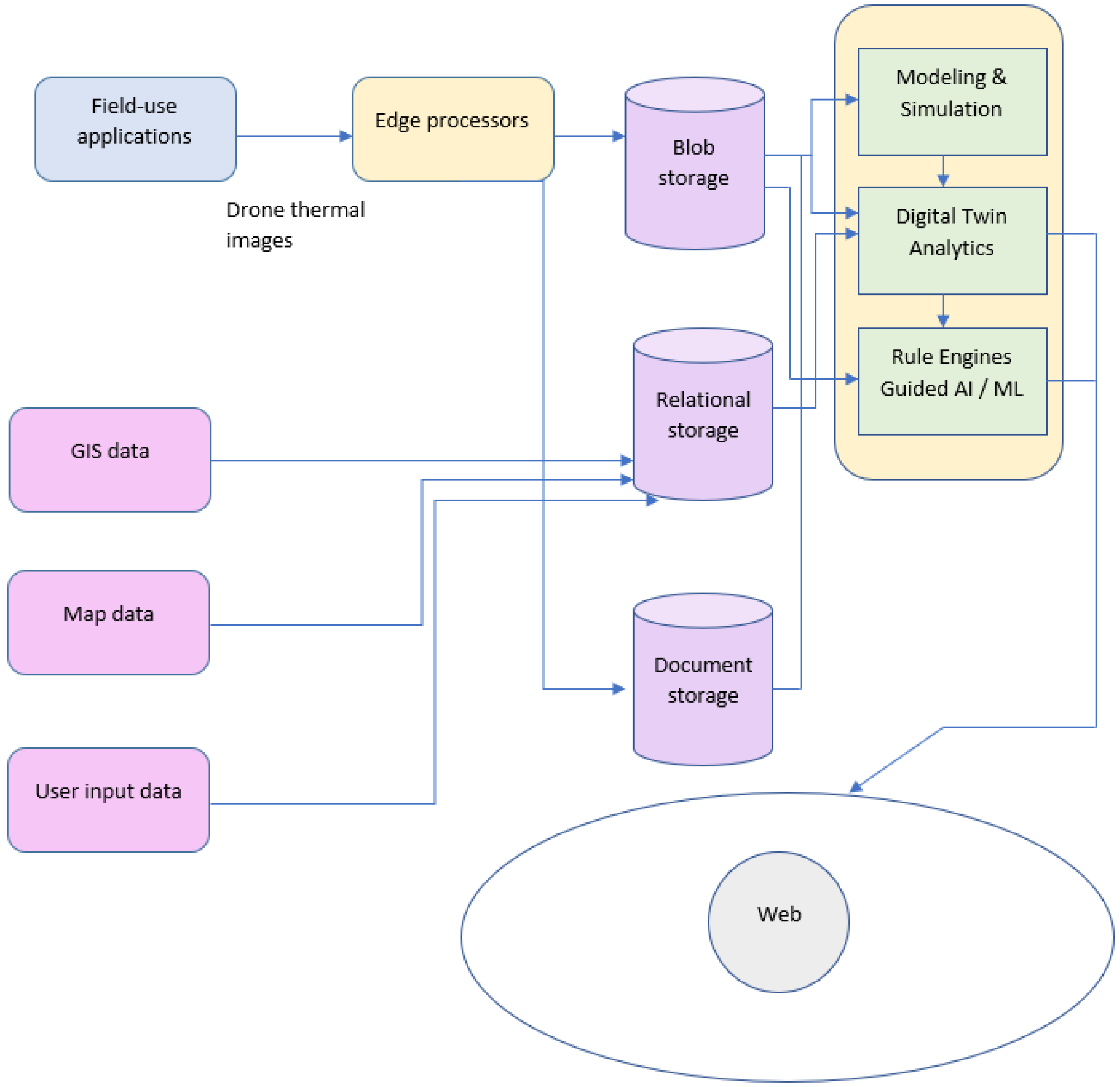

FIGURE 18. BG CLUSTER- USE CASE 3

C Urban Planning

Use case 1

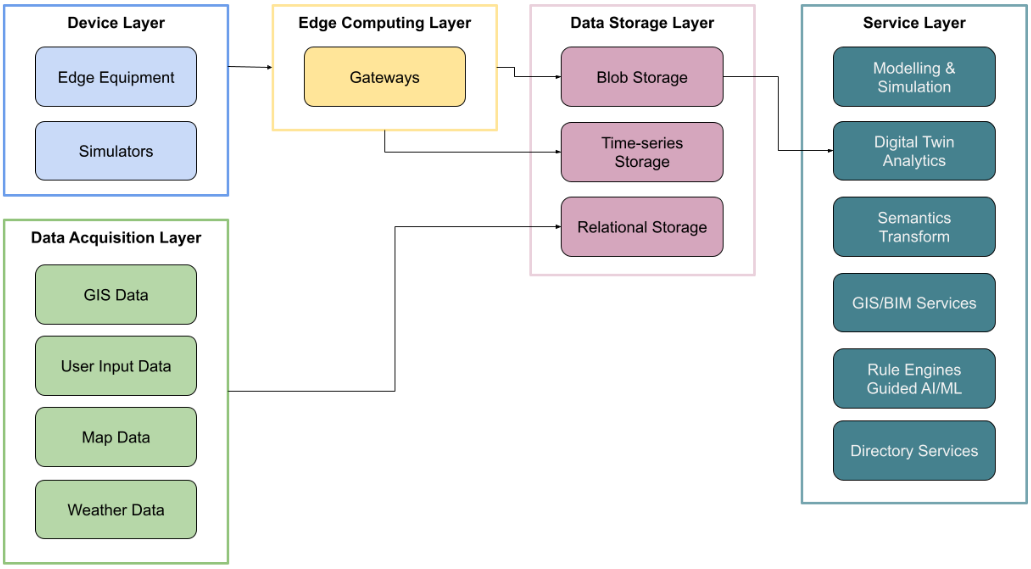

FIGURE 19. CY CLUSTER- USE CASE 1

Use case 2

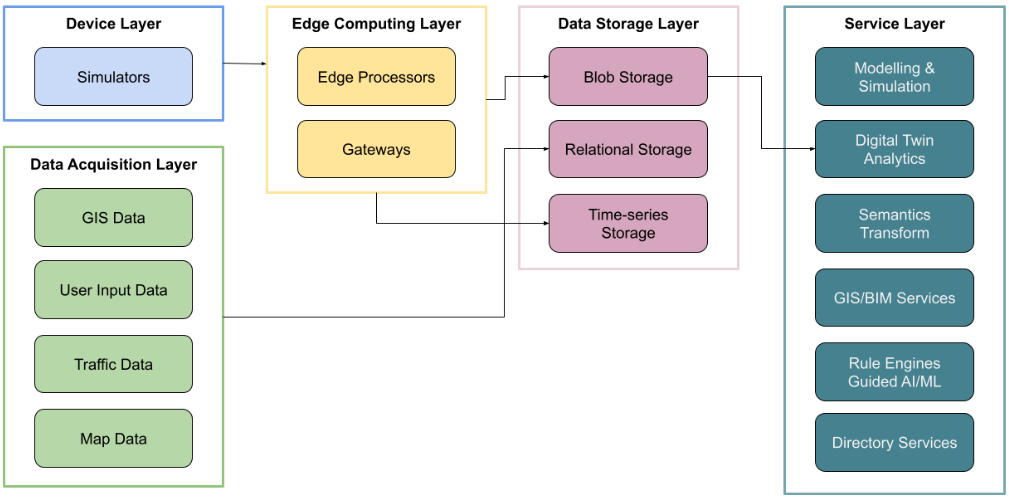

FIGURE 20. CY CLUSTER- USE CASE 2