Smart City Digital Twin

BIG DATA ARCHITECTURES

A.A. 2024/2025

Introduction

- A **Digital Twin** is a virtual replica of a real entity
- Originally named *Mirrored Space Model* by M. Grieves in 2002
- Renamed digital twin by J. Vickers of NASA

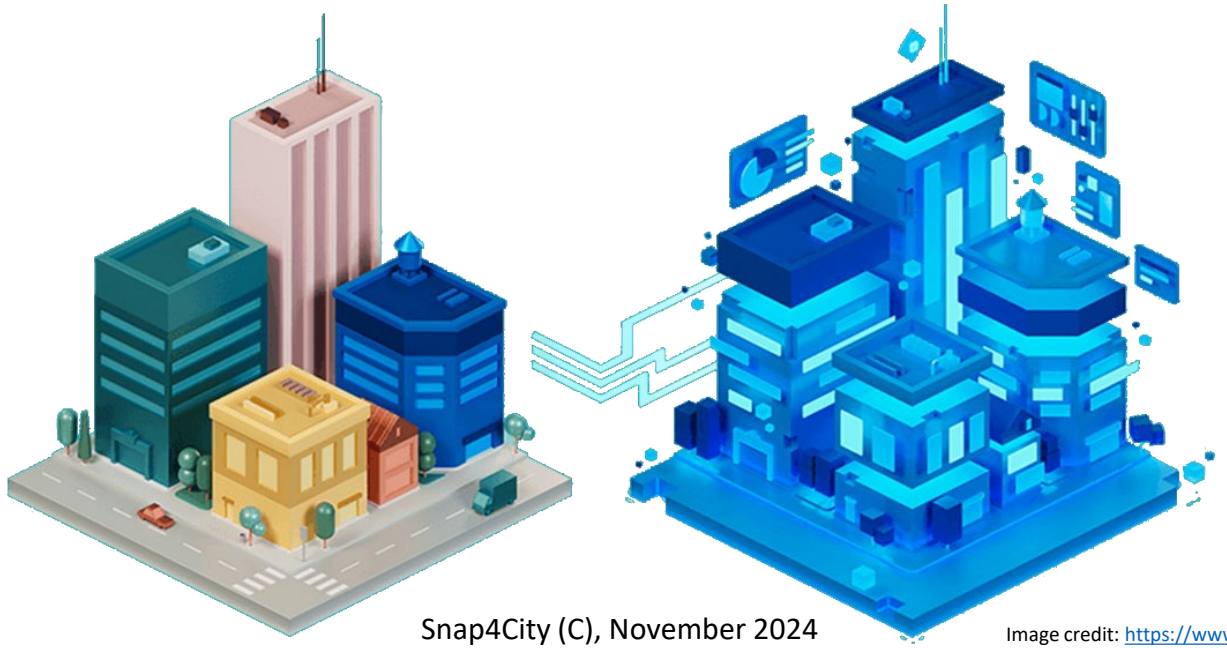
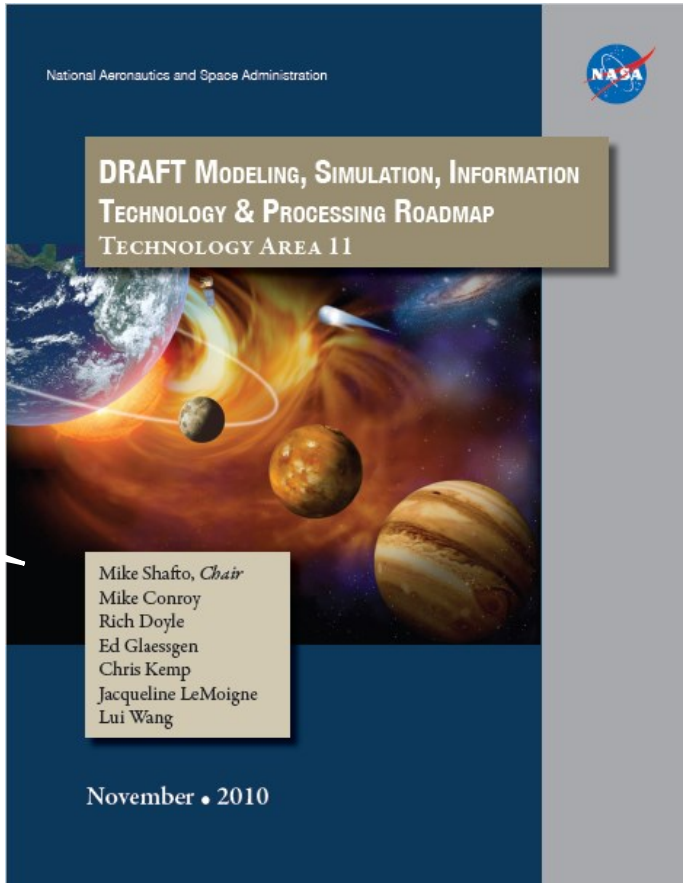


Image credit: https://www.12dsynergy.com/innovation-showcase/digital-twins-explained/

Introduction

- First applications of digital twins emerged in the **aerospace** field

*A digital twin is an **integrated** multi-physics, multi-scale, probabilistic simulation of a vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to **mirror the life of its flying twin**.*



Introduction

- First applications of digital twins emerged in the **aerospace** field

- Then, digital twins appeared in the **manufacturing** and **construction** industries

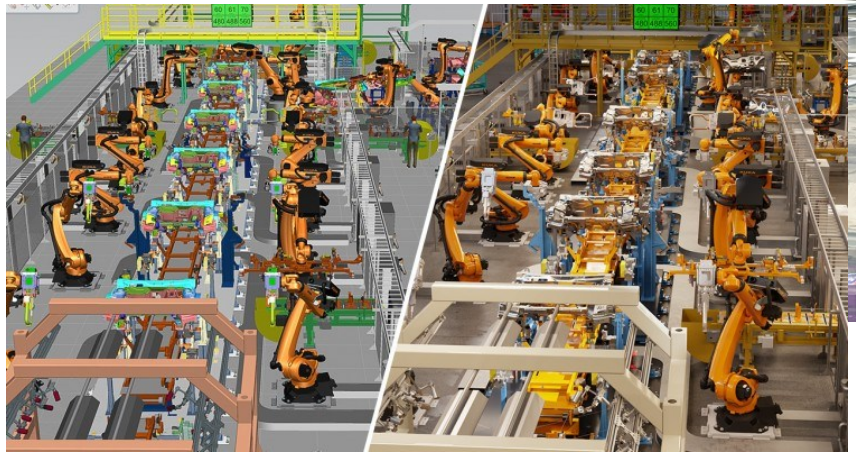


Image credits: Siemens Digital Industries

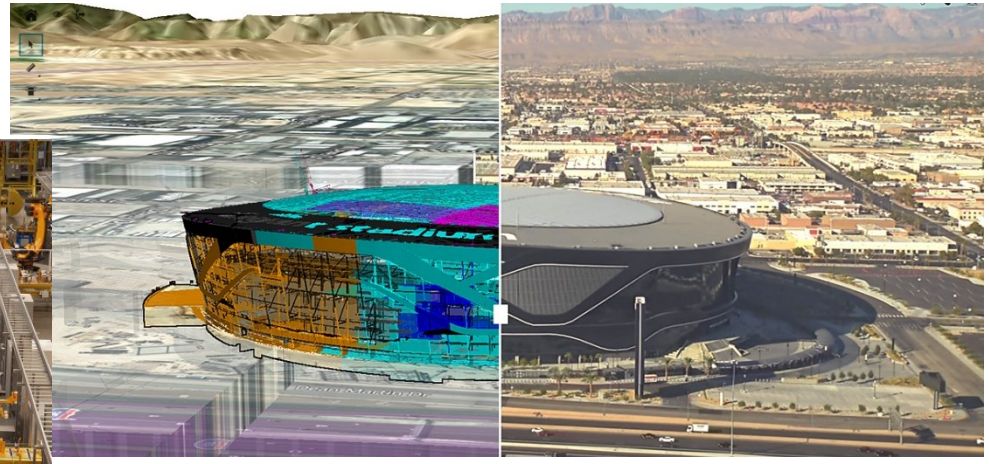
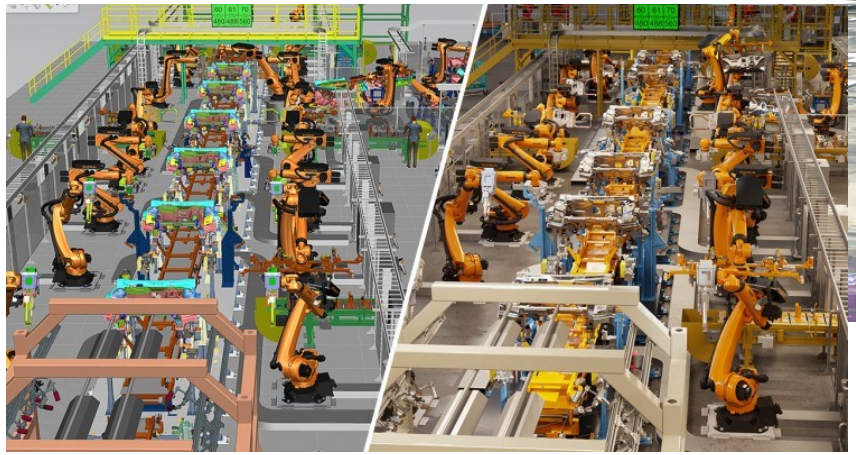


Image credits: https://aec-business.com/earthcam-4d-and-bentley-bring-construction-digital-twins-to-life/

Introduction

- Digital twins are powered by
  - Internet-of-Things/Web-of-Things (IoT/WoT)
  - Big Data
  - Industry 4.0



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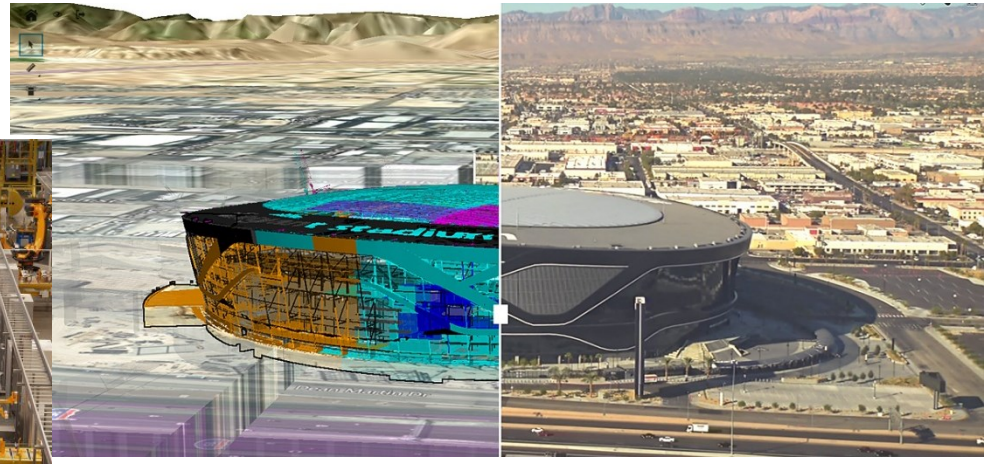

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Introduction

- More recently the concept of digital twins has been adopted in the context of **Smart Cities**
- Digital twin technology can undoubtfully help to face future urban developments in several domains
  - Mobility
  - Environment
  - Energy
  - Urban planning
  - …

Introduction

- According to *VirtualCity* project a smart city digital twin should have six characteristics
  - **Realistic**: The digital twin is a realistic 4-dimensional (in both space and time) visual and acoustic virtual experience of the physical counterpart.
  - **Interactive**: The digital twin is intuitive, accessible, and supports multi-user interaction.
  - **Simulated**: The digital twin is a simulation of the physical twin.
  - **Integrated**: The digital twin is continuously synchronized with the physical twin.
  - **Scalable**: The digital twin is open-ended, scalable from the building to the district to the city level.
  - **Open**: The digital twin is driven by open data and models.

Chalmers University of Technology (2018) Virtual City@Chalmers. https://virtualcity.chalmers.se/about/

Introduction

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A smart city digital twin, even if based on a **3D digital replica** of the urban environment, must go beyond, including **dynamic real-time information**, aggregated in an **accessible interactive interface** where the users can perform **analysis** and **simulations** to study possible evolution of the cities, and from which (with some limits) should be possible to **apply changes** in the real counterpart

Chalmers University of Technology (2018) Virtual City@Chalmers. https://virtualcity.chalmers.se/about/

Introduction

- In (Ketzler et at. 2020) a digital twin is said to be composed by three main layers

Ketzler, B., Naserentin, V., Latino, F., Zangelidis, C., Thuvander, L., & Logg, A. (2020). Digital twins for cities: A state of the art review. Built Environment, 46(4), 547-573.

Introduction

- In (Ketzler et at. 2020) a digital twin is said to be composed by three main layers

A first layer a first layer included the **heterogeneous data types** such as 3D buildings, maps, data from sensors, etc., realizing the so-called **City Information Model (CIM)**.

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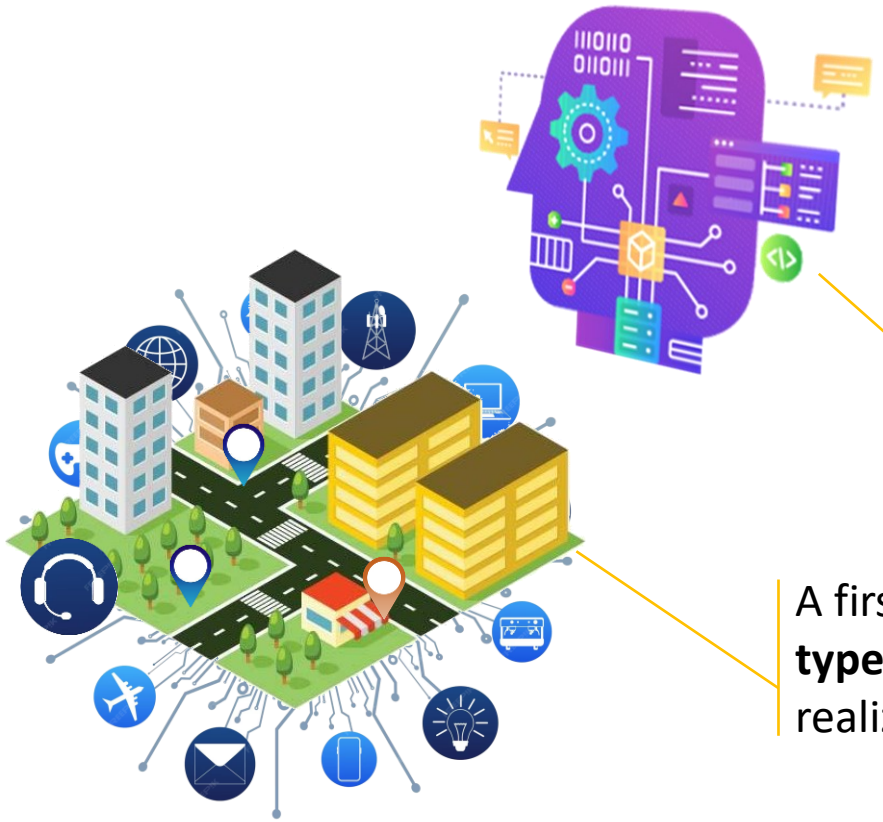

A second layer aimed to cover basic functionalities, communications and can implement **analytics** and **software**. This can be achieved with an adequate IoT/IoE platform able to manage and manipulate huge amount of data.

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A final layer devoted **to visualization and distribution** thought 3D engines and web applications

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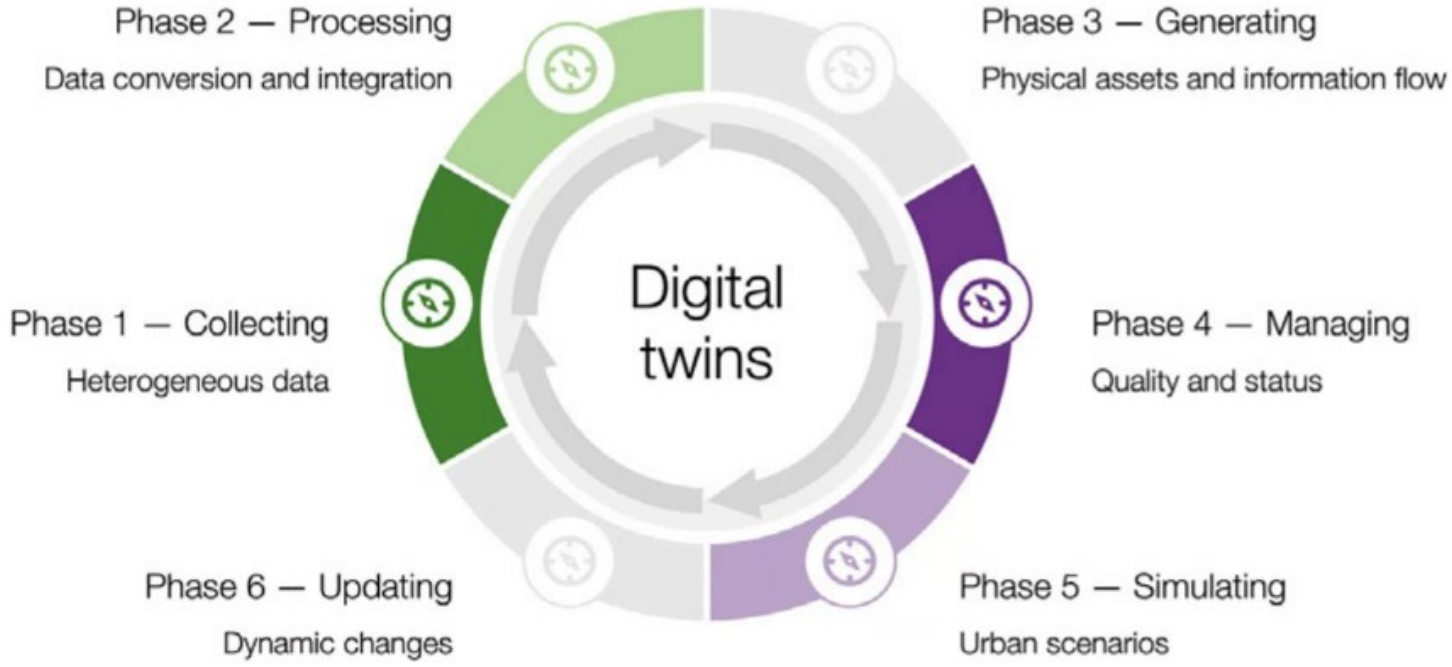
- The three-layer definition is in line with the smart city digital twin life-cycle proposed in (Lei et al. 2023)



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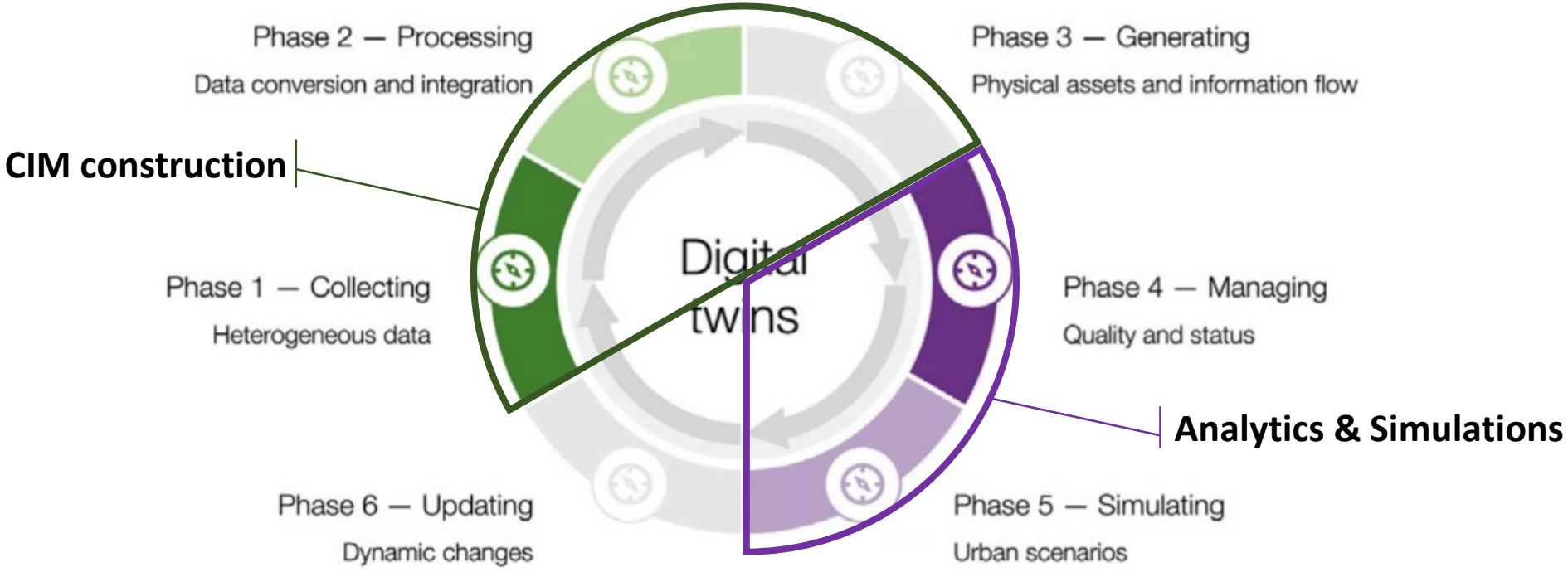

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Requirements

- Based on the literature, we defined a series of requirements to guide the development of a SCDT framework

Field Interoperability

Which function should be included to guarantee an accessible, integrated, and affordable SCDT solution?

Data and Computing for Representation

Which data and software should be included into a SCDT?

Distribution and Interaction

Which kind of user interaction and animation should be offered by the SCDT interface?

Field Interoperability

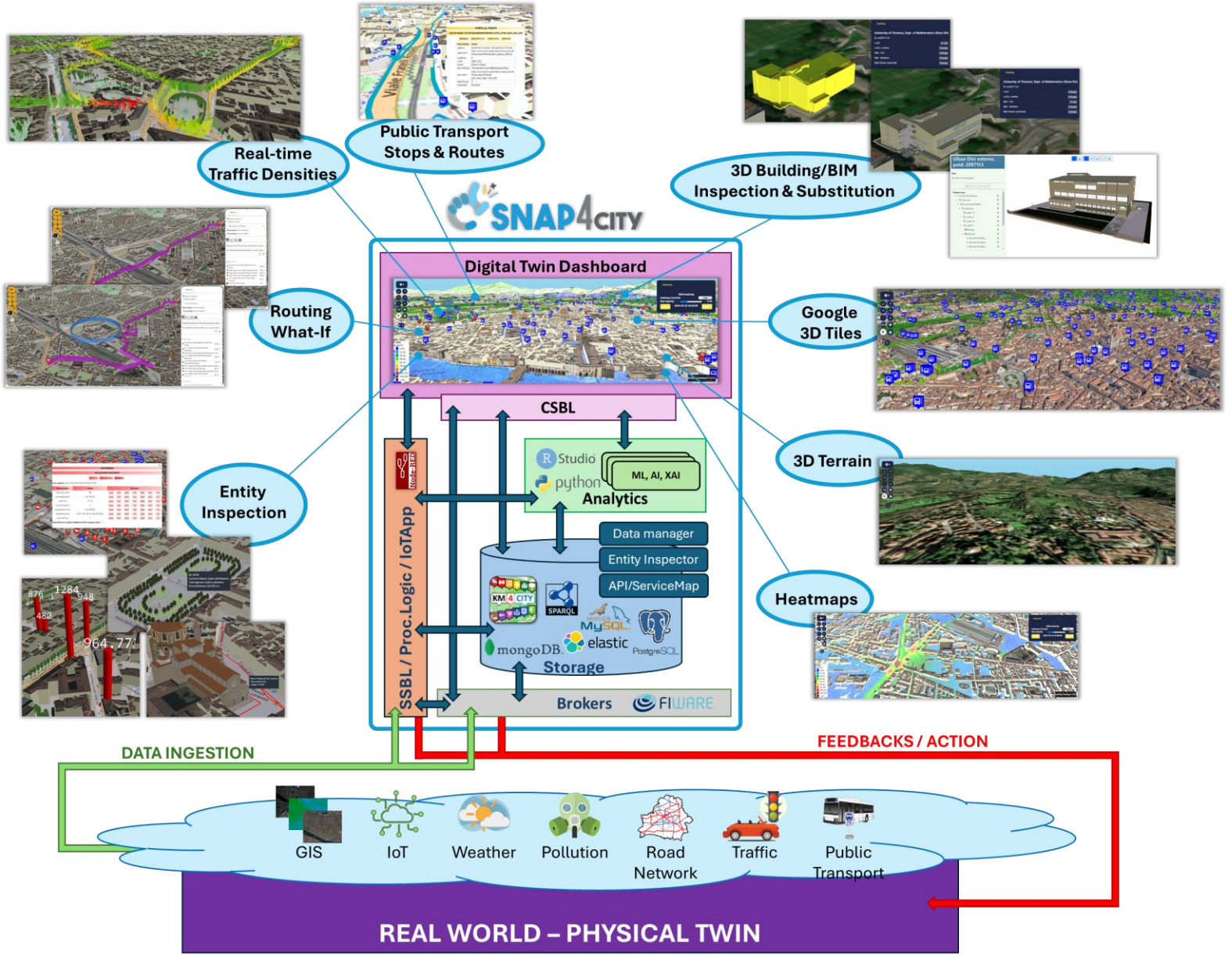
ID	Name	Description	
R1	Network Modeling and Management	The modeling of data networks including gateways, brokers, devices, services and API, external services as web pages, and protocols.	Field Interoperability
R2	Hierarchical modeling of entities	To model data for terrain, city building and shapes (gardens, roads), services, heatmaps, traffic flows, services, IoT devices, public transportation, etc. To be retrievable with relational, geographical, and temporal queries.	
R3	Logics for data transformation	To transform data collected, for example from IoT sensors, and other sources and transform them into different data models and formats. For example, collecting data from some web service, GIS, FTP and process them for interoperability and for ingestion.	
R4	Smart Data Model compatibility	To guarantee interoperable and replicable Smart Cities, interoperability at level of data formats, FIWARE Smart Data Models, etc.	
R5	Smart City Federation	Model and data federation among platforms at level of protocols and APIs	
R6	Integration with workflow management systems	To enable ticket/event management. For example, when a fault is detected, it is highlighted in the SCDT and linked to a CMMS (Computerized Maintenance Management System).	

Data and Computing for Representation

ID	Name	Description	
R7	Terrain information and elevation	Terrain elevation must be taken into account to properly elevate the city buildings and to model city hills and surrounding mountains	Data and computing for representation
R8	Ground information	Road shapes and names, names of squares and localities, etc., exploiting orthomaps, with eventual real aerial view patterns, and the graph road.	
R9	Heatmaps	To be superimposed (with variable transparency) on the ground level without overlapping the buildings, to represent distribution of temperature, pollutant, noise, humidity, vegetation, etc.	
R10	Paths and areas	To be used to describe perimeters/shapes of gardens, cycling paths, trajectories, borders of gov areas, elements of origin destination matrices, traffic flows, people flows, trajectories, pipes, severs, etc.	
R11	Data analytic	Data analytic processes must be available to let the user develops and/or execute specific data analytics: prediction, traffic flow reconstruction, anomaly detection.	
R12	Single Services	To mark the positions of services, IoT Devices, Point of Interest (POI), Key Performance Indicator (KPI), moving devices as fleets, etc.	
R13	Buildings of the city	Each single building should be represented. Multiple LoD could be included: (i) simple LoD1 structures, or (ii) higher LoD structures represented as 3D meshes, and (iii) BIMs	
R14	Automated 3D building construction	(i) 3D buildings must be created automatically, to be able to scale and replicate the SCDT framework; and (ii) the used software must be released with open or free license.	
R15	Additional 3D entities	To augment the realism of the 3D representation. For example (i) trees, benches, fountains, semaphores, and any other city furniture, and (ii) water bodies to better represent rivers, lakes, etc.	

Distribution and Interaction

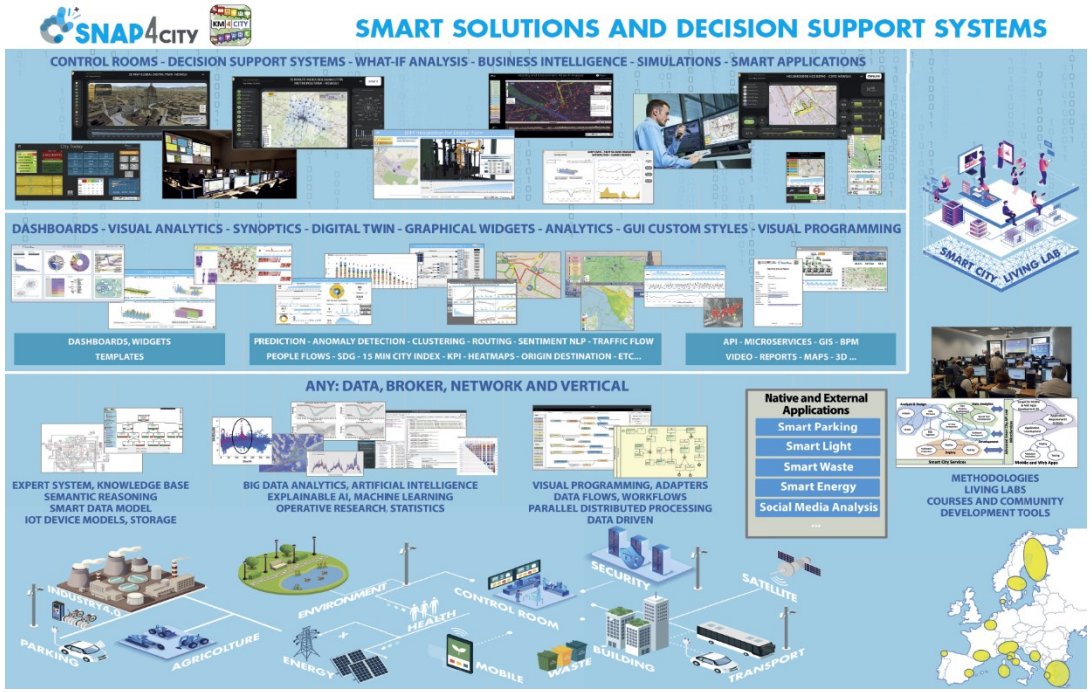
ID	Name	Description	
R16	Dynamic 2D/3D structures	Elements such as PINs, shapes, paths, should be represented in 3D dynamically, changing color and shape according to their kind or some real-time value.	Distribution and interaction
R17	Dynamic data management	To have elements to be automatically reported in the SCDT as soon as they are included in the platform, event driven rendering of data.	
R18	No reloading	Changes in the SCDT must be rendered without the needs of a full reload of the map.	
R19	View Map controls	To change the point of view by zooming, rotating, tilting, and panning the scene.	
R20	Dynamic sky and lighting	To model and show different sky conditions and to change the light source position, simulating different times of day/night.	
R21	Building picking/manipulation	To select single building to: (i) show detailed information, or (ii) move into a BIM view of the building, or (iii) to change the building 3D model.	
R22	Services and element data access	To show data associated with IoT Devices, POI, KPI, shapes, paths, etc., including real time and historical data.	
R23	Independent element management	To hide, show, replace specific elements (e.g., to disable the building view to see only the city PINs, or to load different heatmaps or paths)	
R24	Web player	The SCDT must (i) be accessible thought a web browser without additional plugins, and (ii) the player must be released with open or free license.	
R25	Business logic call-back	To provide the possibility of selecting an element (3D, PIN, ground, heatmap) to provoke a call back into a business logic tool for intelligence activities, analytics, etc.	
R26	Underground and elements inspection	To provide the possibility of selecting and inspecting specific areas and see detailed 3D elements placed underground, such as water pipes, metro lines, etc.	


Real-time Traffic Densities
Public Transport Stops & Routes
3D Building/BIM Inspection & Substitution
SNAP4CITY
Digital Twin Dashboard
Routing What-If
Google 3D Tiles
CSBL
Entity Inspection
Studio
python
ML, AI, XAI
Analytics
3D Terrain
Data manager
Entity Inspector
API/ServiceMap
SSBL / Proc.Logic / IoTApp
KM4 CITY
SPARQL
MySQL
mongoDB.
elastic
PostgreSQL
Storage
Heatmaps
Brokers
FIWARE
DATA INGESTION
FEEDBACKS / ACTION
GIS
IoT
Weather
Pollution
Road Network
Traffic
Public Transport
REAL WORLD – PHYSICAL TWIN

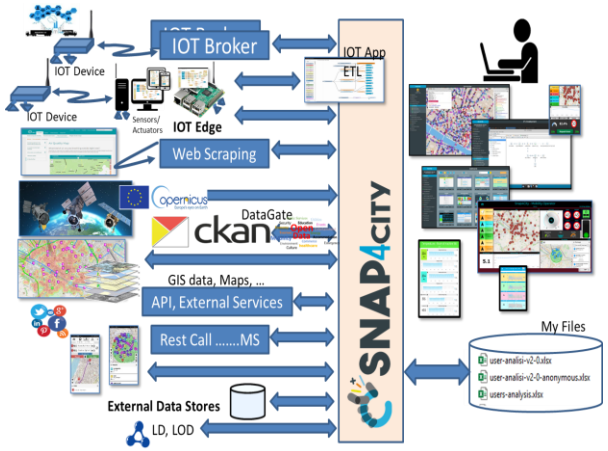
Snap4City Platform

- Snap4City is an **open-source IoT platform** developed at **DISIT Lab**, with continuous evolution from 2016 (Sii-Mobility project)

Sii-Mobility

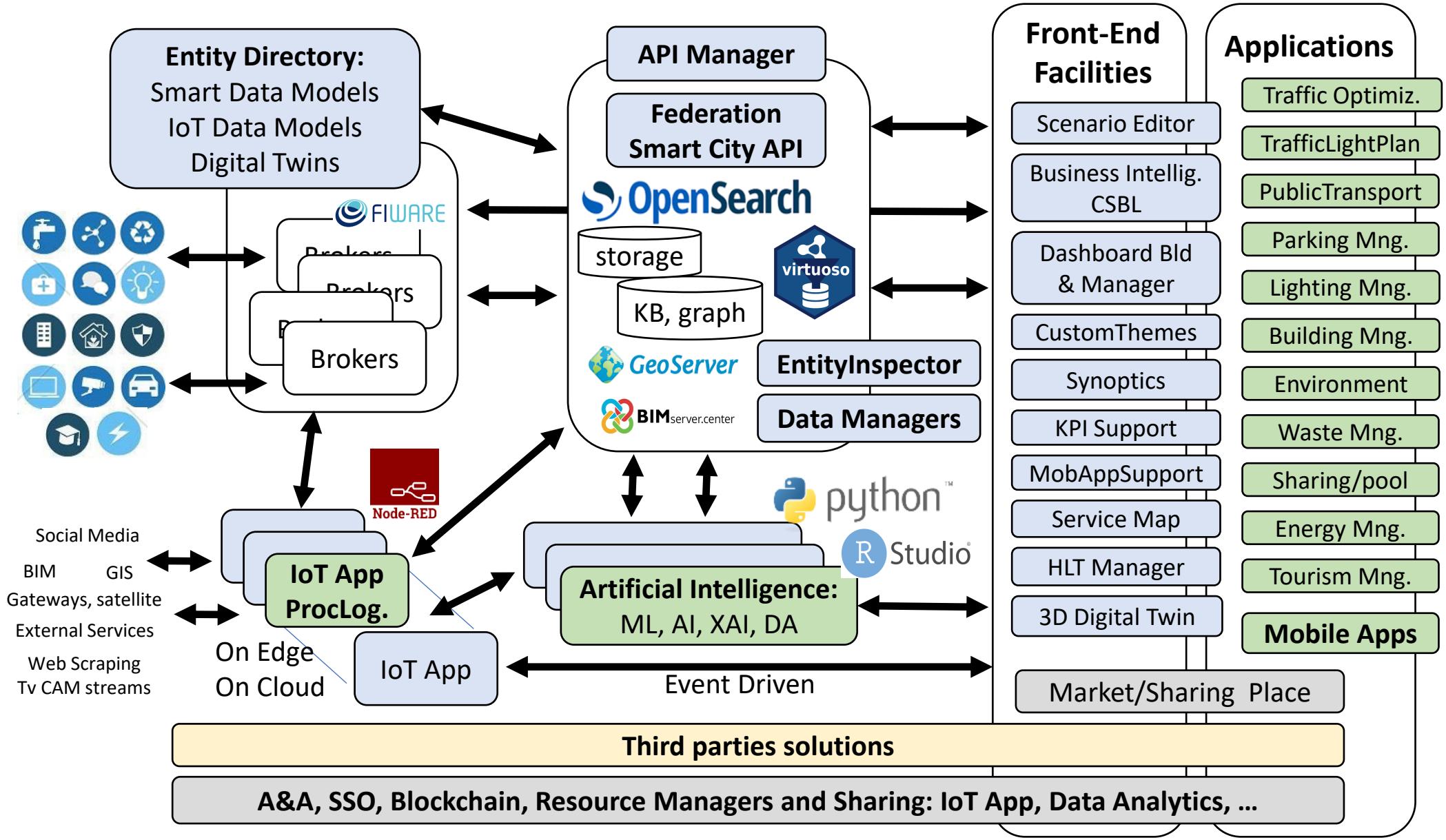


- The platform manages **heterogeneous data sources** (IoT devices, Open Data, external services, etc.)

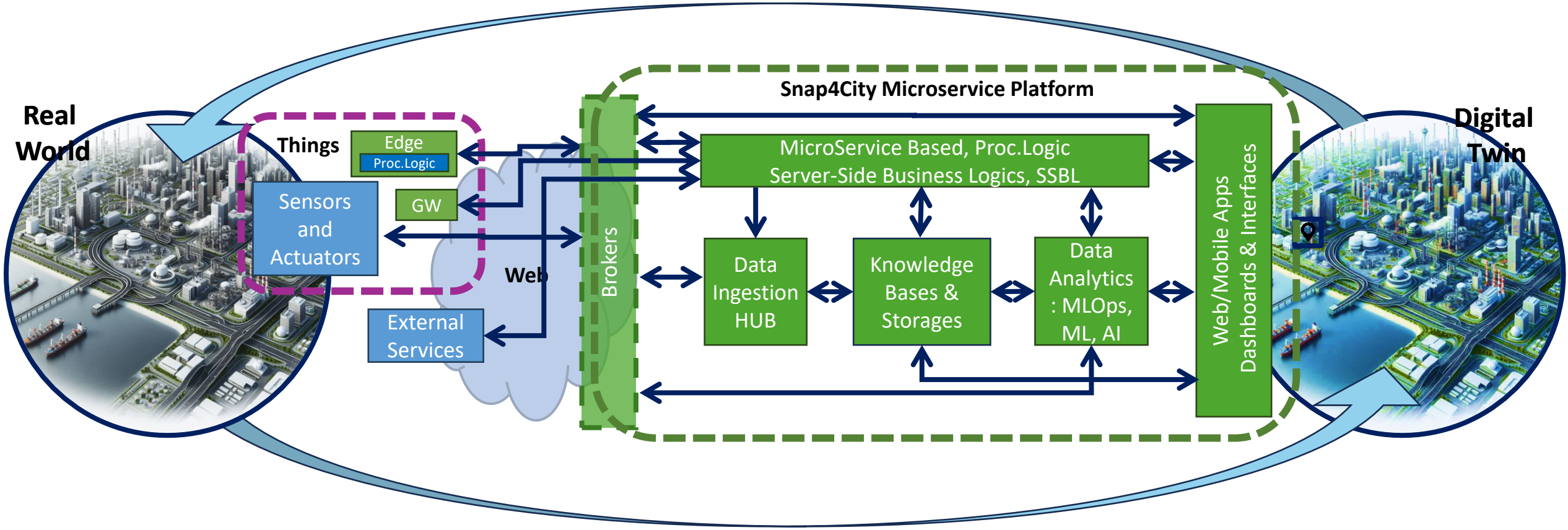


- Data retrieved by dedicated APIs and exploited by **Data Analytics processes** and **IoT applications** can be shown to the user through **dashboards** and **widgets**

100% OPEN SOURCE
Powered by FIWARE
FREE TRIAL
PEN Test Passed
EU GDPR COMPLIANT
SNAP4 Appliances and Dockers Installations
EUROPEAN OPEN SCIENCE CLOUD
Node-RED
JS Foundation
EØ15 digital ecosystem
NVIDIA

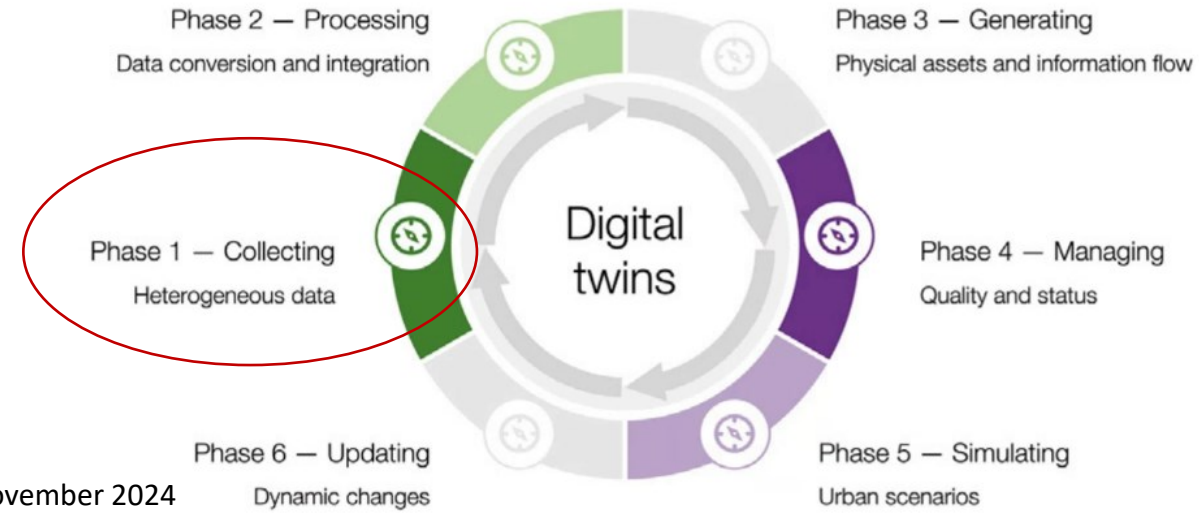

Entity Directory:
Smart Data Models
IoT Data Models
Digital Twins
API Manager
Federation
Smart City API
OpenSearch
storage
KB, graph
virtuoso
GeoServer
BIMserver.center
EntityInspector
Data Managers
FIWARE
Brokers
Brokers
Brokers
Node-RED
python
RStudio
Social Media
BIM
GIS
Gateways, satellite
External Services
Web Scraping
Tv CAM streams
IoT App
ProcLog.
On Edge
On Cloud
IoT App
Artificial Intelligence:
ML, AI, XAI, DA
Event Driven
Front-End
Facilities
Scenario Editor
Business Intellig.
CSBL
Dashboard Bld
& Manager
CustomThemes
Synoptics
KPI Support
MobAppSupport
Service Map
HLT Manager
3D Digital Twin
Applications
Traffic Optimiz.
TrafficLightPlan
PublicTransport
Parking Mng.
Lighting Mng.
Building Mng.
Environment
Waste Mng.
Sharing/pool
Energy Mng.
Tourism Mng.
Mobile Apps
Market/Sharing Place
Third parties solutions
A&A, SSO, Blockchain, Resource Managers and Sharing: IoT App, Data Analytics, …

Snap4City Platform



SCDT Development Phases

- **Data acquisition**: city graph, IoT sensor/actuators, POIs, orthomaps, paths, digital surface model (DSM) and terrain elevation (DTM), images, etc.



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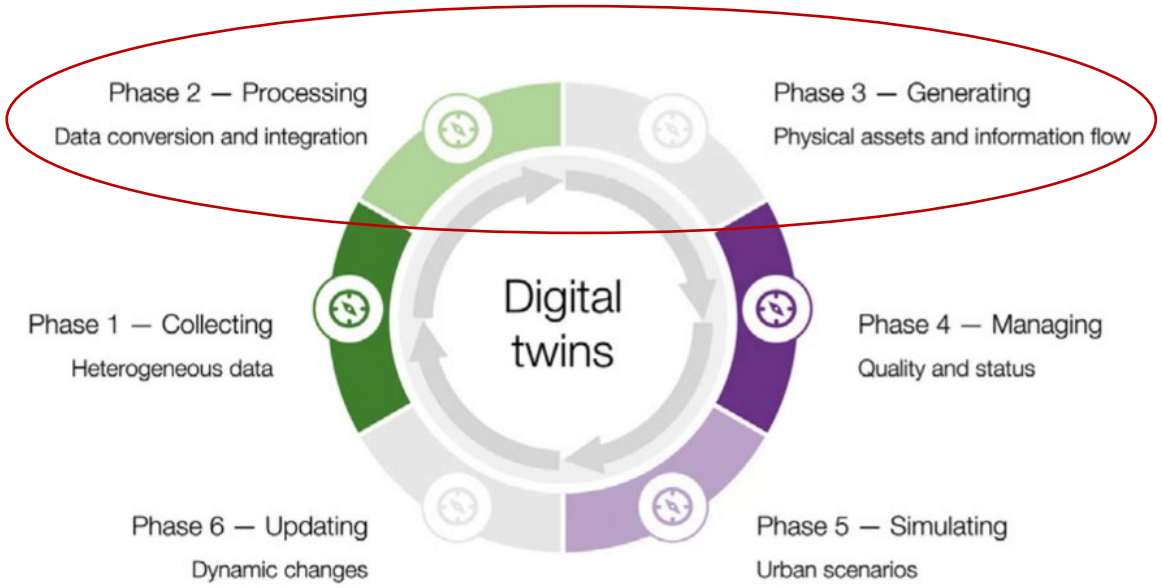

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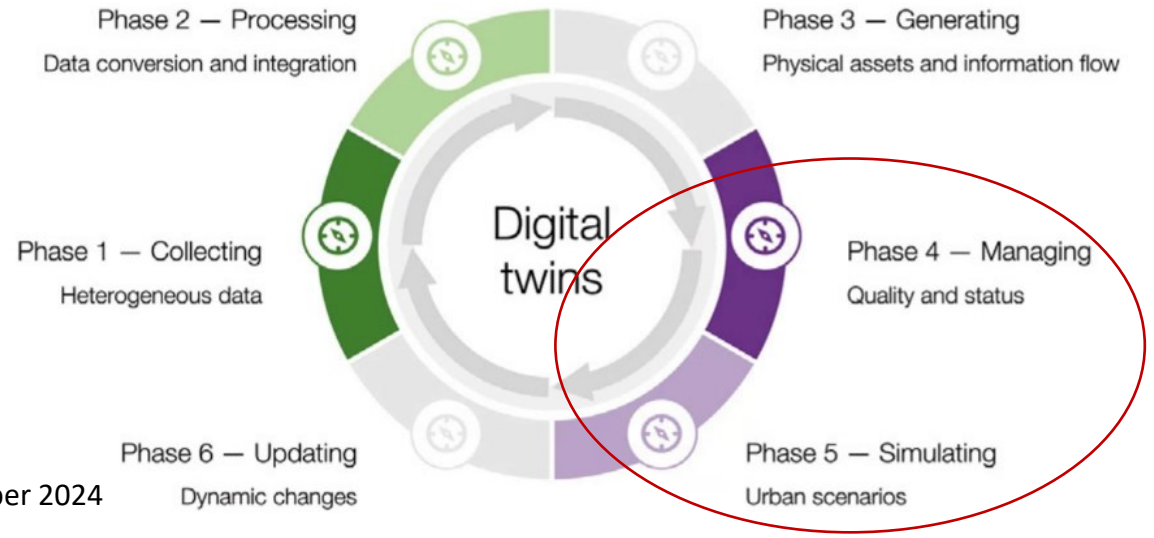
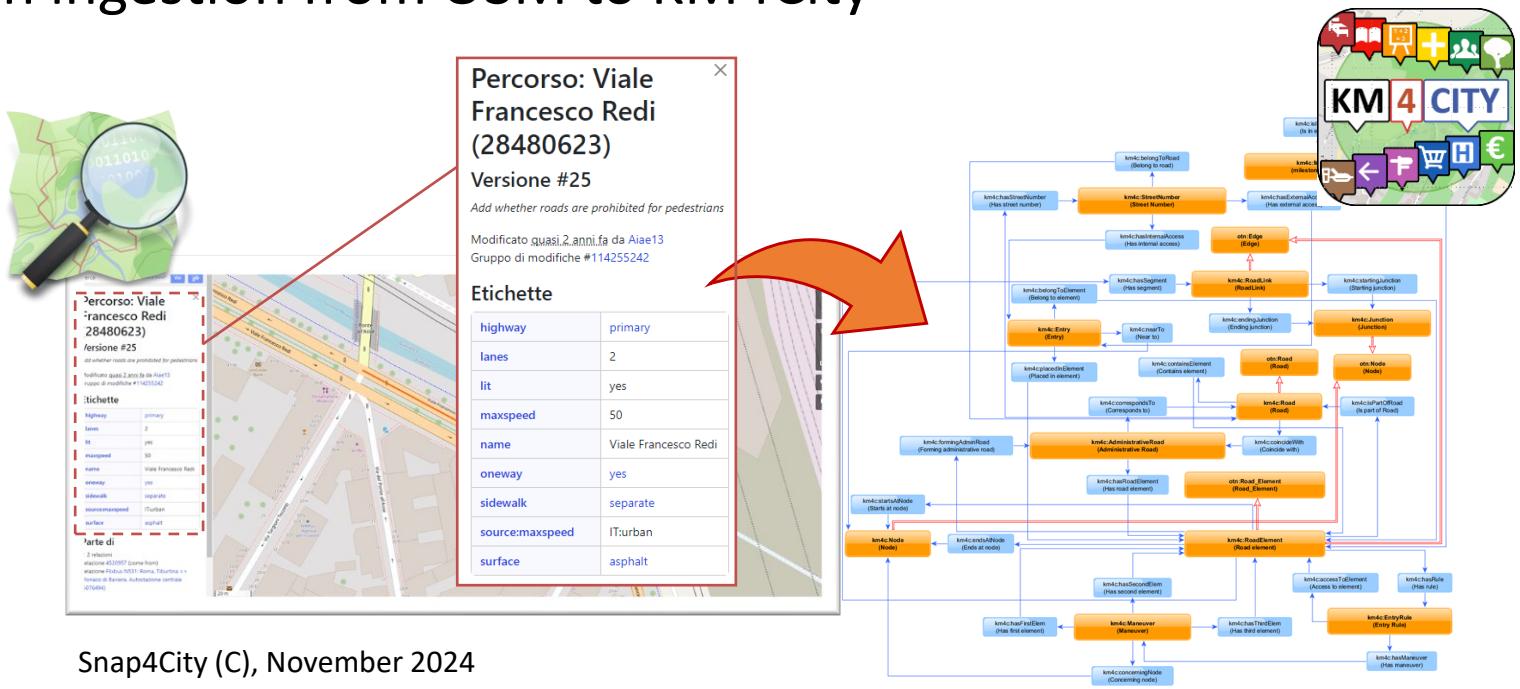
- **Integration and distribution**: acquired and produced data are integrated into a global digital twin model and rendered as 3D multi-data map and distributed as an interactive web interface.



Data acquisition

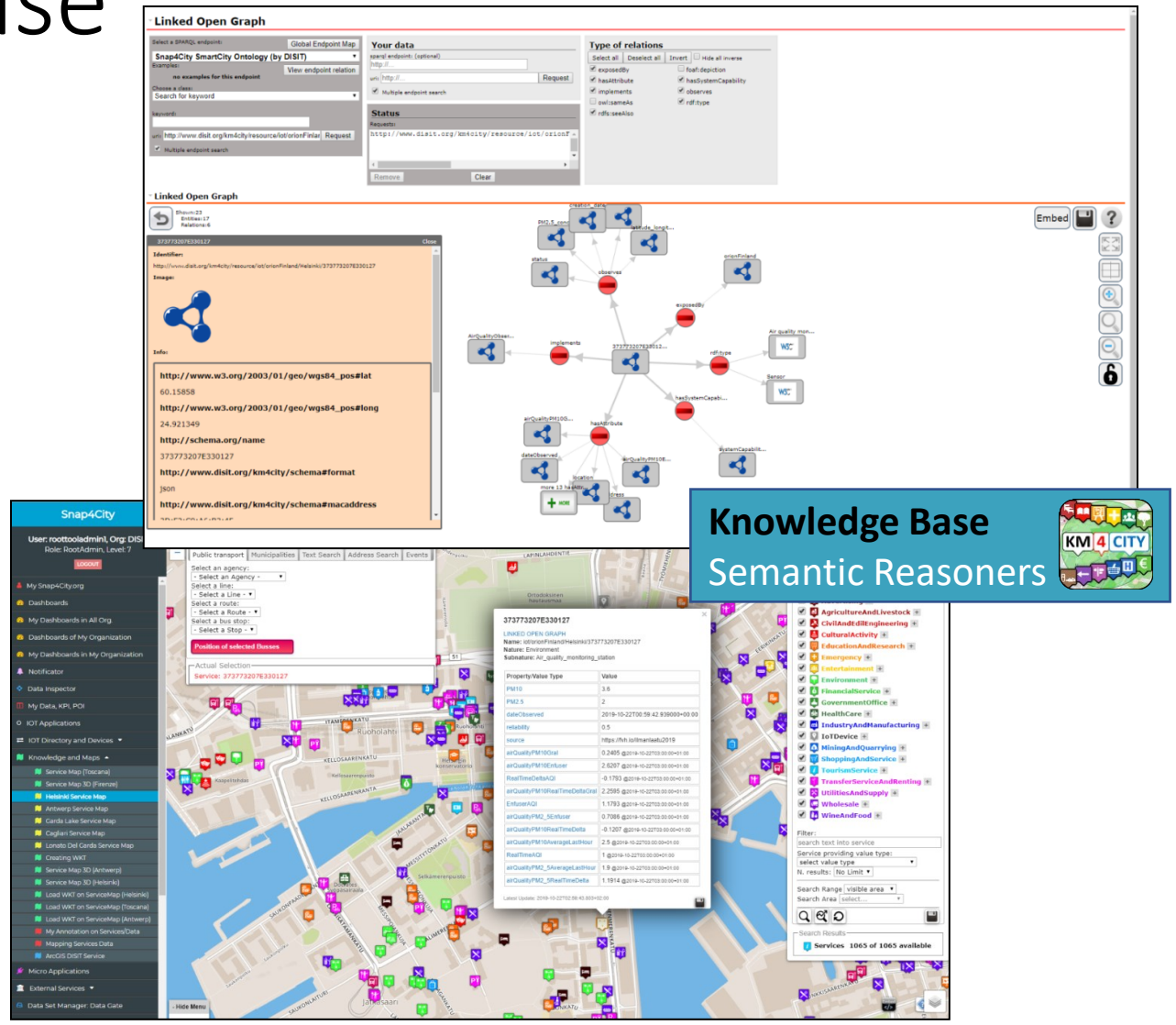
- Data acquisition is handled directly by the Snap4City platform
  - **Static data** are ingested with ETL process and sent to the KB or to specific databases, e.g., road graph ingestion from OSM to KM4City



KM4City Knowledge Base

- Collected static and real-time data are **semantically indexed** in a graph based RDF Knowledge Base, named **KM4City**

- Several API have been defined in order to **retrieve data from the KB** using relational, spatial, and temporal queries



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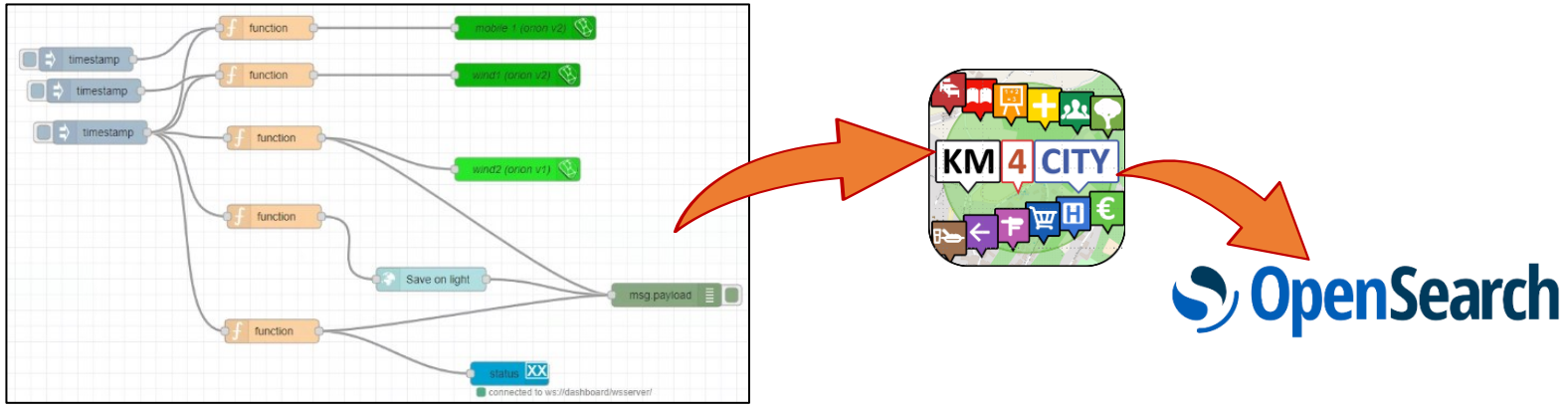
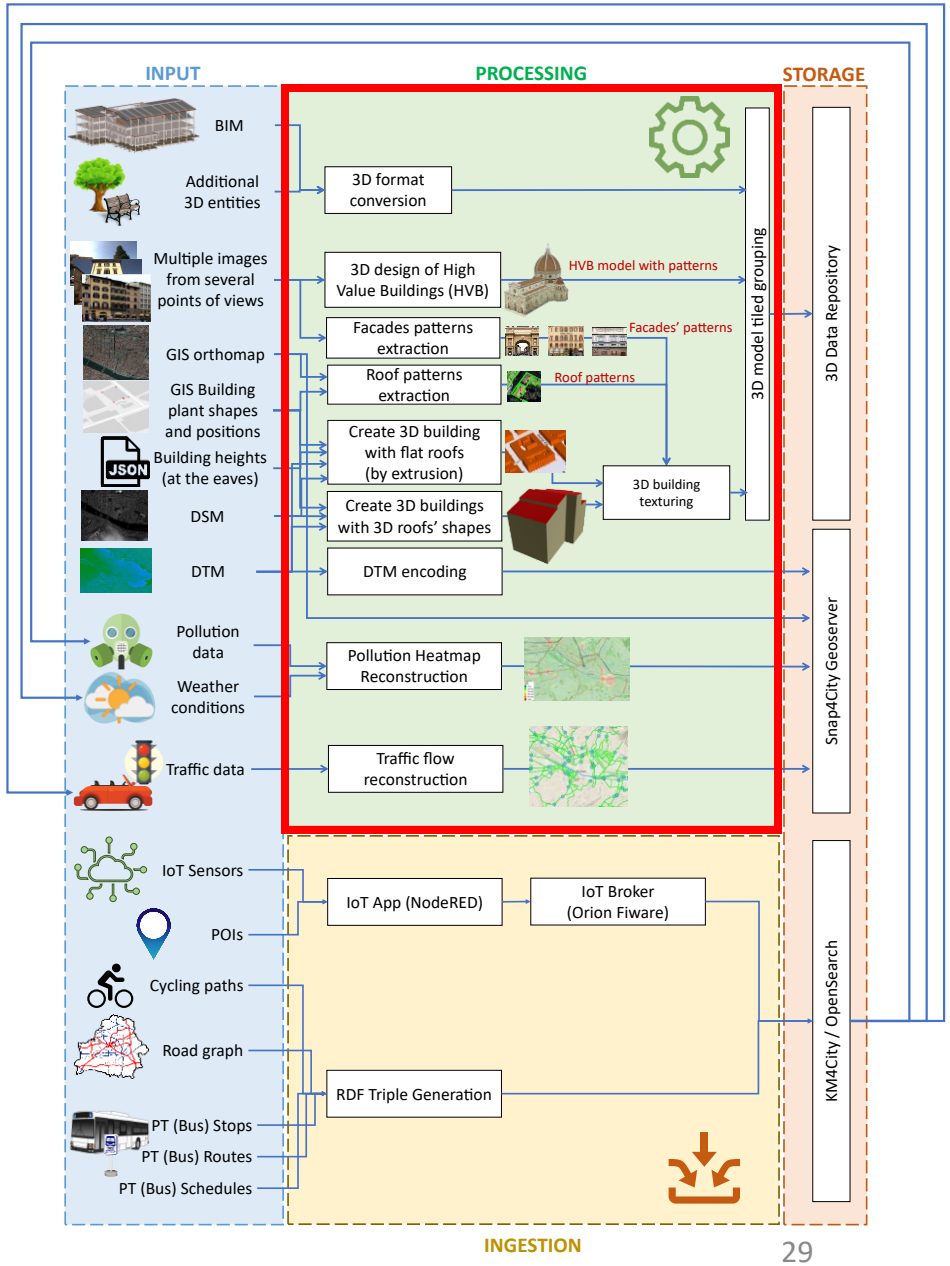
  - **Real-time data** from IoT sensors can be ingested using IoT App (i.e., NoreRED flows) and sent to an OpenSearch cluster for indexing



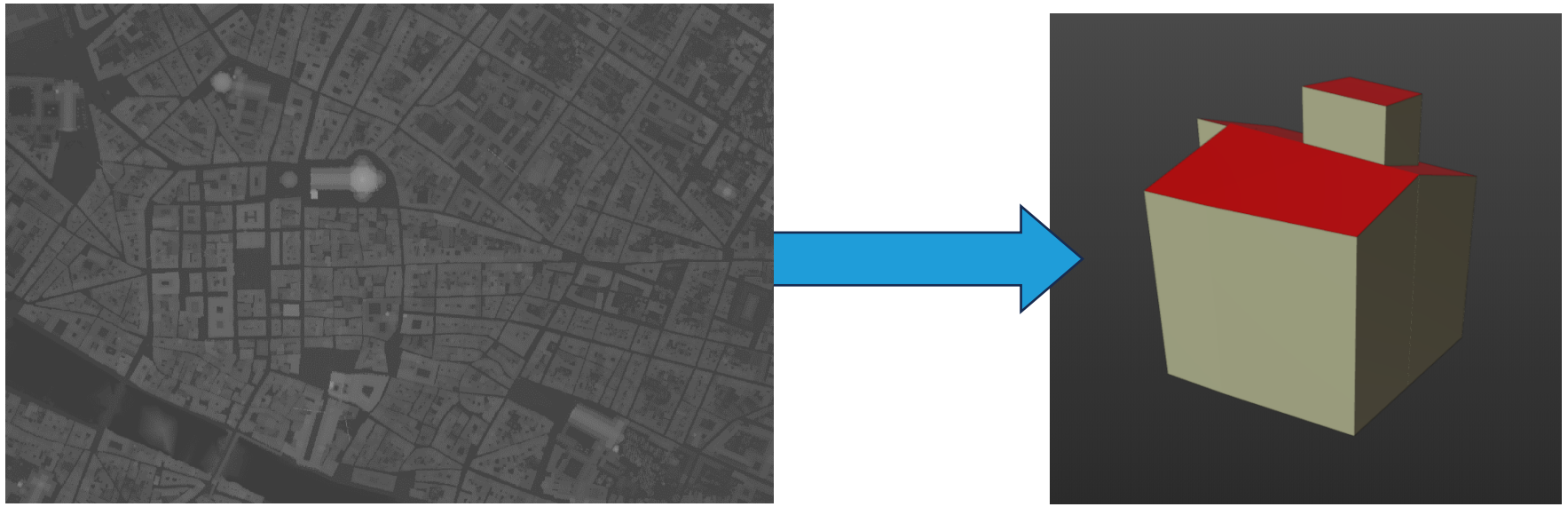
Production

- Ingested data can then be used as input for analytic processes in order to obtain
  - Traffic flow reconstruction
  - Heatmaps, e.g., to describe the pollutant dispersion
  - Etc…
- In this phase, the 3D map to be shown in the SCDT is built



3D Map Production

- To obtain 3D building models, a **Digital Surface Model (DSM)** of Florence was used
- Our algorithm exploits also the **OSM building shapes**, in order to segment building patches from the DSM

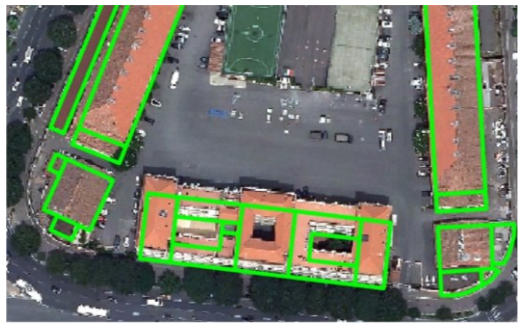


Rooftop texturing

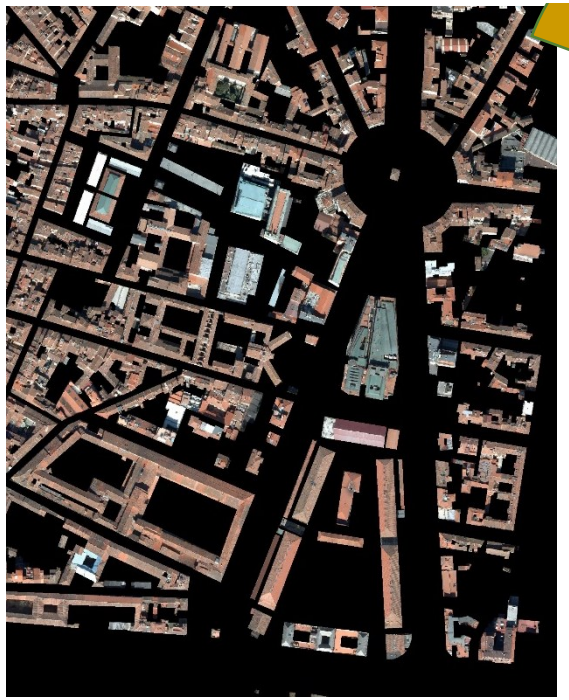
Orthomaps

Building shapes

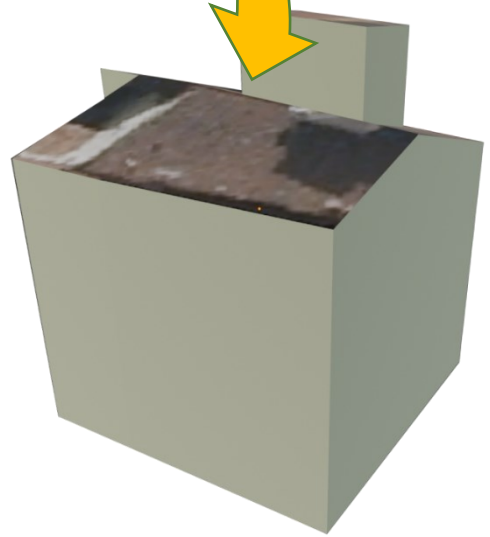
Input



Deep network alignment



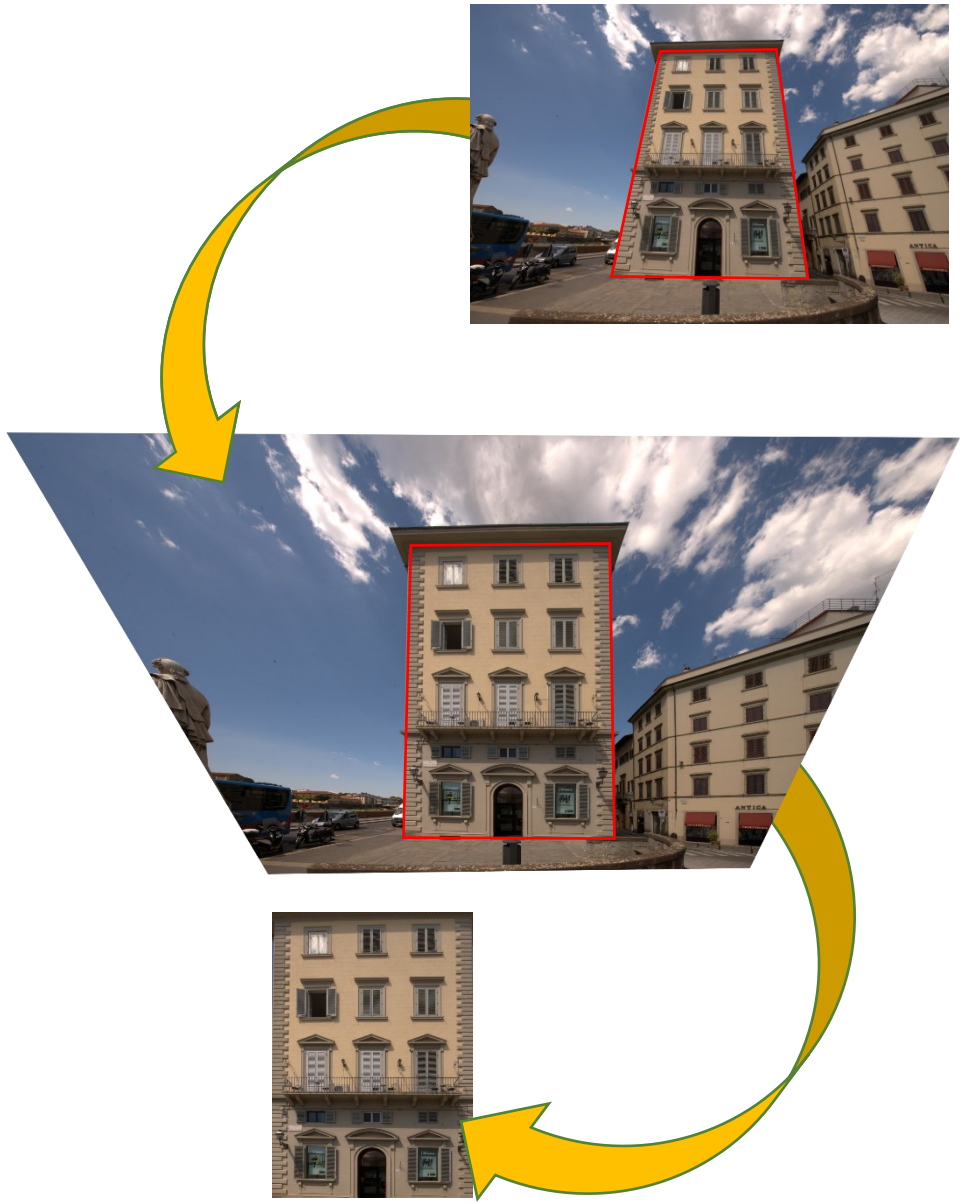
Rooftop texture extraction and warping



Apply the texture on the 3D model

Façade texturing

- Façade texturing is more difficult
  - It requires specific acquisition campaign
  - A single photo can include few buildings simultaneously
  - Perspective and radial distortion must be removed
  - Building façades must be segmented from the image



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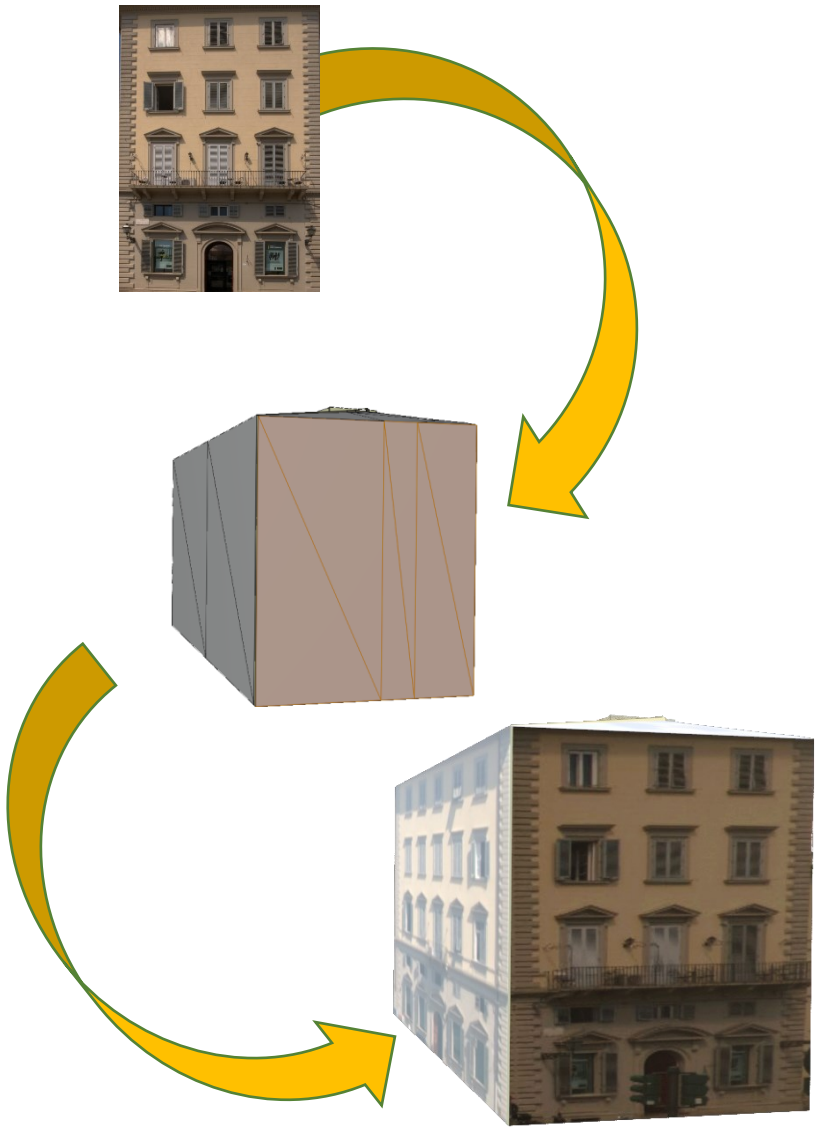
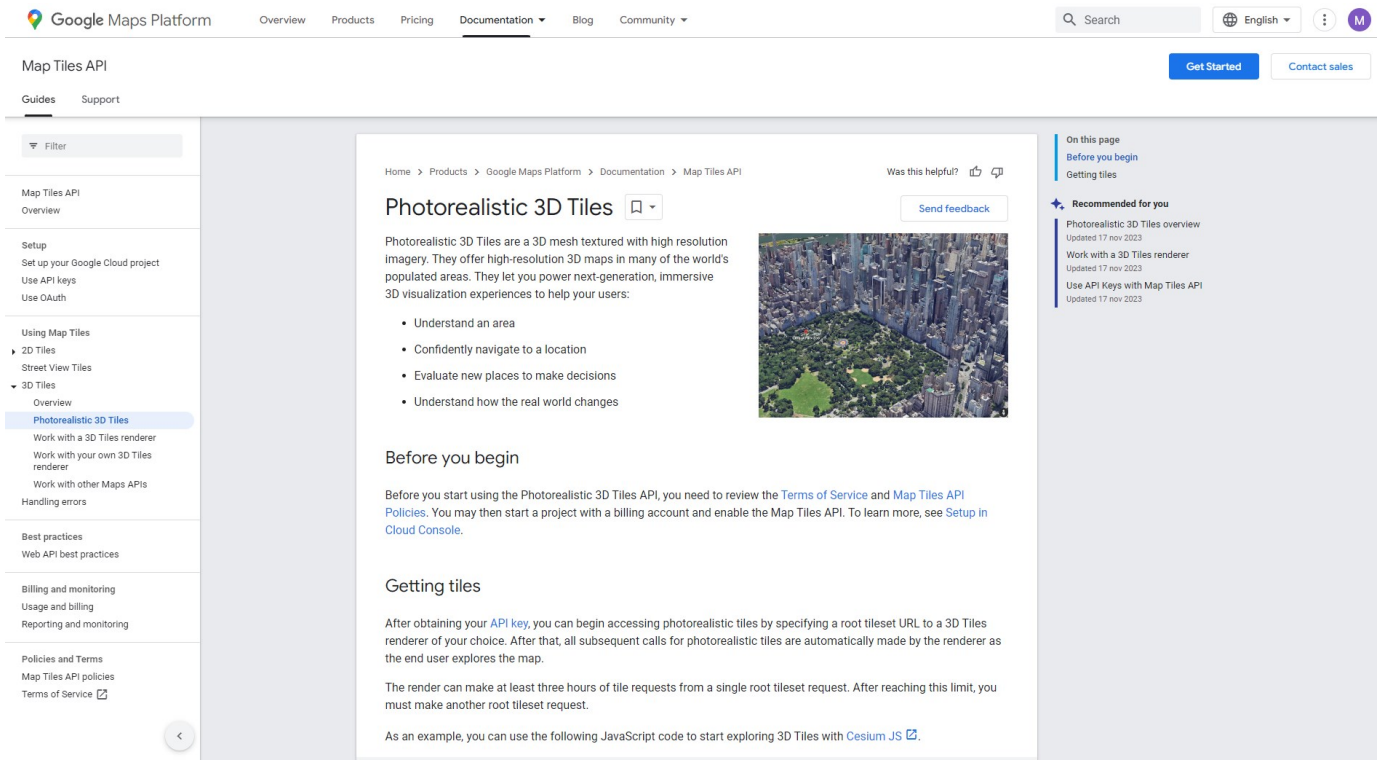
  - The correct 3D model face must be selected to apply the texture

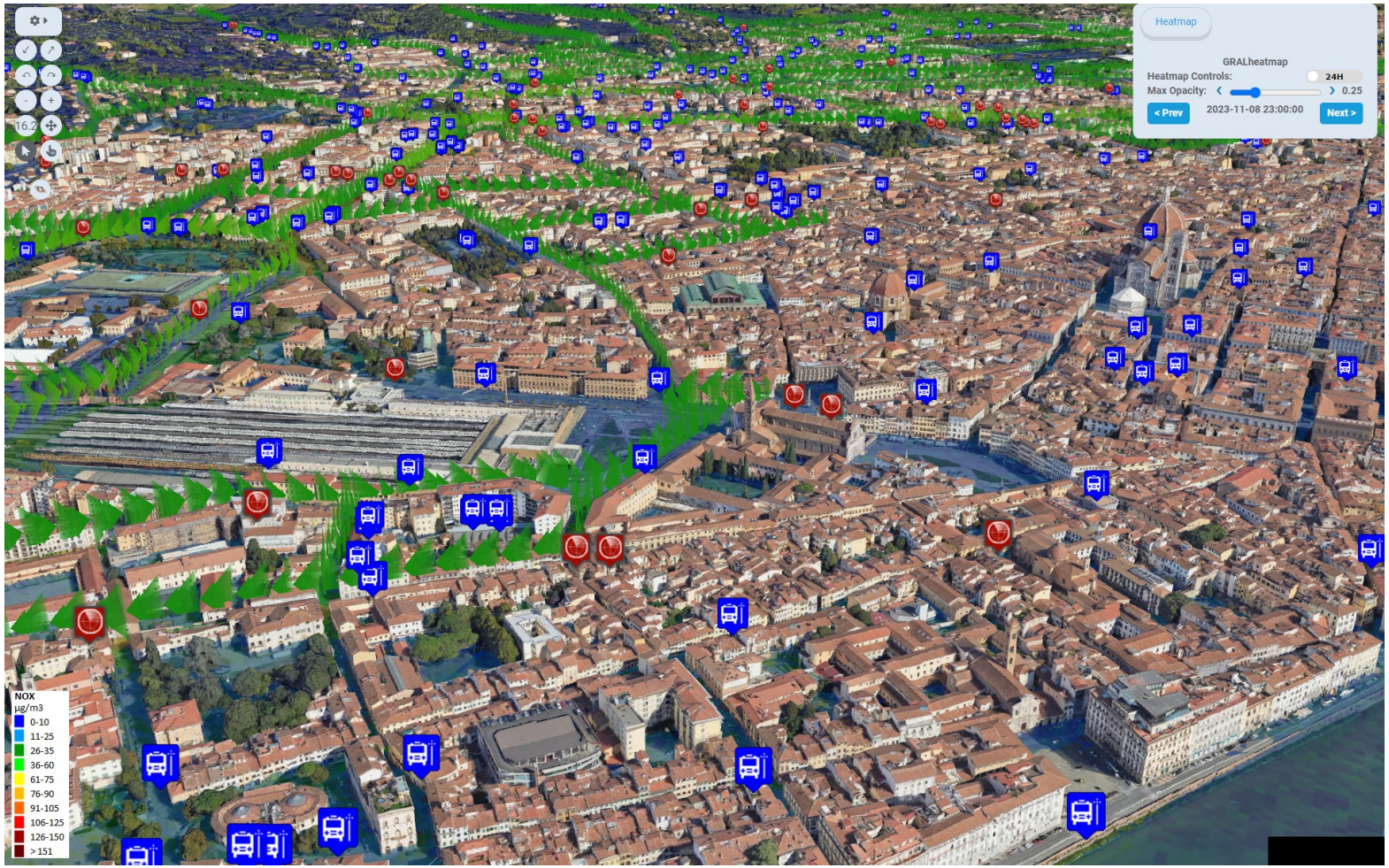


Google 3D Tiles

- Recently, Google released photorealistic 3D tiles
- REST API can be used to query the Google servers and retrieve 3D tiles of good quality to be shown in your web application



Google 3D Tiles



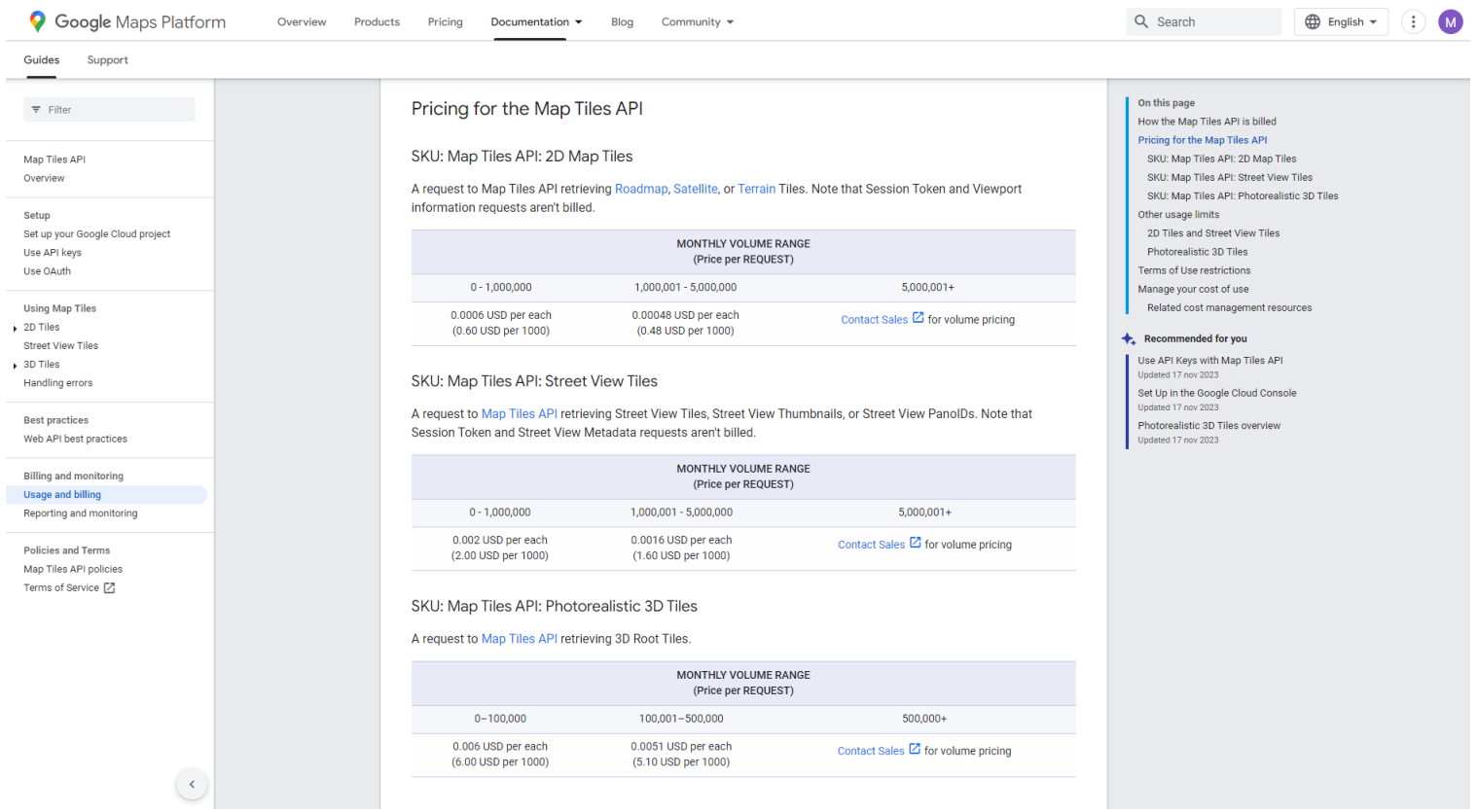
Florence, Italy

Google 3D Tiles

Helsinki, Finland

Google 3D Tiles

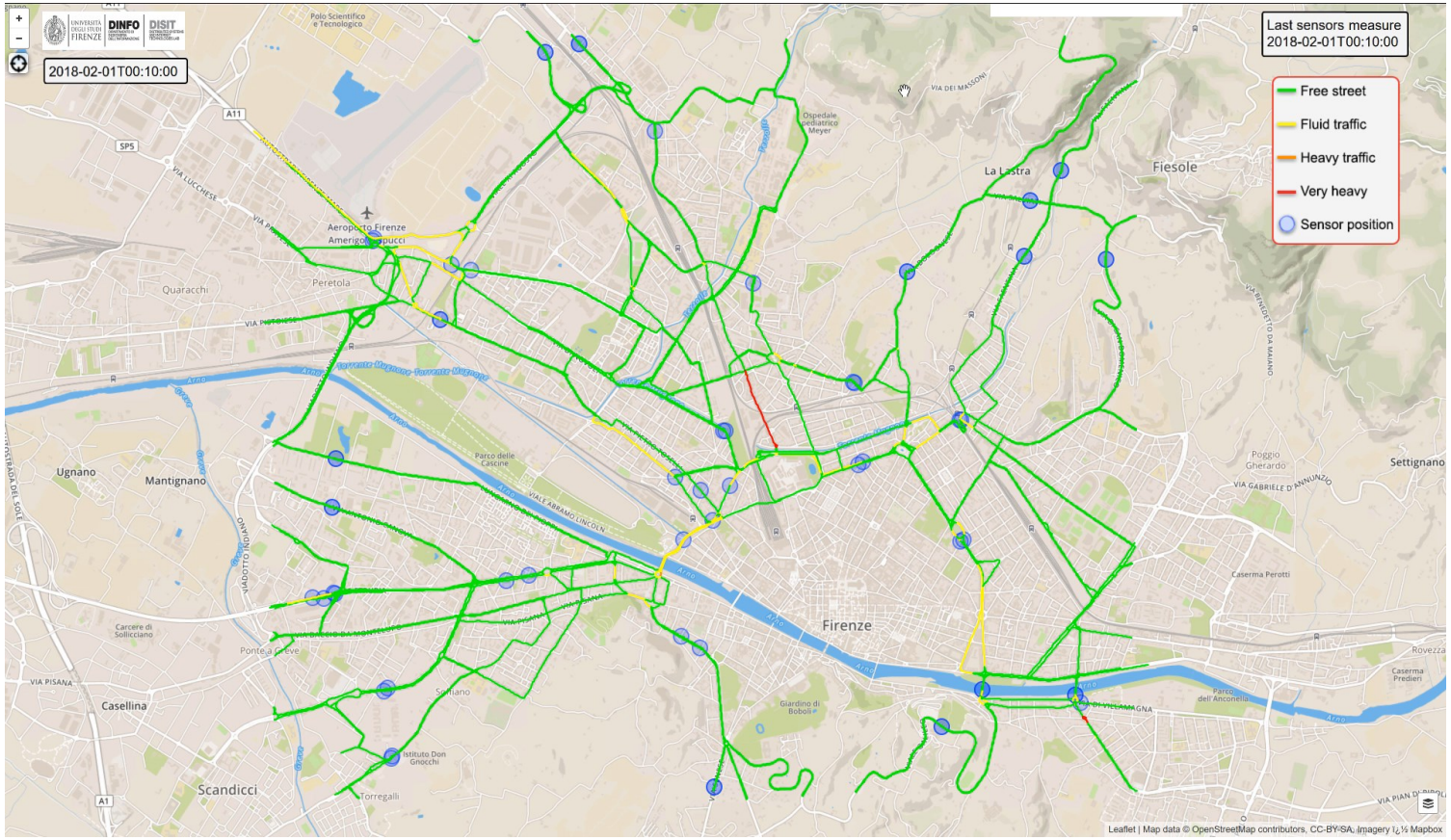
- The service is **not free**
- A per-request cost is applied
- Careful consideration must be taken when designing your web application



Data Analytics in Snap4City

More than **90 data analytics processes** are available!

- **Traffic flow reconstruction** based on a fluid-dynamic model



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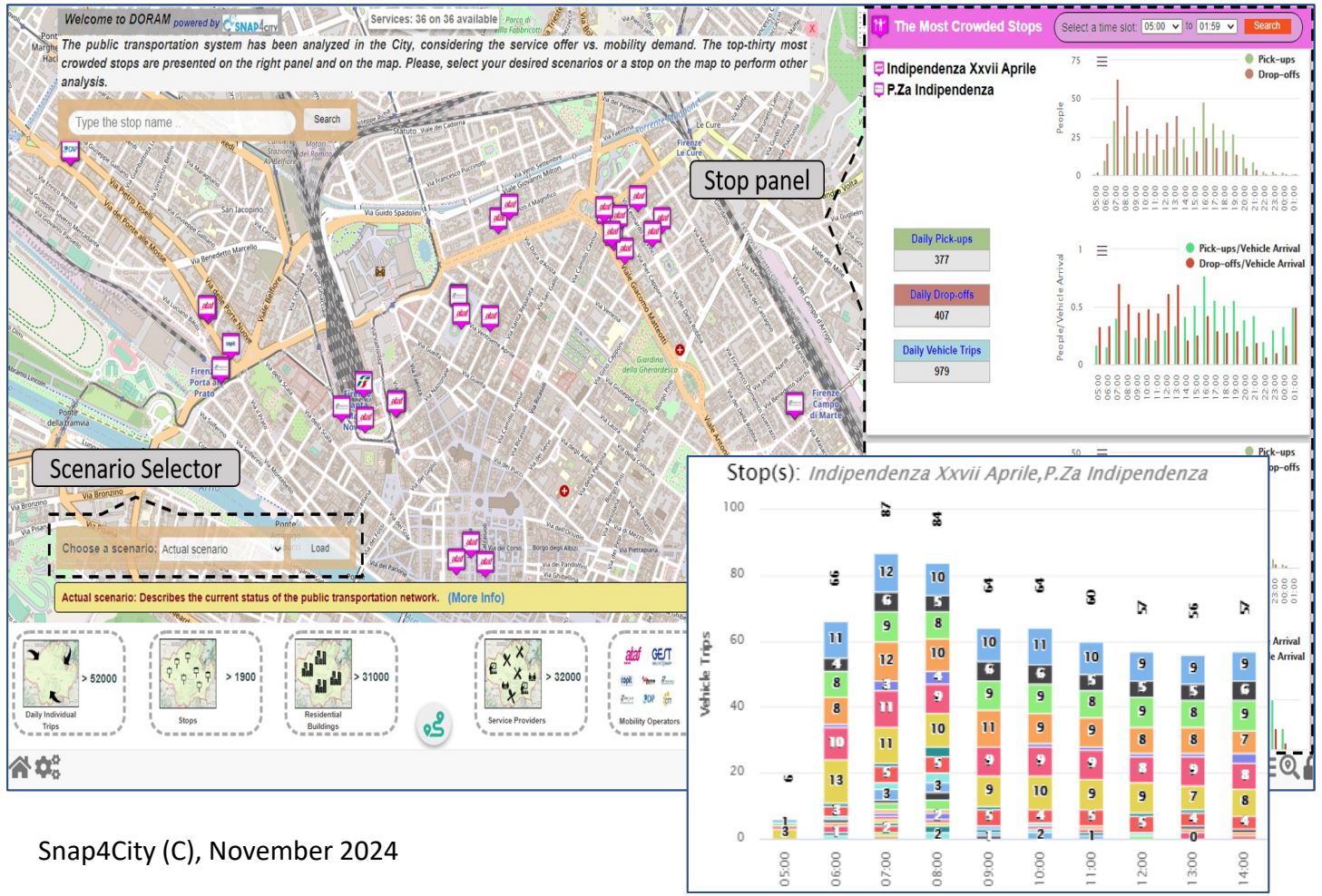

Data Analytics in Snap4City

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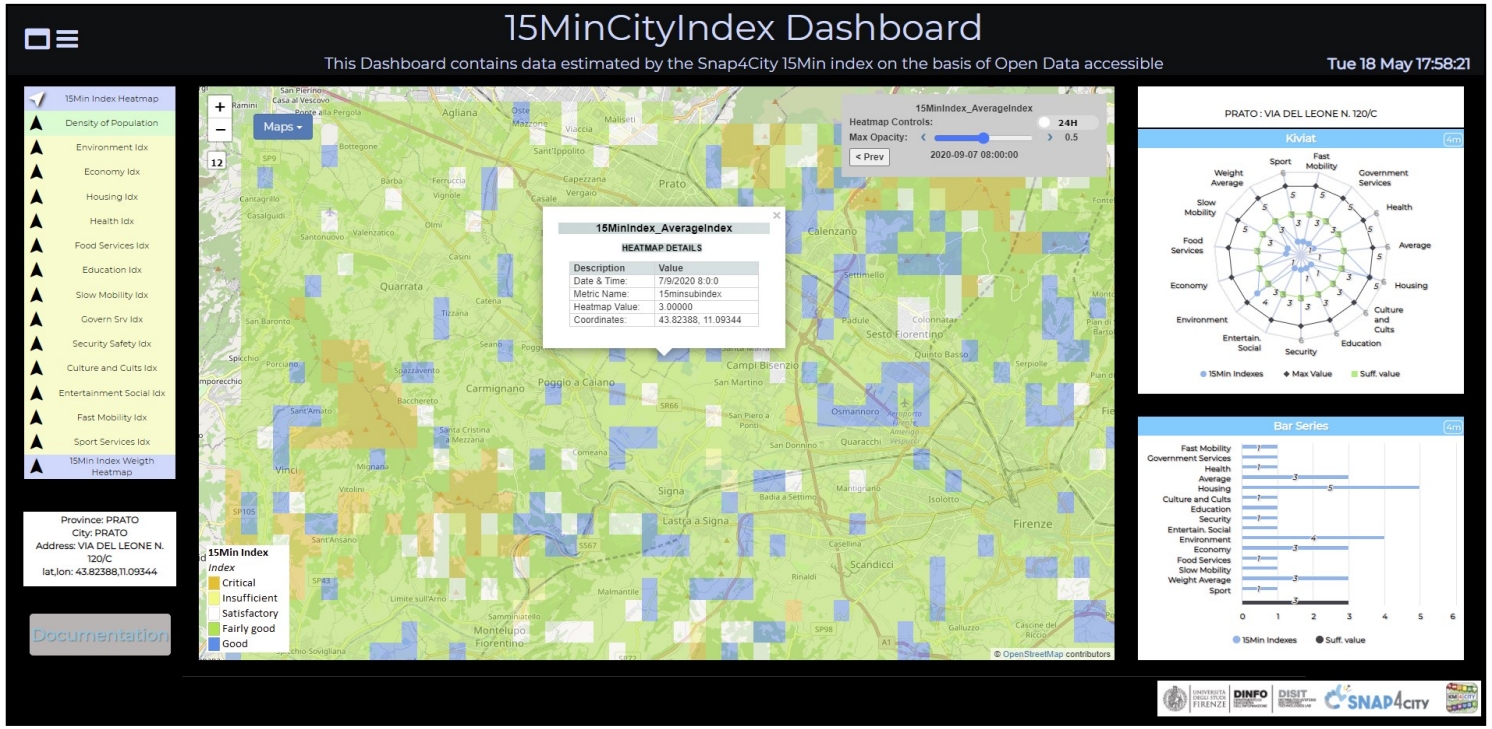
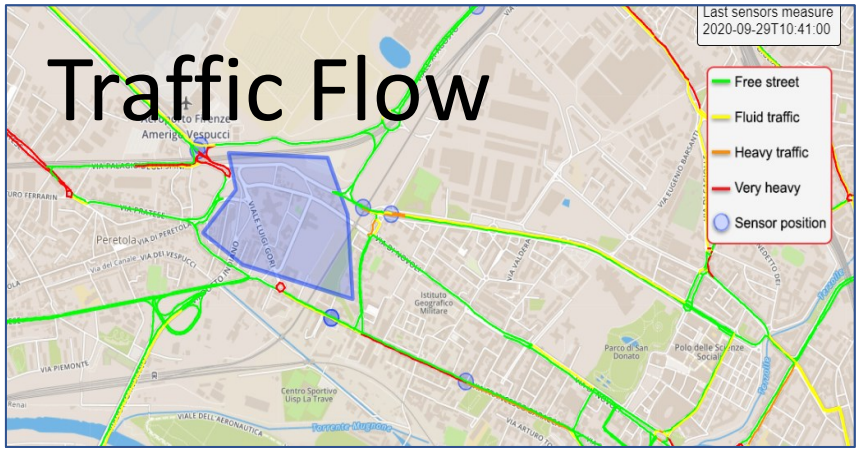


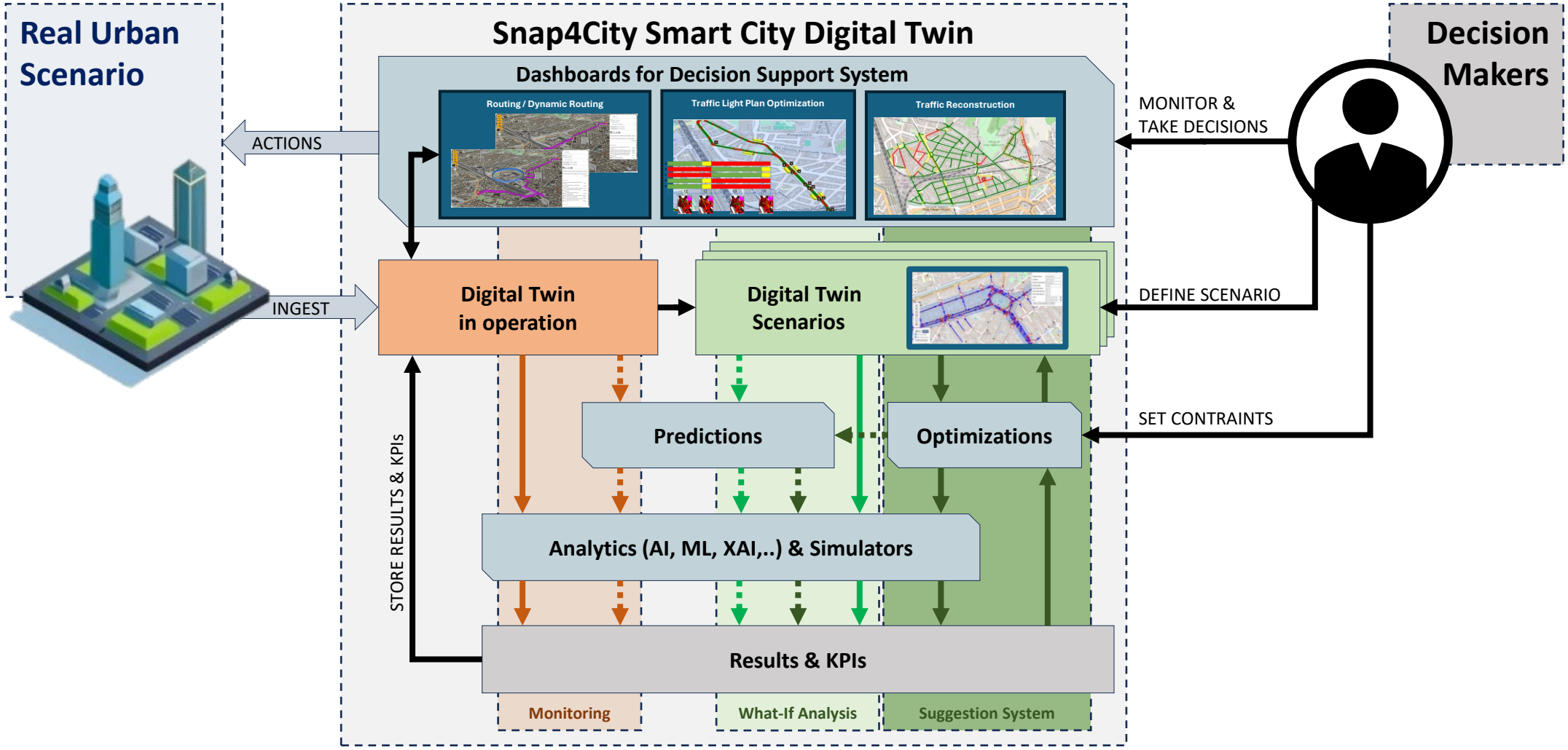
Data Analytics in Snap4City

More than **90 data analytics processes** are available!

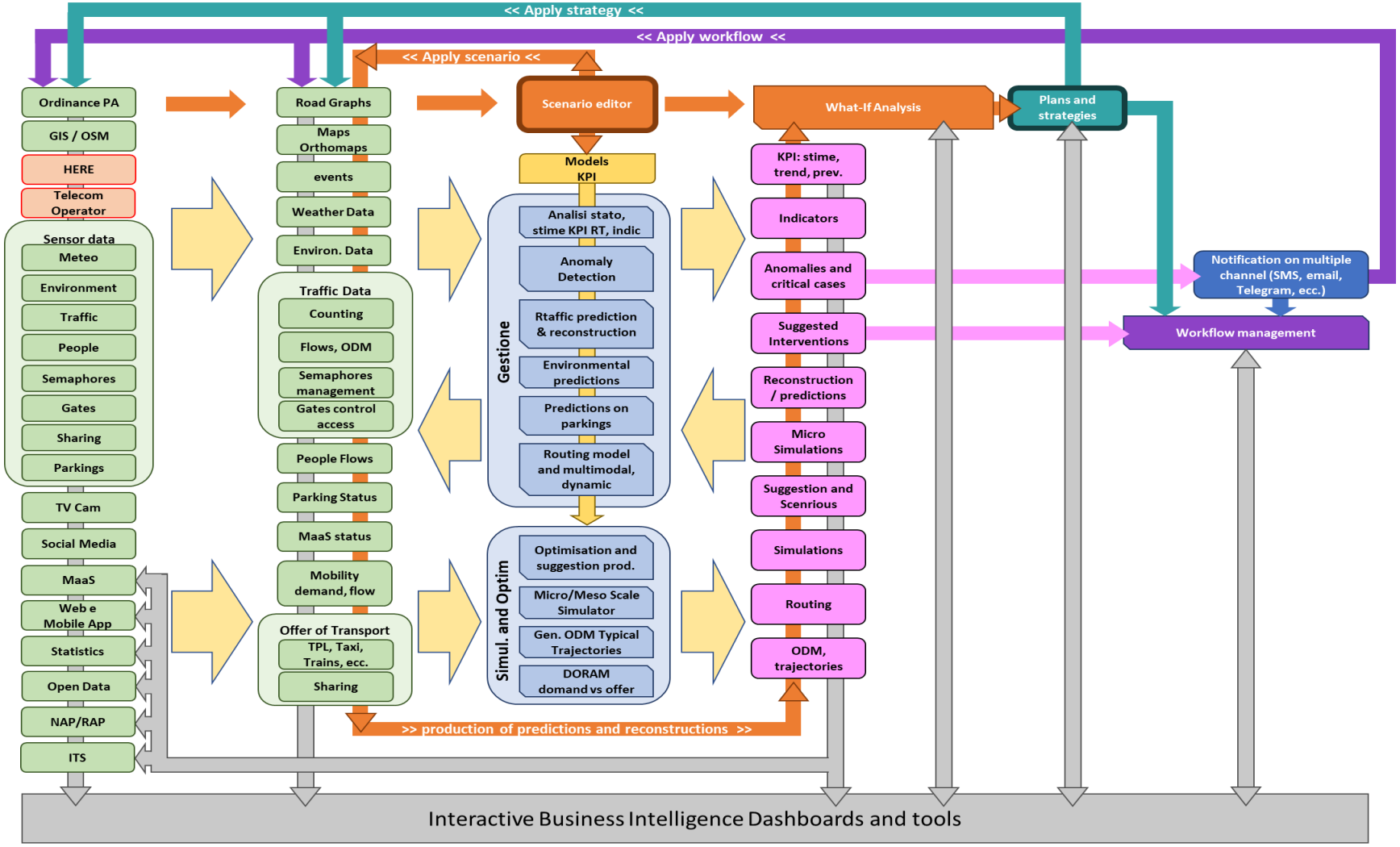
- **Traffic flow reconstruction** based on a fluid-dynamic model
- Analysis of **public transport offer and demand**
- Assessment of the **15-minute index**
- Capabilities to perform **What-If analysis**



Smart City Digital Twin Uses



What-if analysis



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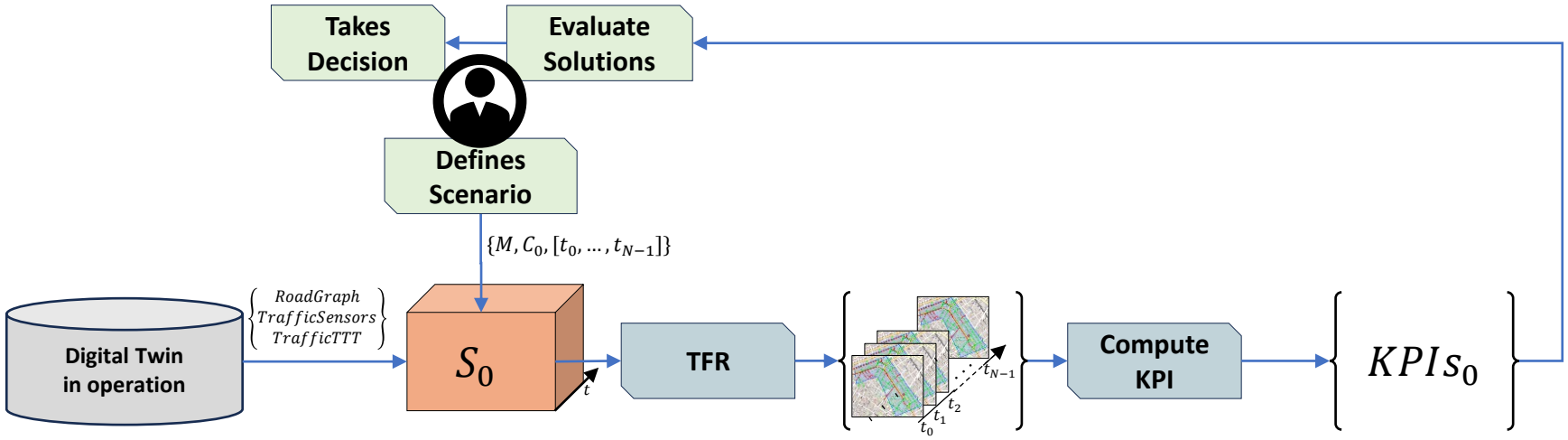
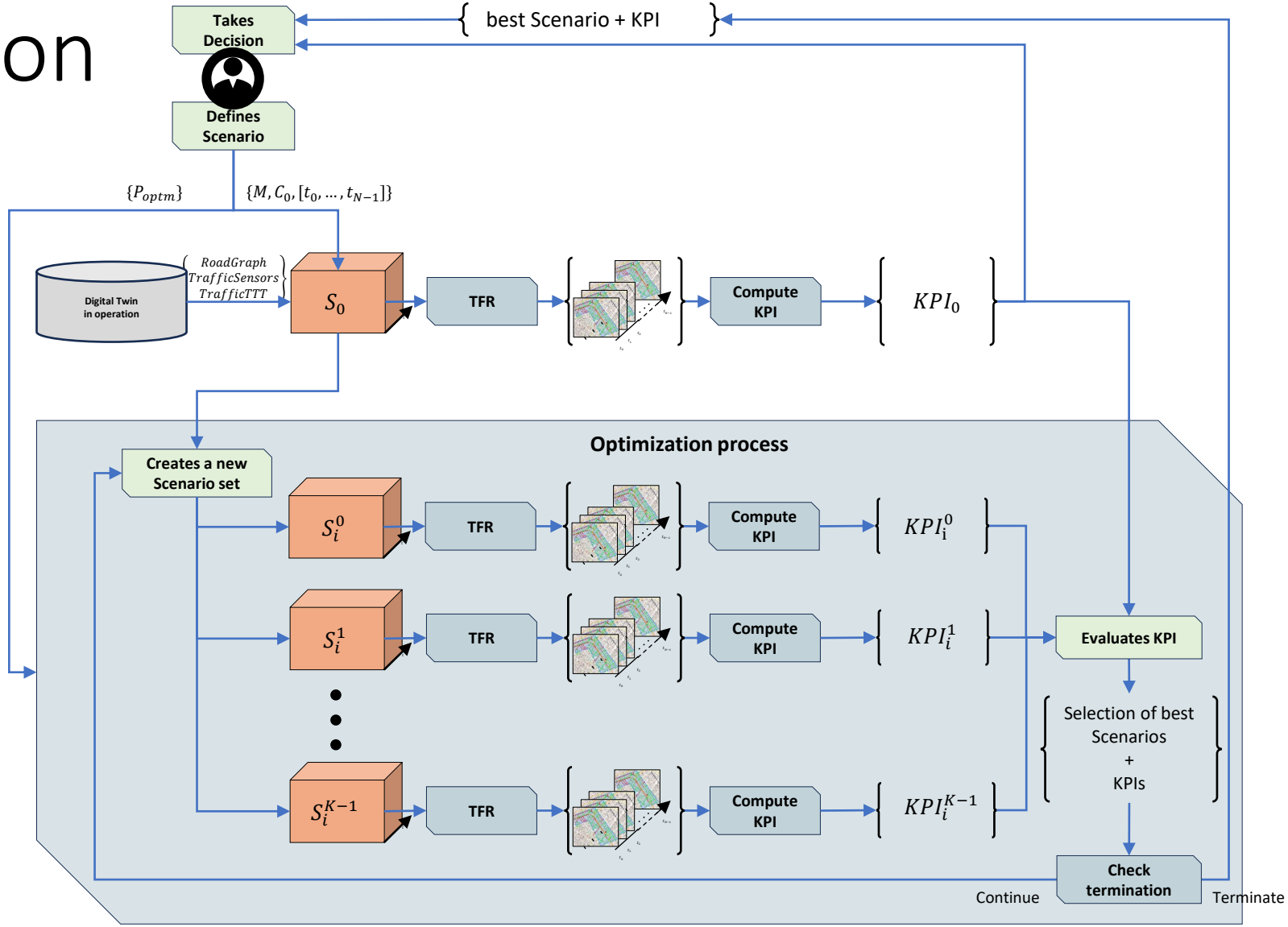


Optimization



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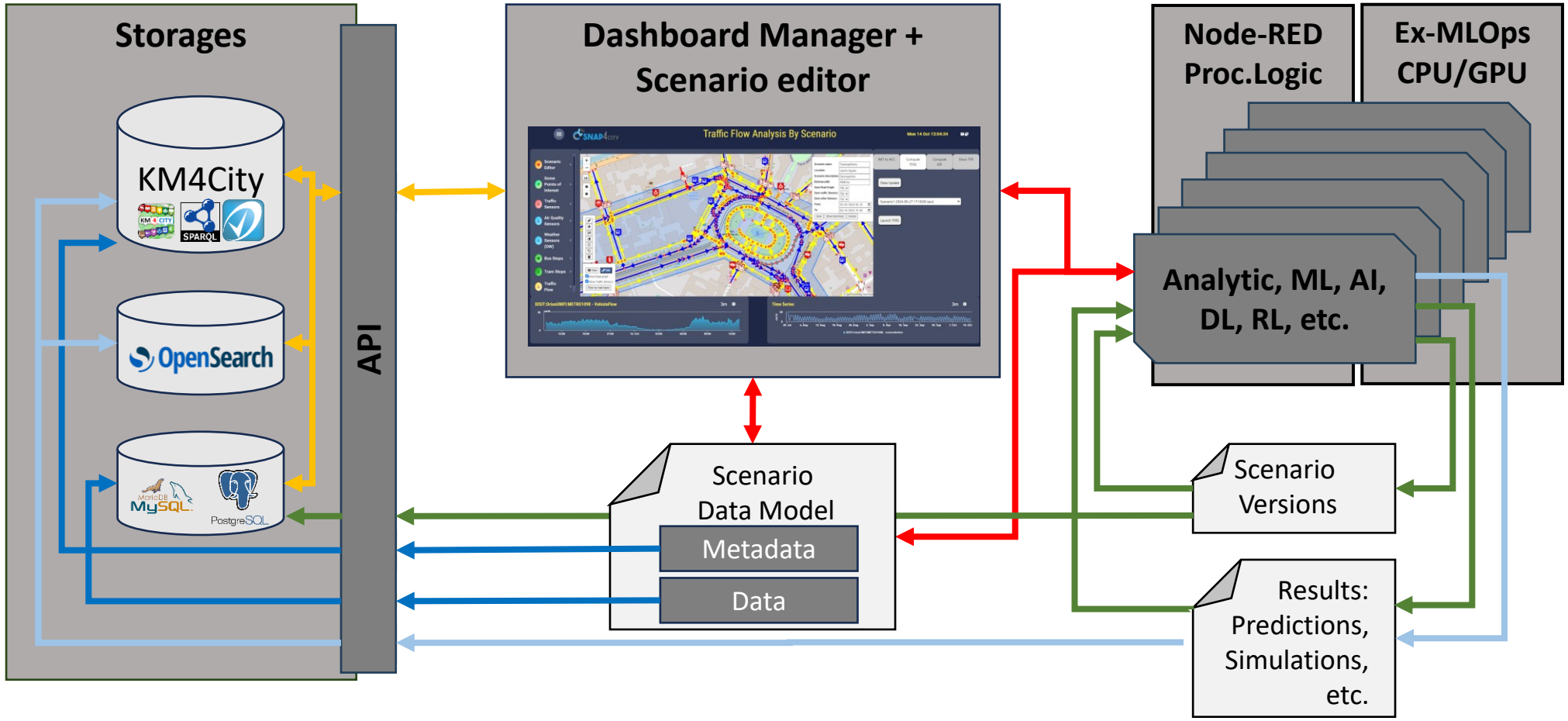
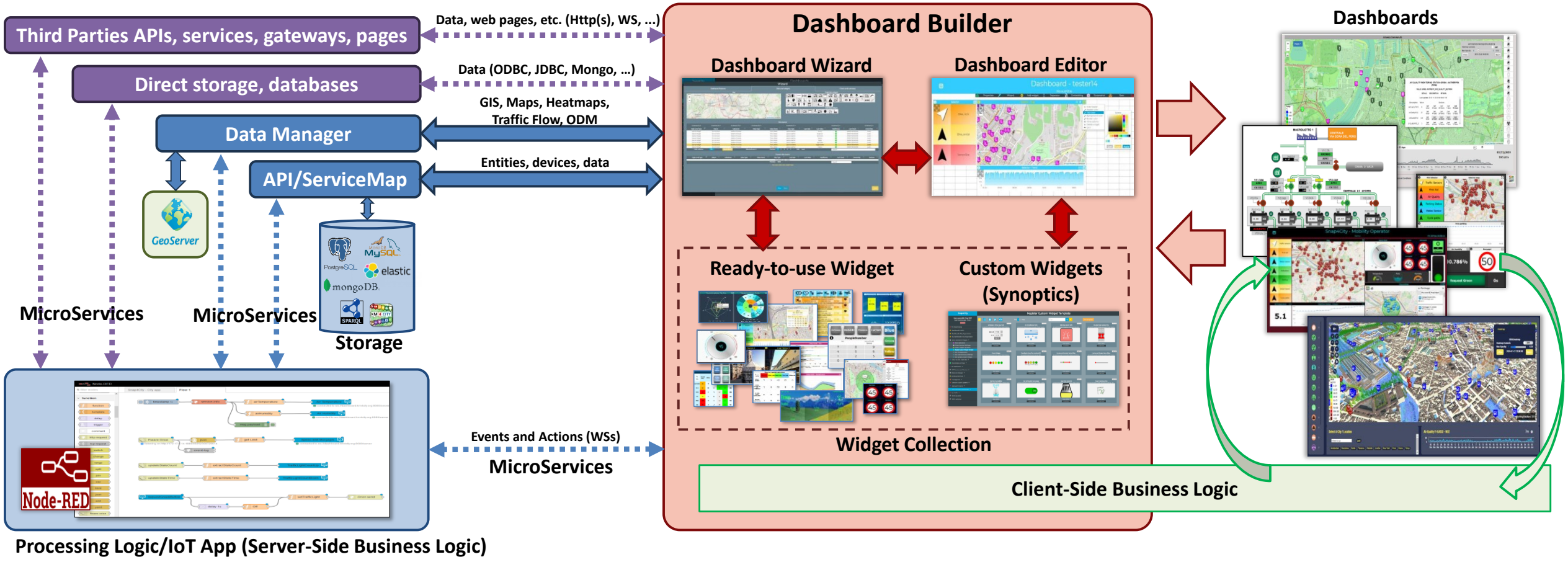


GUI - Human Interfaces

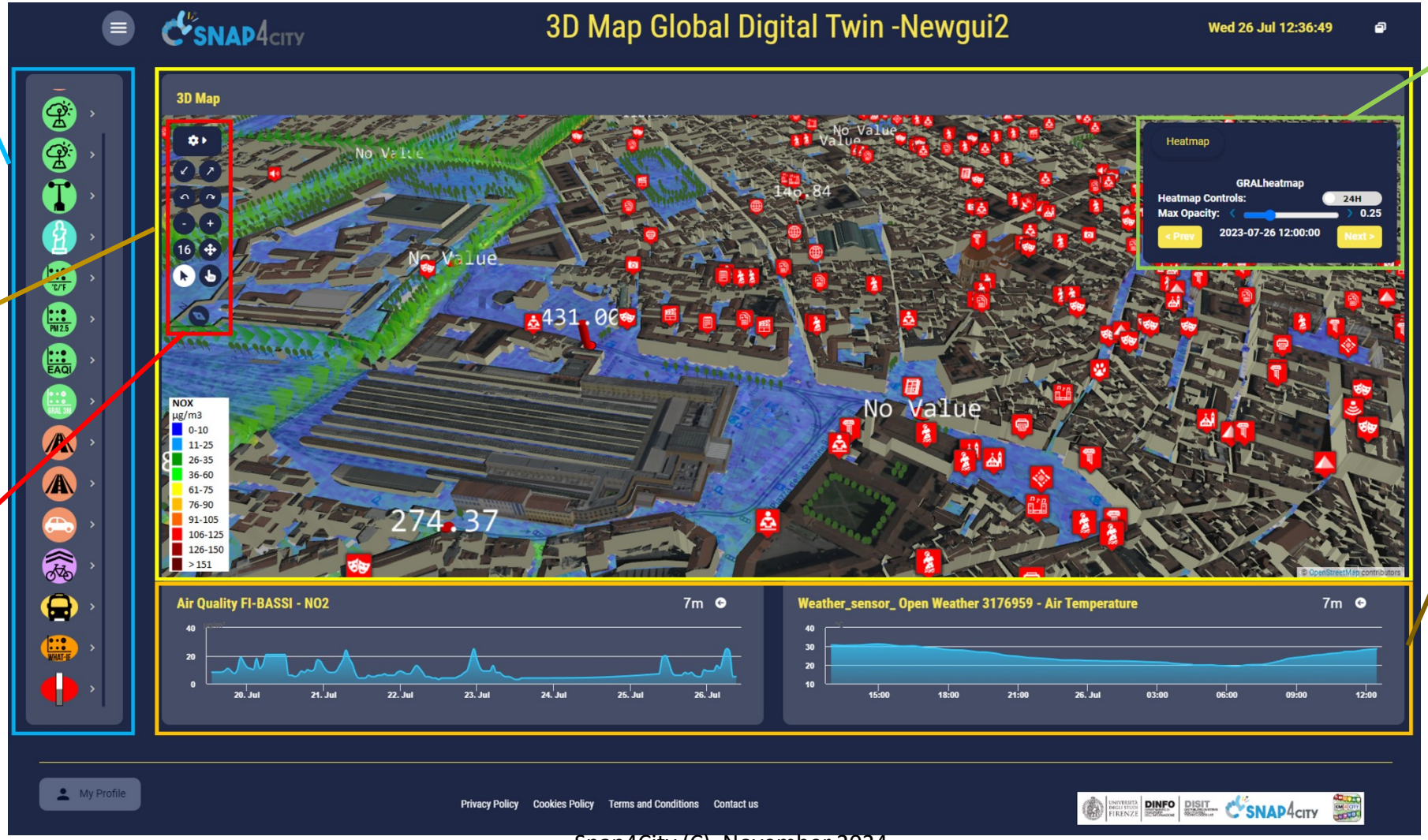


GUI - Human Interfaces

Selector

Main map

In-map menu



Panel for additional info

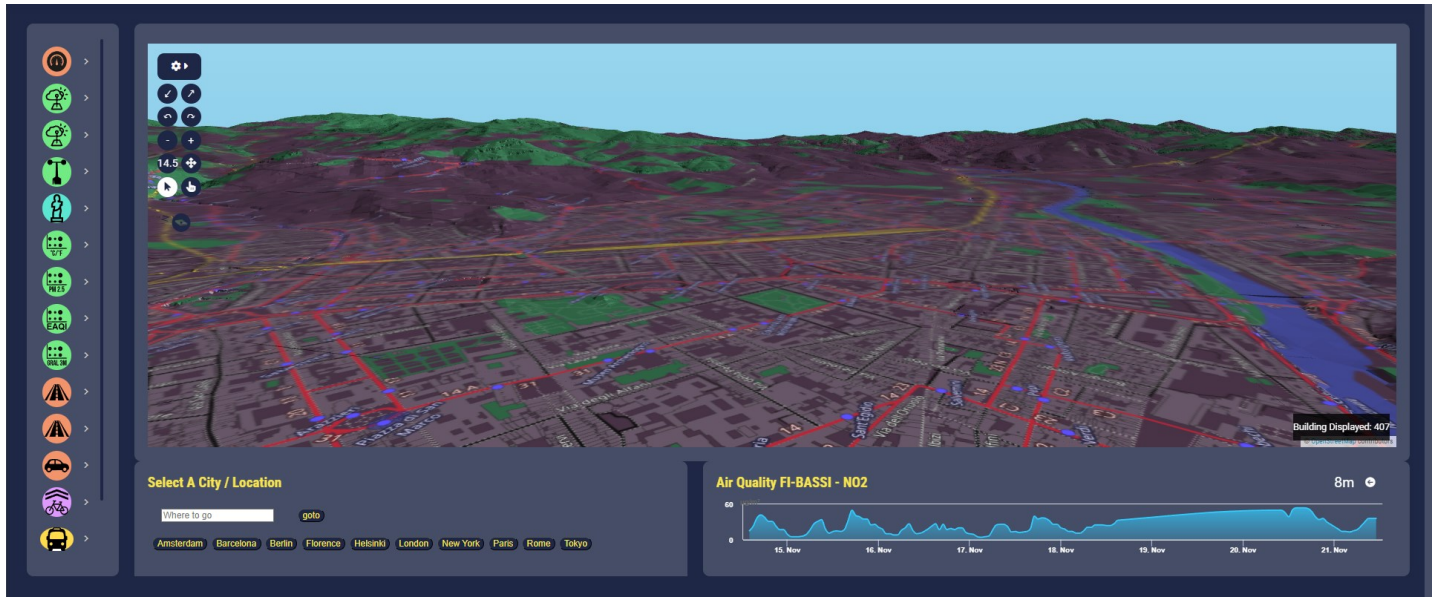
Additional widget (CSBL)

Main functionalities

- The SCDT in Snap4City includes the following functionalities:
  - 3D terrain

Main functionalities

- The SCDT in Snap4City includes the following functionalities:
  - 3D terrain, over which different orthomaps



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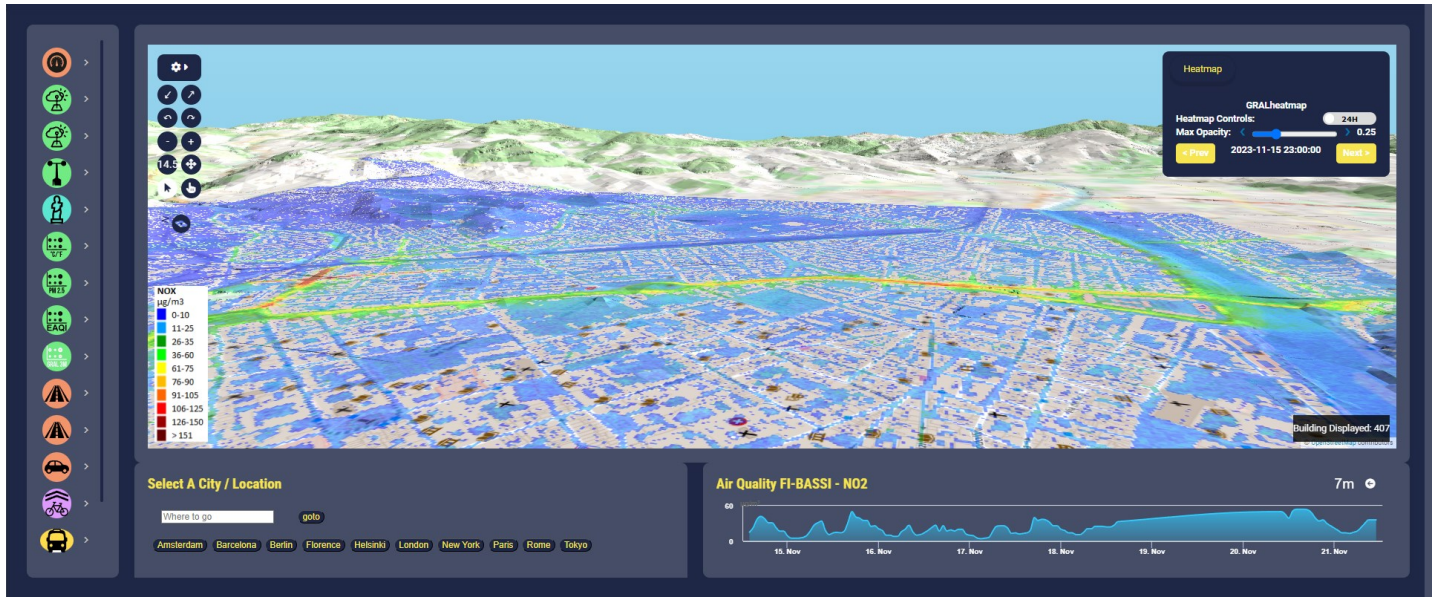
Main functionalities

- The SCDT in Snap4City includes the following functionalities:
  - 3D terrain, over which different orthomaps and heatmaps can be shown



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- The SCDT in Snap4City includes the following functionalities:
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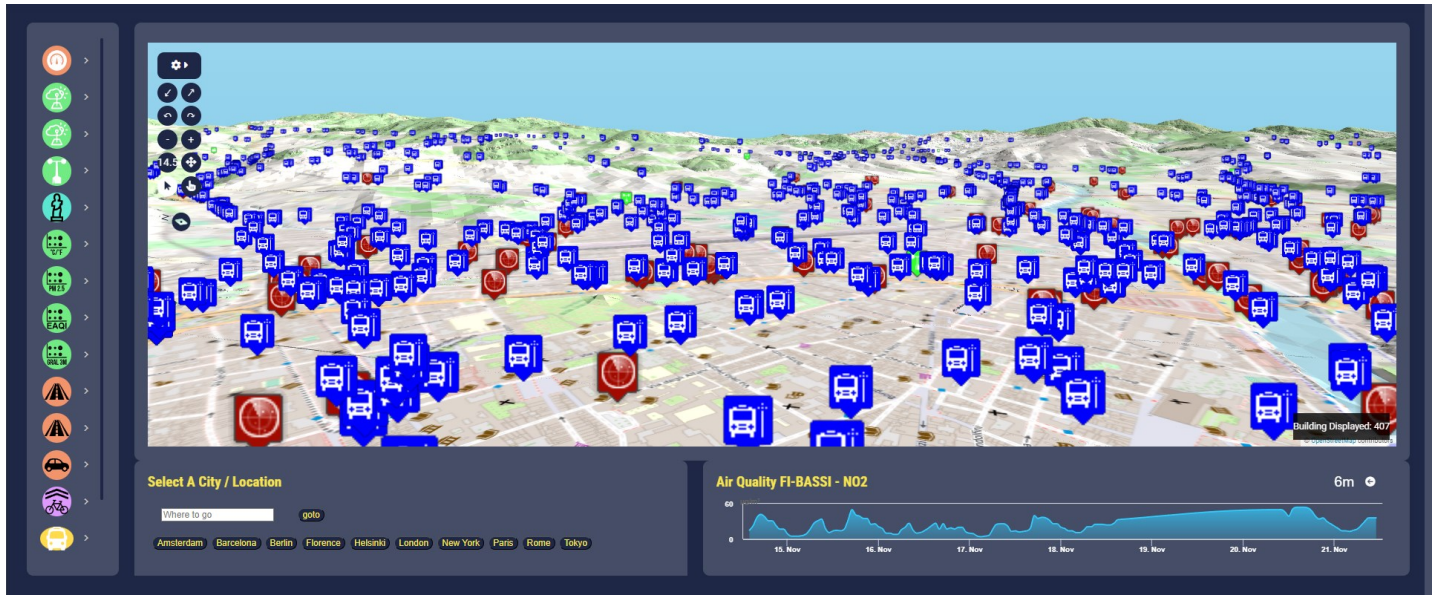
  - PINs are used to represent IoT devices, Services, Public Transport stops



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  - Each PIN can be clicked to open a pop-up with detailed information

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  - 3D terrain, over which different orthomaps and heatmaps can be shown
  - PINs are used to represent IoT devices, Services, Public Transport stops
  - Each PIN can be clicked to open a pop-up with detailed information
  - RT-data can be queried and shown in dedicated widget using CSBL

Main functionalities

- The SCDT in Snap4City includes the following functionalities:
  - 3D building of the city are represented

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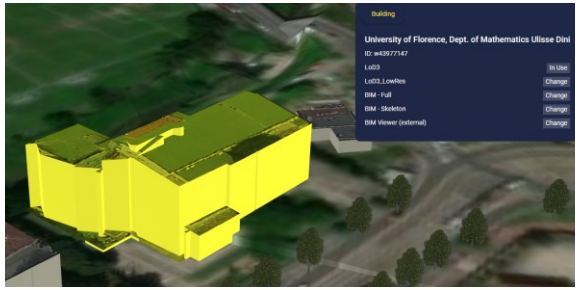

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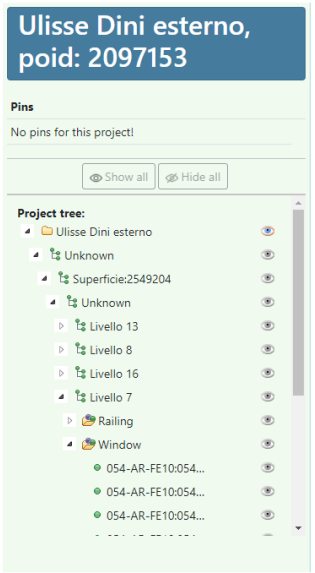

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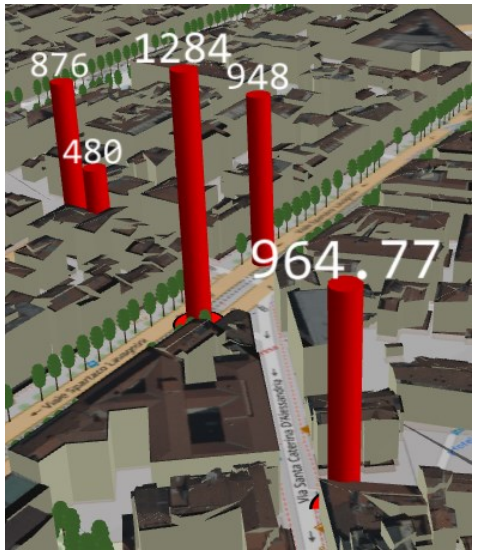
  - For specific buildings, after selecting it the 3D model can be changed
  - When available, access to inspect the BIM of the building is provided
  - In the case of Google 3D tiles, the picking functionality was implemented exploiting invisible extruded buildings

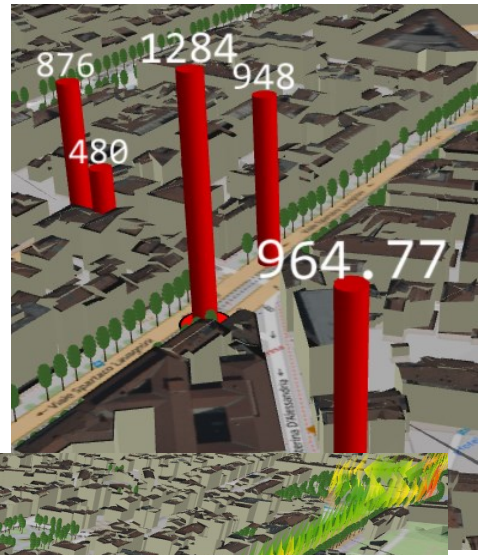
Main functionalities

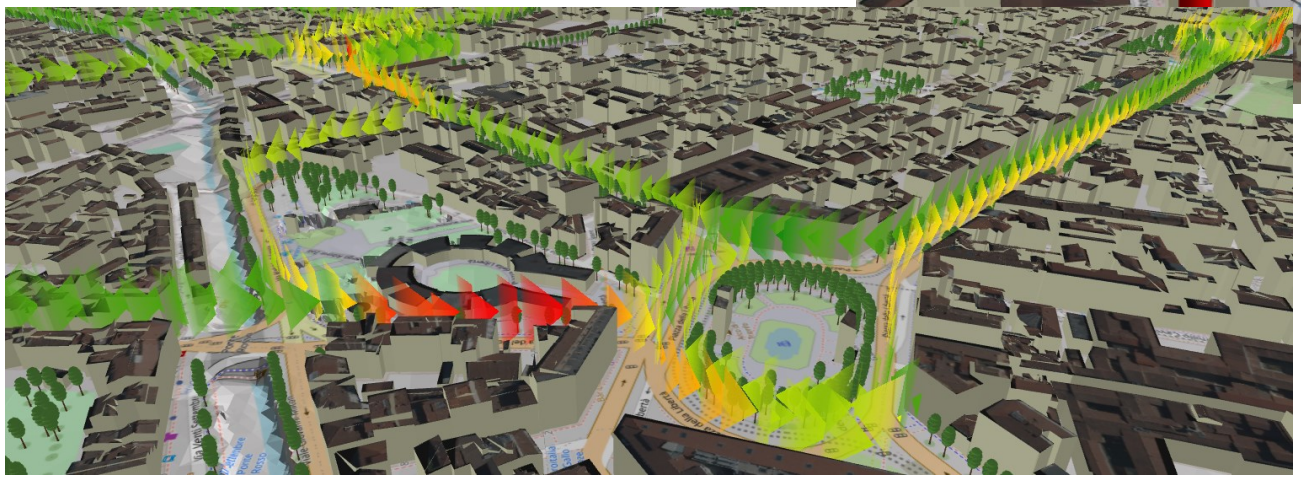
- Specific 3D representation have been devised to show
  - Sensor measurements



Main functionalities

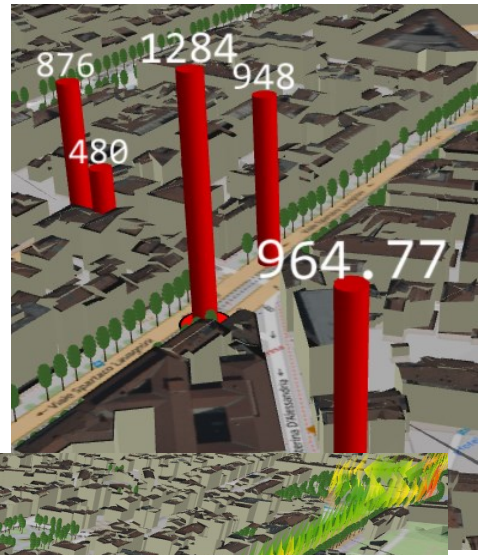
- Specific 3D representation have been devised to show
  - Sensor measurements
  - Traffic flows

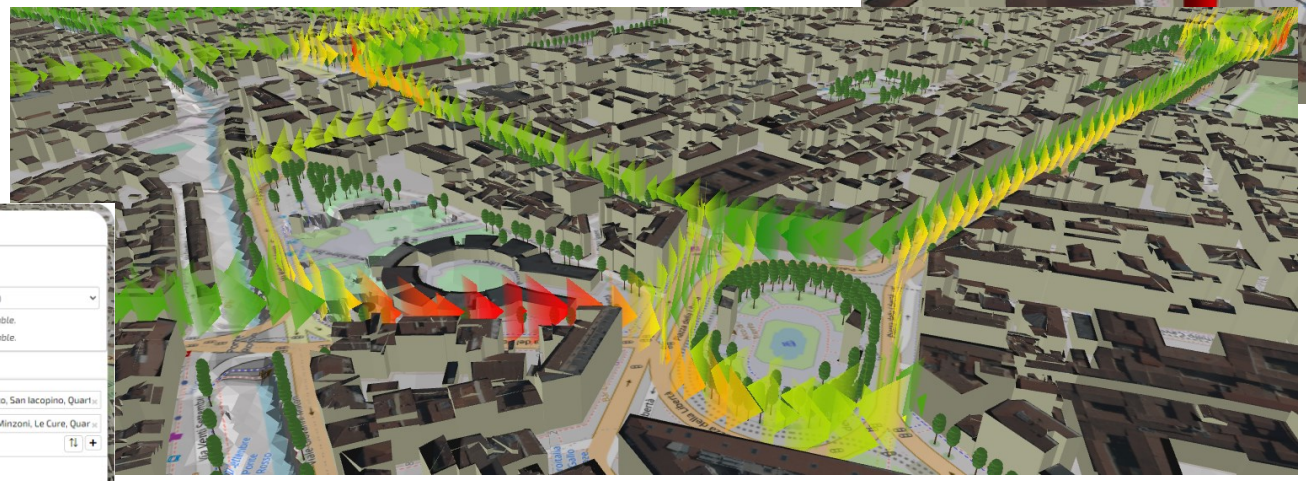


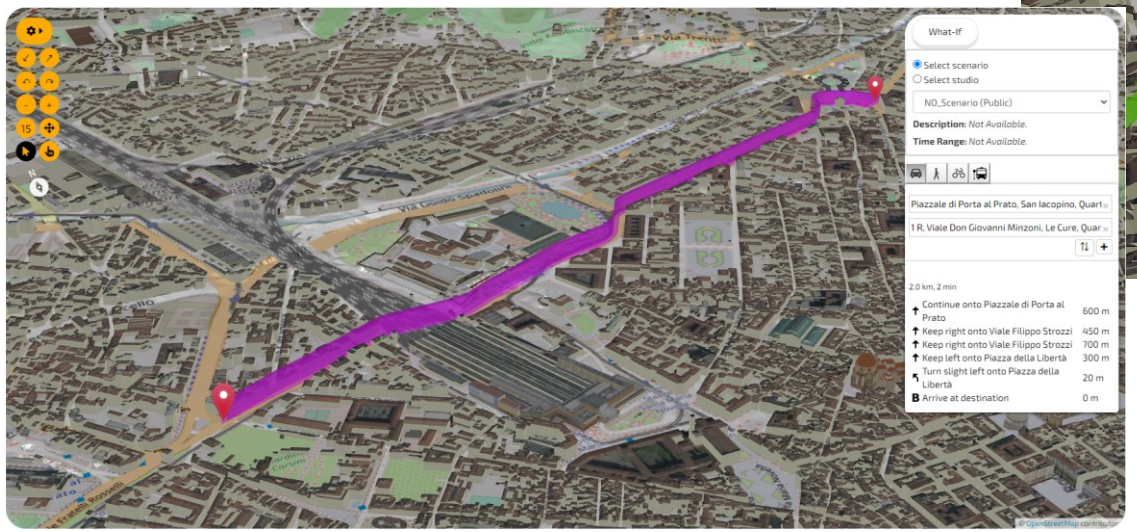


Main functionalities

- Specific 3D representation have been devised to show
  - Sensor measurements
  - Traffic flows
  - Routing paths

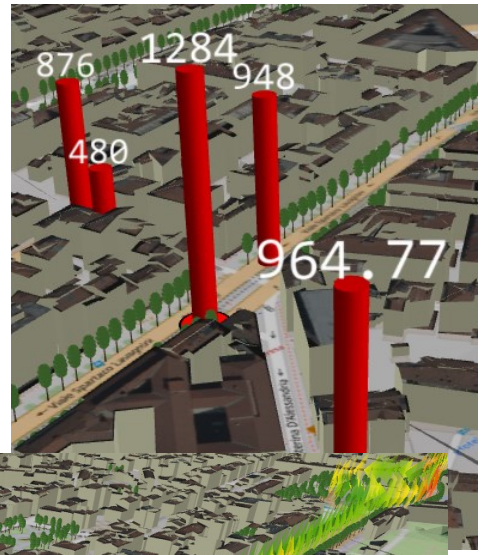


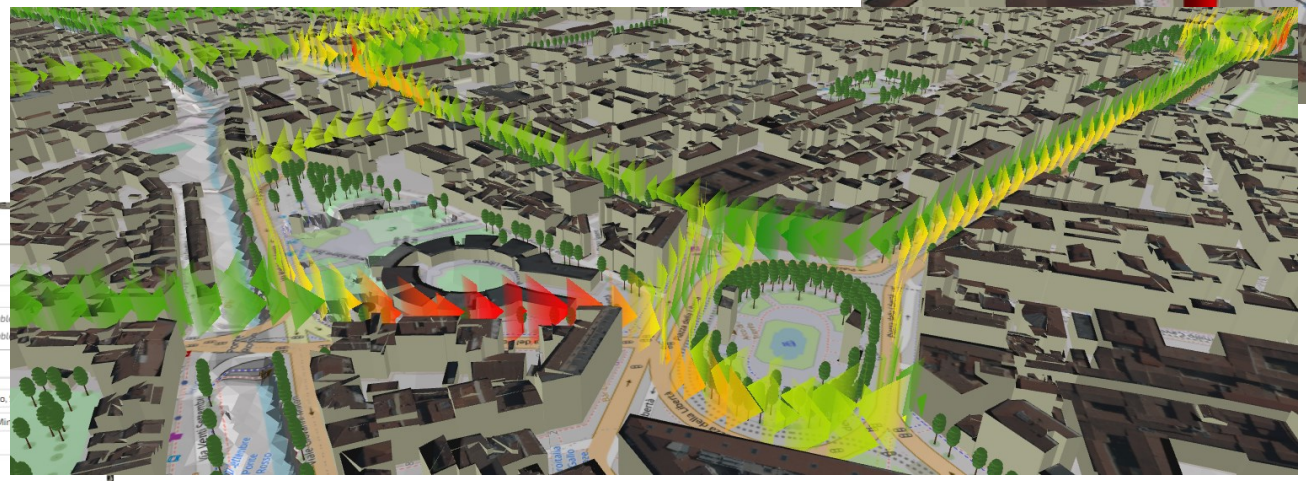


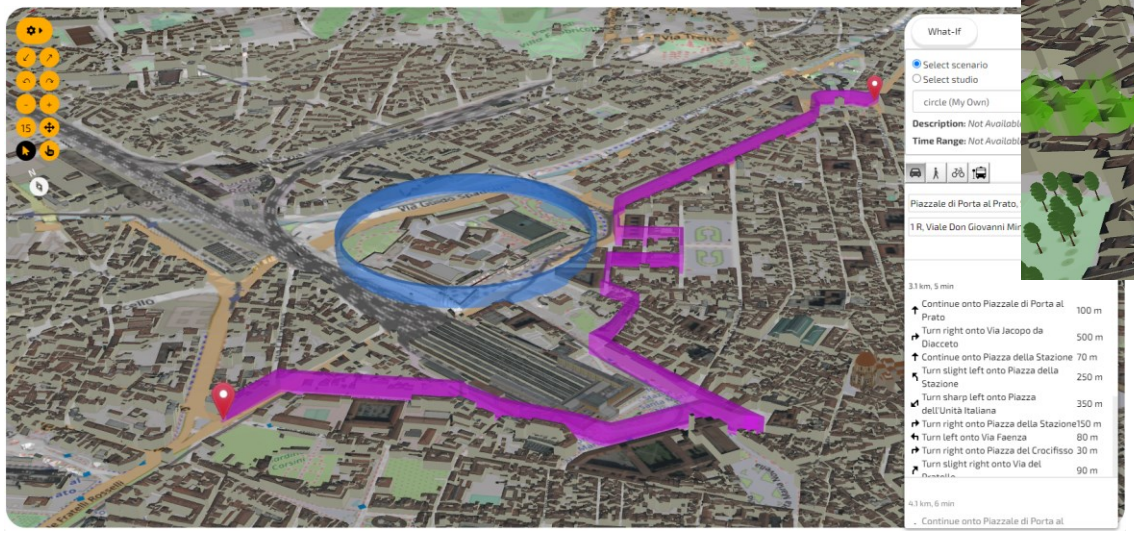


Main functionalities

- Specific 3D representation have been devised to show
  - Sensor measurements
  - Traffic flows
  - Routing path, also for What-if analysis

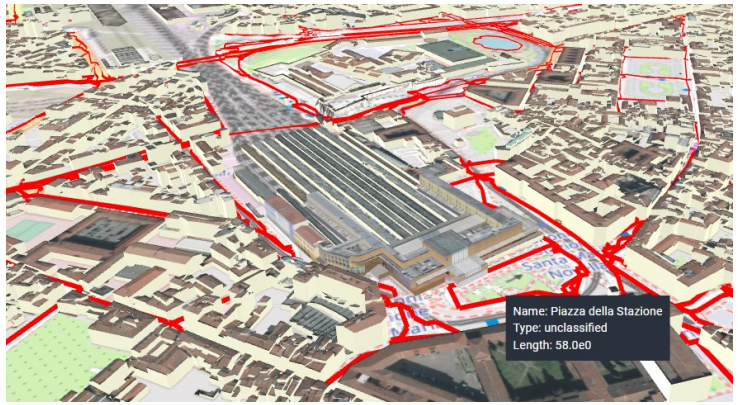


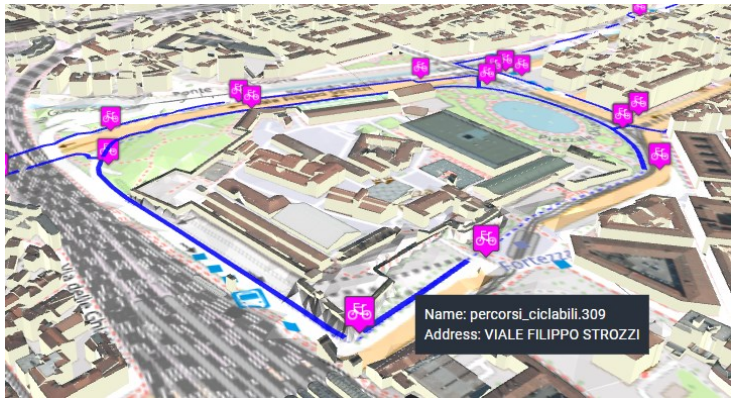




Main functionalities

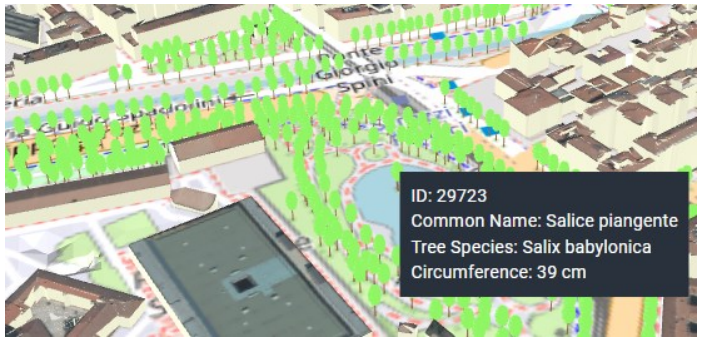
- The SCDT also includes
  - Roads, cycling paths, bus routes

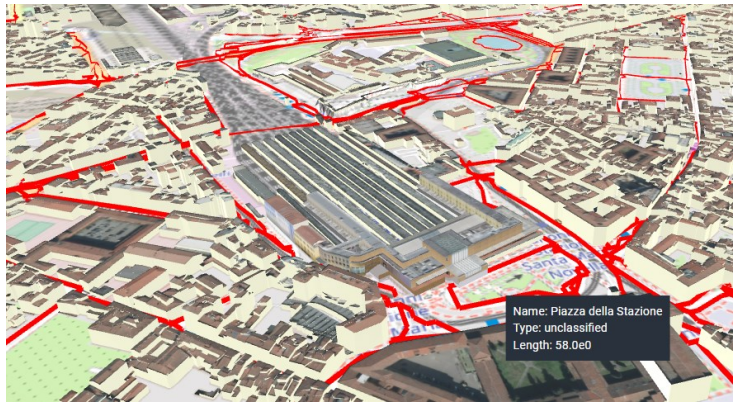


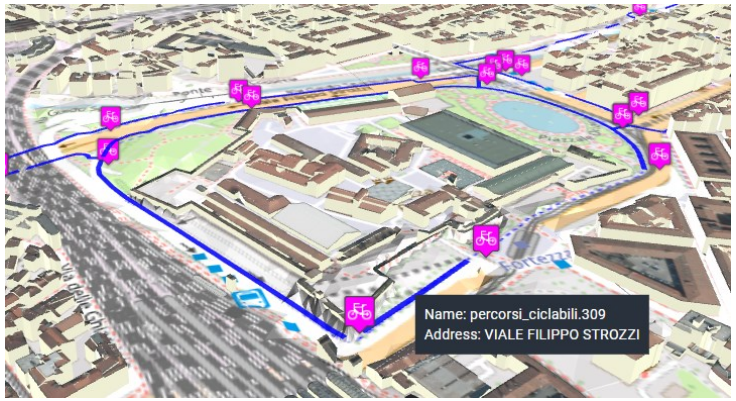


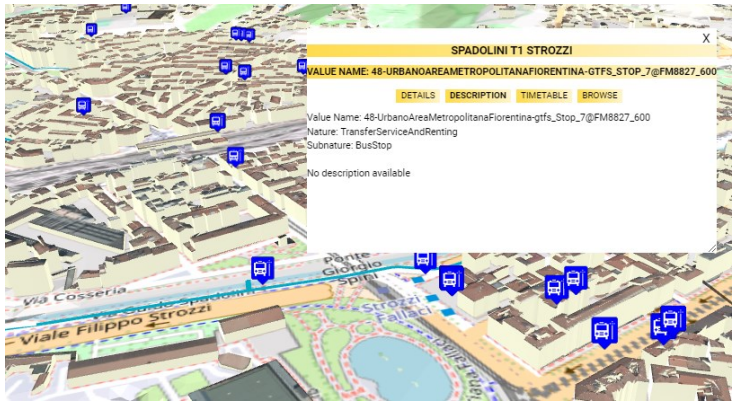
Main functionalities

- The SCDT also includes
  - Roads, cycling paths, bus routes
  - Additional 3D elements like trees, that can be requested with different level of details







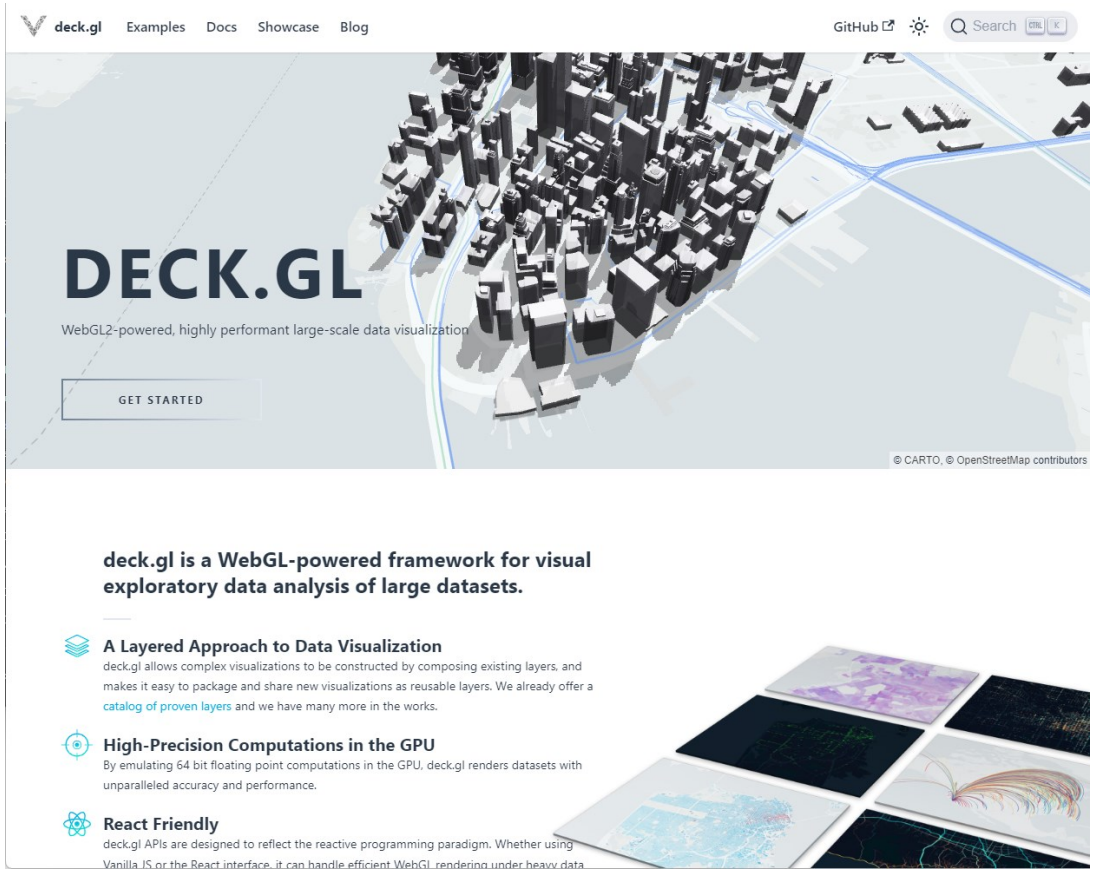


3D Multi-data Map Interactive Web Interface

- The architecture implements a **client-side business logic** developed in JavaScript exploiting the **Deck.gl framework**
- REST calls are used to query Snap4City API and **load data on user demands**
- PINs for POIs or IoT Devices, and paths and areas are **retrieved with geographic queries** toward the Snap4City SuperService Map (the KM4City interface)
- Heatmaps, Orthomaps, and the RGB DTM are instead **provided via WMS protocol** with HTTPS requests toward the Snap4City GeoServer

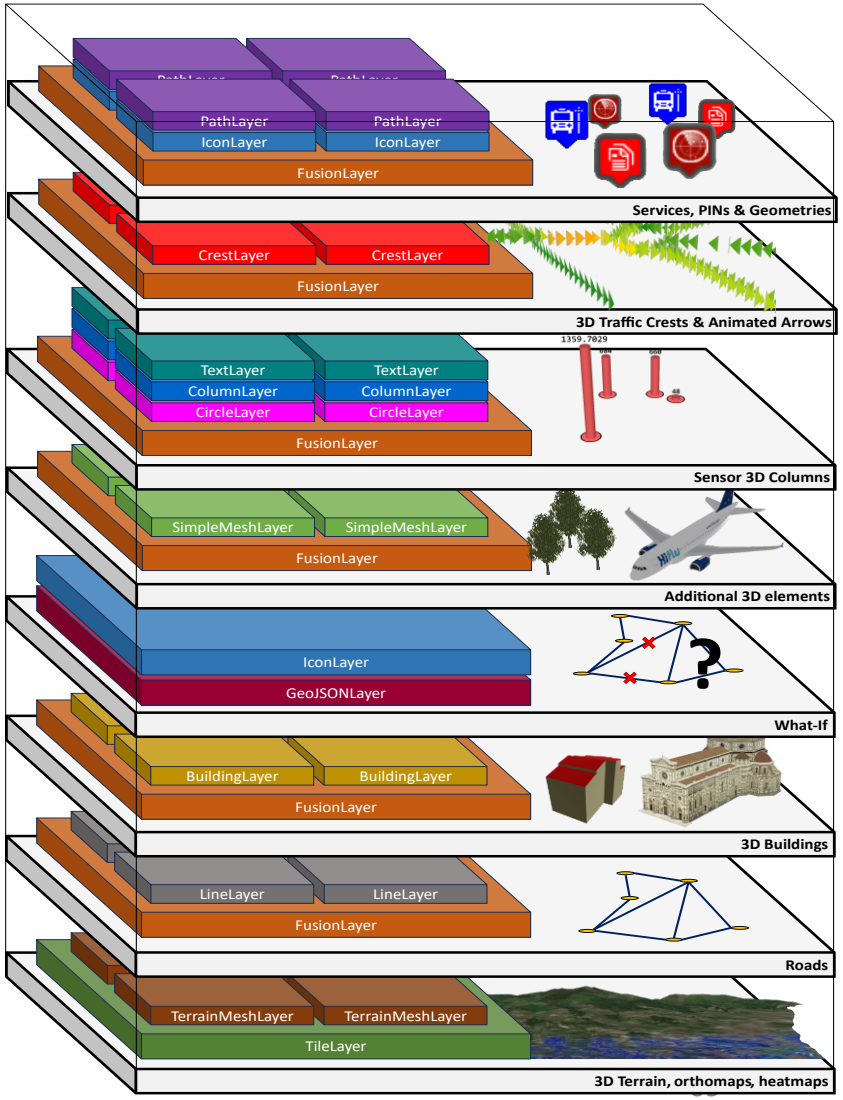
Deck.gl

- Deck.gl is a **JavaScript** framework to handle large database and create web applications
- It is based on a **layered architecture**…
- …and provide tools to integrate and visualize **geographical data**



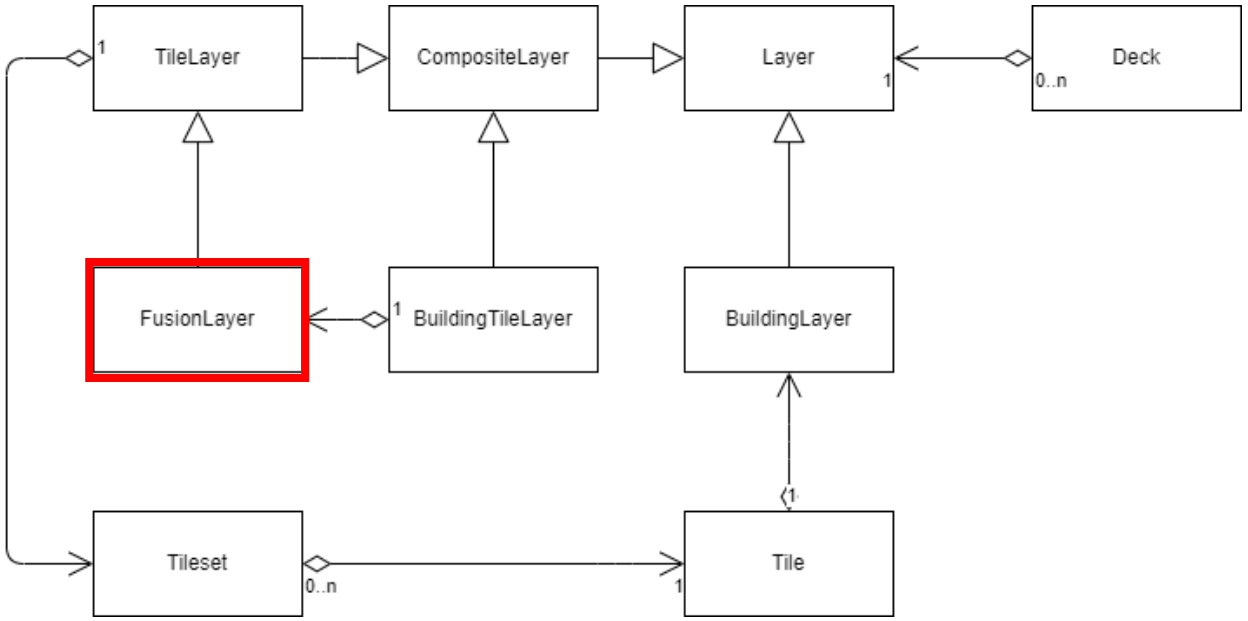
Layered architecture

- Deck.gl **layered structure** was exploited
- Different entities are rendered in **different layers**, each with its **own safe context** to avoid interferences and be able to load each of them **independently**
- Data are rendered with a **tiled approach**, in order to display only the visible data. This is fundamental to handle **large SCDT**



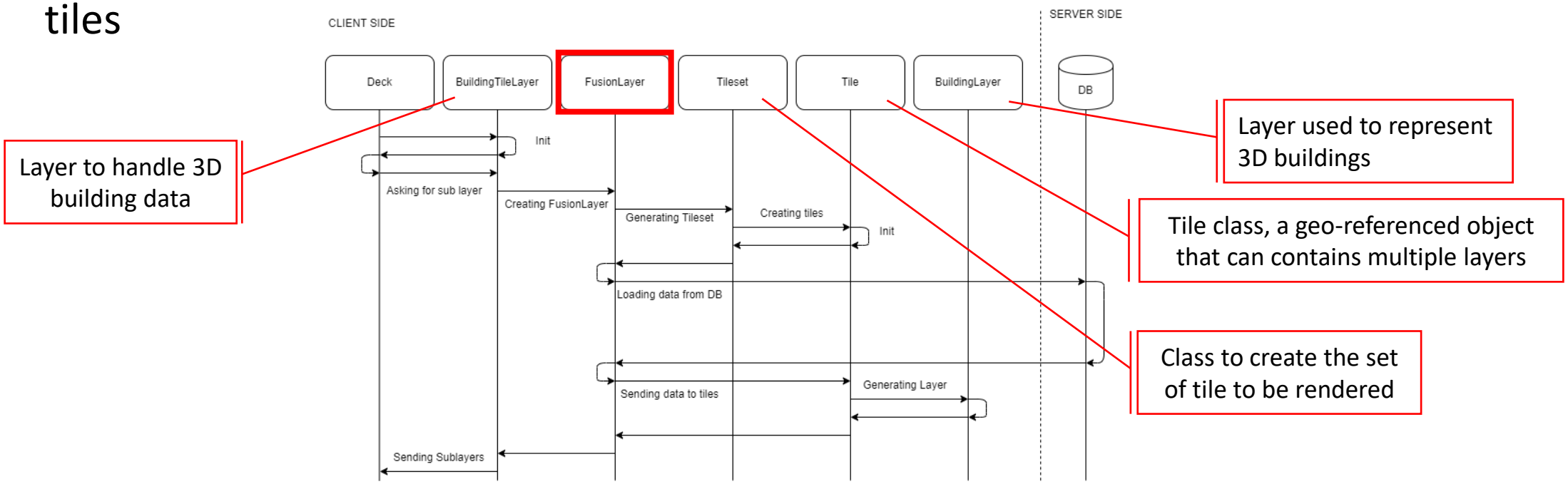
Fusion Layer

- The core of the architecture is the so-called **FusionLayer**
- The FusionLayer **extends** the Deck.gl architecture



Fusion Layer

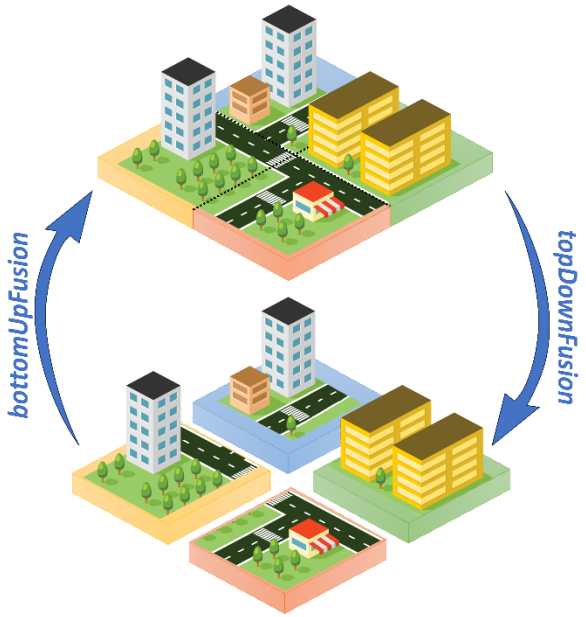
- The core of the architecture is the so-called **FusionLayer**
- The FusionLayer **extends** the Deck.gl architecture
- The FusionLayer **is specialized to manage the data to be rendered** in the SCDT tiles



Fusion Layer

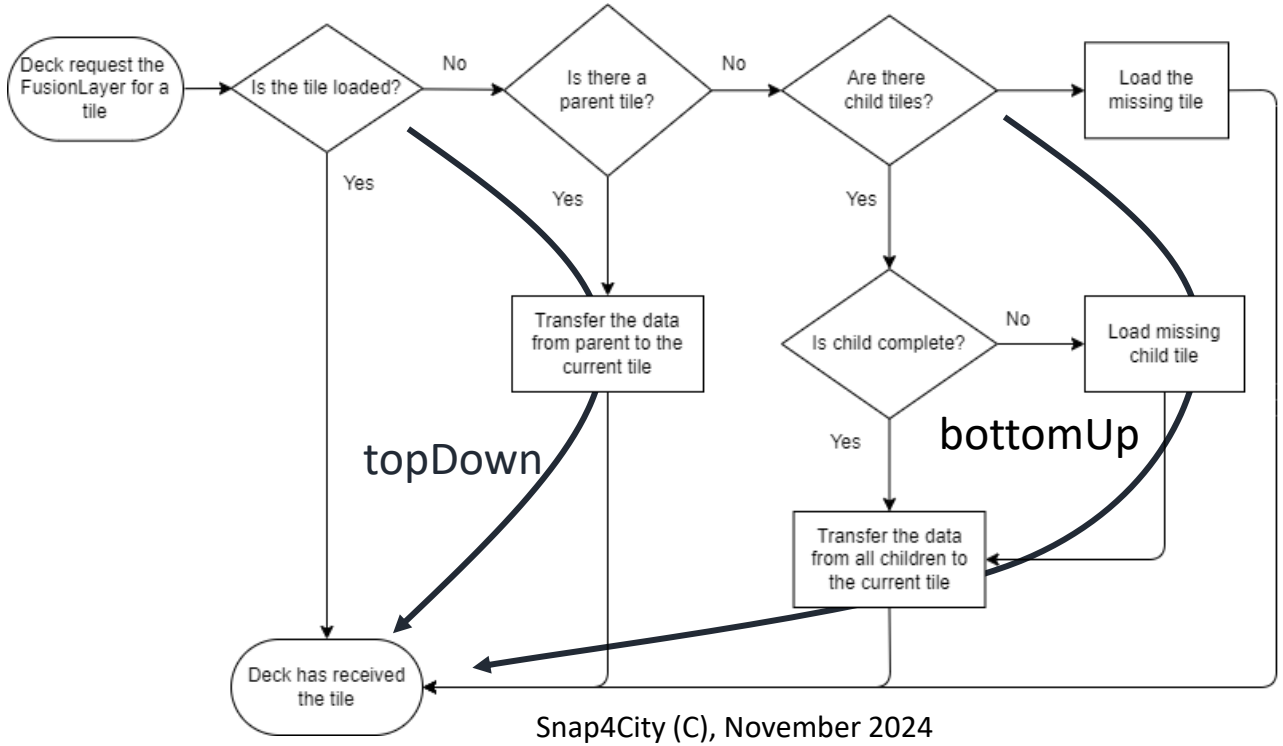
- FusionLayer implements two main functionalities

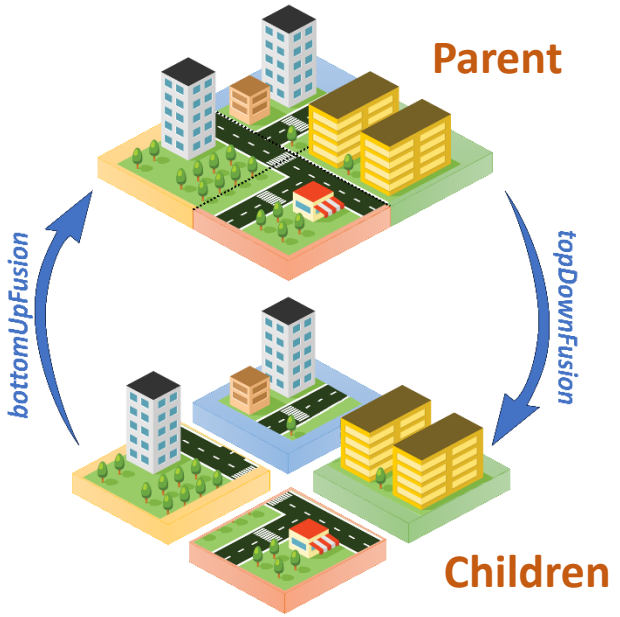
1. The **bottomUp** and **topDown** Fusions
2. The **deepLoad**



Fusion Layer

- The bottomUp and topDown fusion are used to **reduce server calls and exchanged data** by reusing data already downloaded for tile at different zoom levels

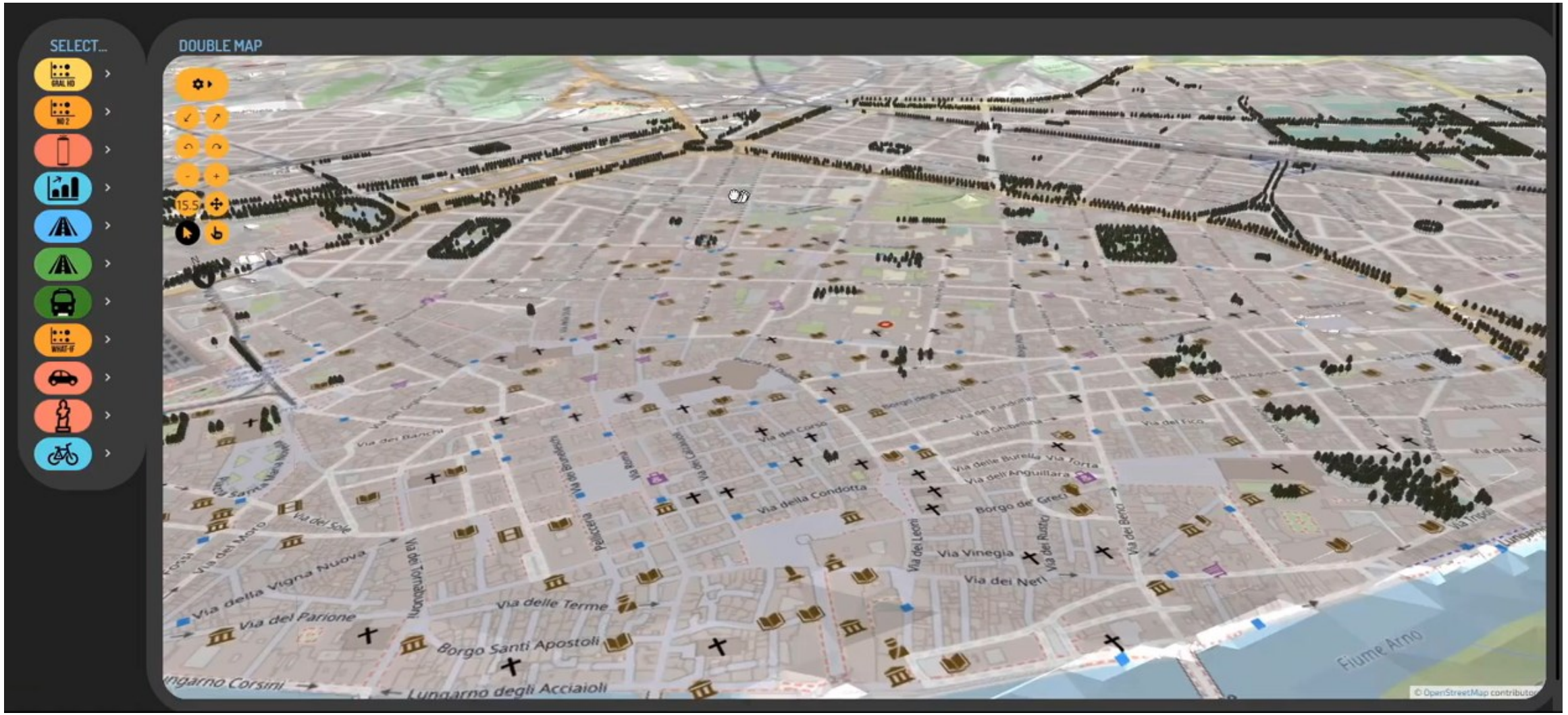




Fusion Layer

- The **deepLoad** function is used when dealing with **data available at a single zoom level** (e.g., traffic flows, 3D buildings)
- In the standard Deck.gl, such data would be retrieved at the available zoom **regardless of the actual zoom** used in the map
- At low zoom level, this behavior would lead to a **very large number of tiles to be rendered**, slowing down the performance
- The deepLoad solve this problem by requiring data at the available zoom, then **creating virtual tiles with dimension according to the actual zoom level** and filling these virtual tiles with the retrieved data, thus **reducing the rendering processes** to be carried out

Digital Twin of Florence

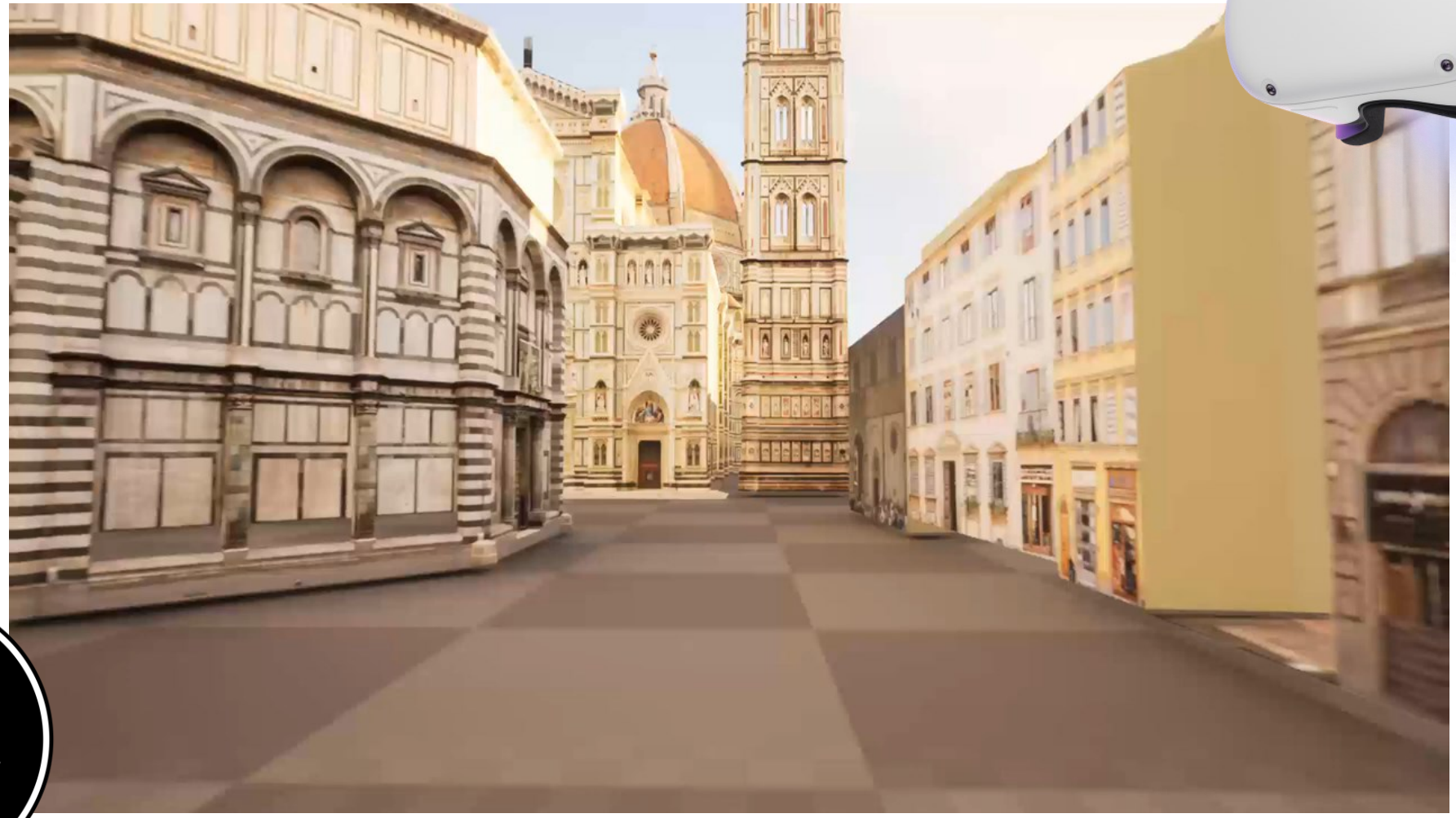


https://digitaltwin.snap4city.org - https://www.youtube.com/watch?v=AWy7poKtTLc

OCULUS

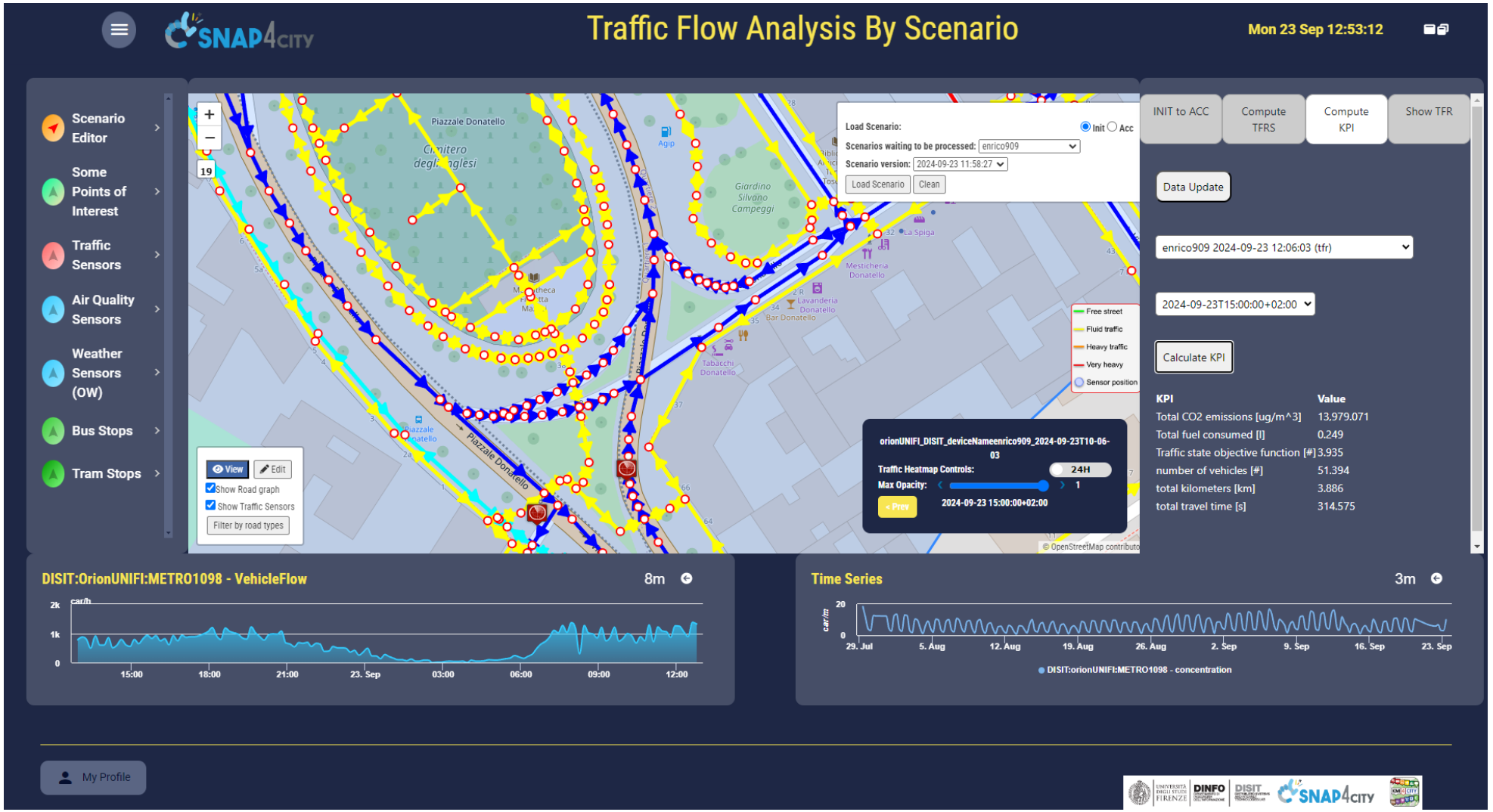

Perspective
Lit
Show
Scrivi qui per eseguire la ricerca
6°C
19:09
30/11/2022

Digital Twin of Florence



https://www.youtube.com/watch?v=Rcf_B2_GOio

Scenario Editor



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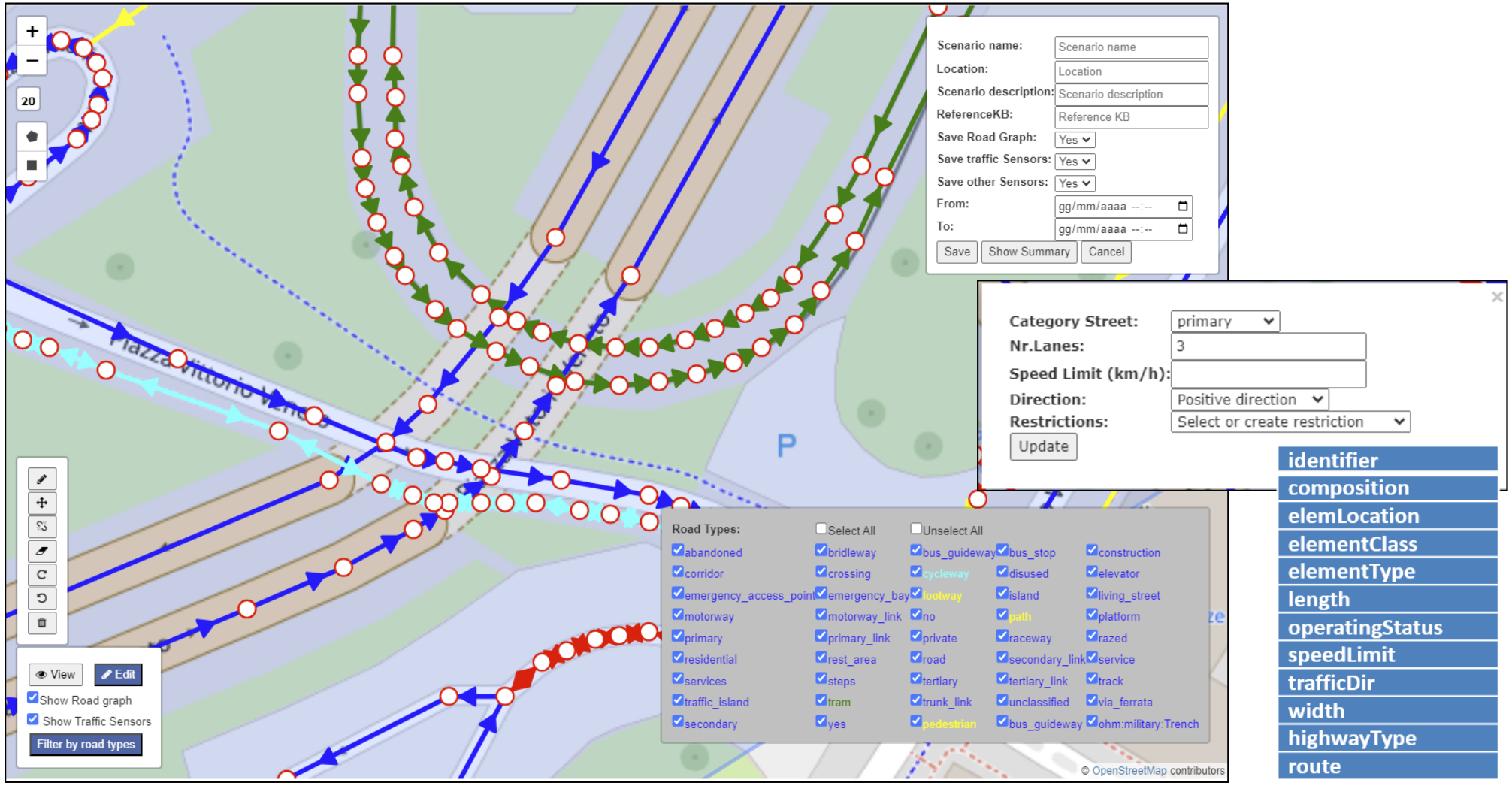
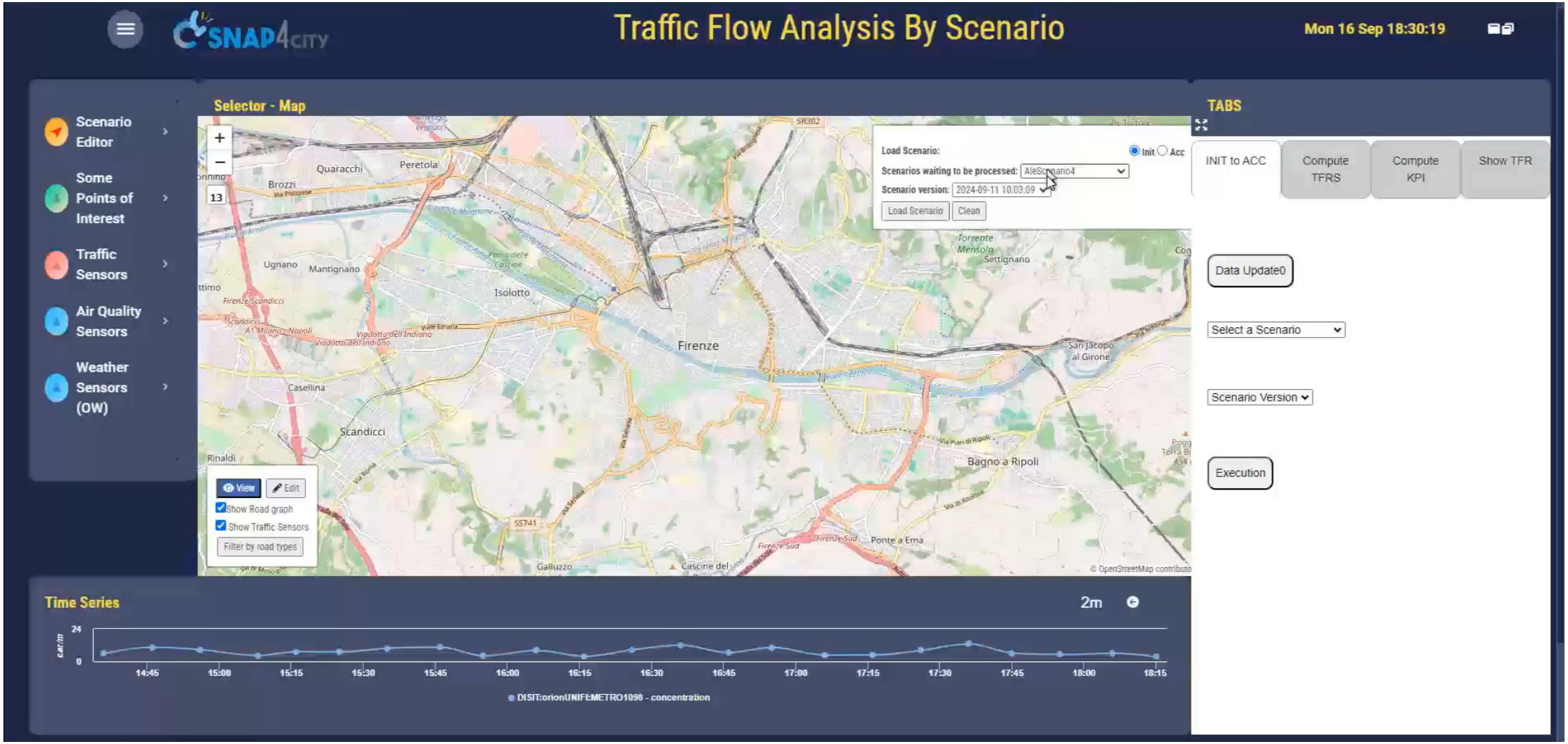


Properties of Road Elements

- identifier
- composition
- elemLocation
- elementClass
- elementType
- length
- operatingStatus
- speedLimit
- trafficDir
- width
- highwayType
- route

Scenario Editor



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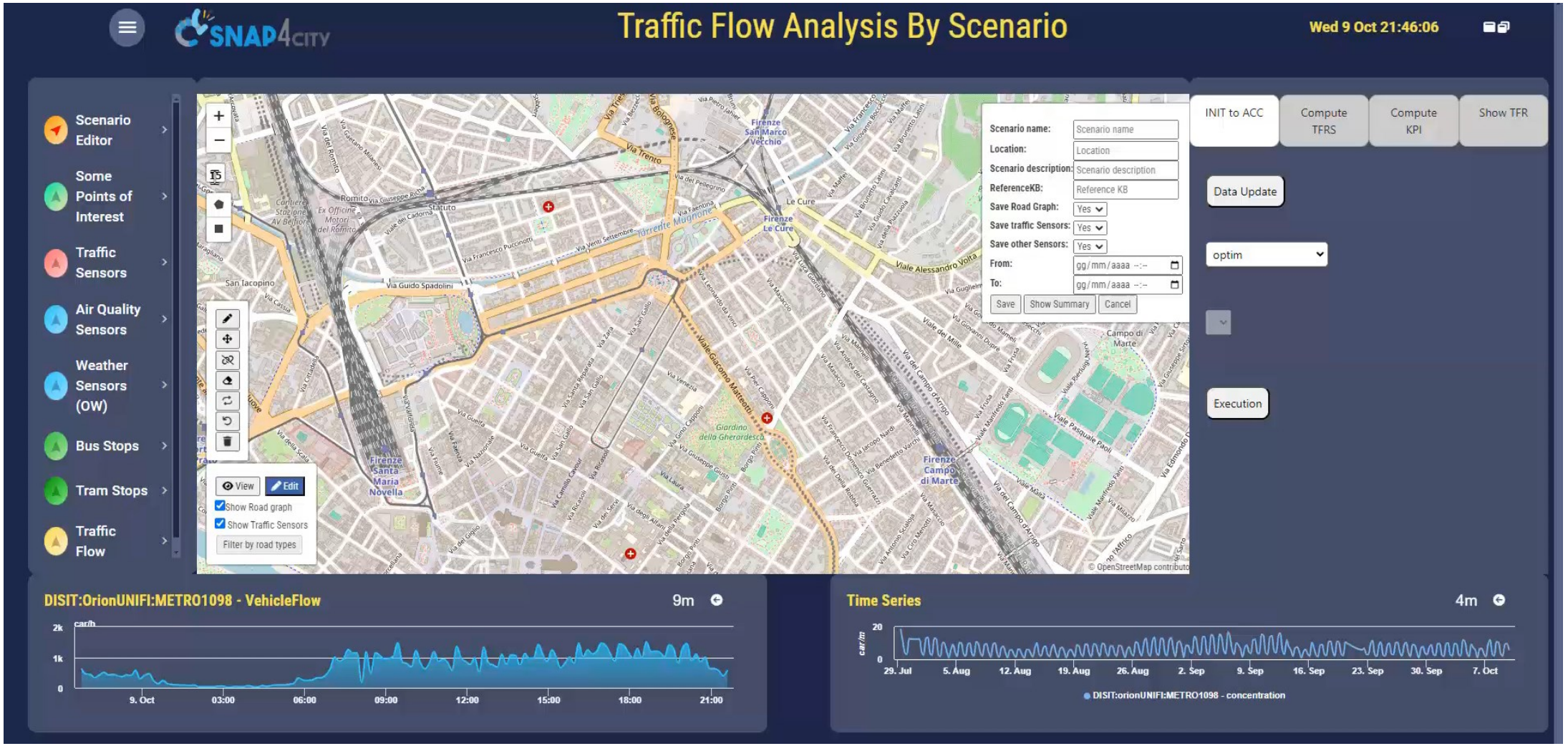

Scenario Editor