COMPAIR

DELIVERABLE

# D3.6 Digital Twin CS Integration

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# List of Abbreviations

| Abbreviation | Definition |
| --- | --- |
| API | Application Programming Interface |
| BC | Black Carbon |
| CS | Citizen Science |
| Digital Twin | Digital Twin |
| DUET | Digital Urban European Twins (project name) |
| EU | European Union |
| GDPR | General Data Protection Regulation |
| GIS | Geographic Information System |
| IoT | Internet of Things |
| NO2 | Nitrogen Dioxide |
| OGC-STA | Open Geospatial Consortium SensorThings Application Programming Interface |
| PM | Particulate Matter |
| SC | Smart City |
| 3DCM | 3D City Model |

# Executive Summary

The D3.6 Digital Twin Citizen Science Integration report is part of the COMPAIR deliverables in line with Annex 1 to the Grant Agreement. The document explores the integration of citizen science (CS) air quality and traffic counting sensor data gathered within COMPAIR into a Digital Twin (Digital Twin) and provides examples from another European project called DUET (Digital Urban European Twins)[1] where some of the CS sensor data was integrated into the Digital Twin.

DUET combined the power of simulation modelling to predict the potential outcomes of domain-overarching policy cases and scenarios. It also provided near real-time data from a wide range of sensors, including COMPAIR sensors like Telraam traffic counting sensors and air quality measuring stations. COMPAIR contributes to the Digital Twin concept by supporting the combination of sparse high-fidelity measurements and local networks of lower-fidelity measurements. Automated calibration engines help to improve the quality of local measurements done via citizen science projects. Additionally, the sensor data is standardised to help with data interpretation and facilitate integration.

D3.6 describes the sensor data acquired during the COMPAIR project, the aspects of the sensor data which allow its integration into a Digital Twin, the integration approach utilised in DUET and the results of Digital Twins in Flanders (Belgium) and Athens (Greece). COMPAIR and DUET show that Digital Twins can support local decision-making by leveraging citizen science initiatives to allow data collection through low-cost sensors which enable a more comperehensive coverage of the physical environment.

[1] See: https://cordis.europa.eu/project/id/870697

# 1. Introduction

Digital Twins are virtual representations of physical systems and their associated environments and processes. They can be used to describe, analyse, and simulate processes through data integration, artificial intelligence, and machine learning. This not only allows us to understand better and describe and analyse reality, but it also enables predicting these processes' potential (future) impact more accurately.

To build Digital Twins for cities, data integration methods are crucial (Lei et al., 2023a; Shahat et al., 2021), especially since data is derived from disparate and heterogeneous sources such as existing geodatabases, real-time sensor data, actuators, crowdsourcing, etc. and span different time and spatial scales (Jeddoub et al., 2023). The effective integration of such heterogeneous data in Digital Twins is not limited to the geometric aspects of data integration (derived from various sources, related to 3D city models (3DCMs, Deng et al., 2021) or Digital Twins for cities as the input layer of the urban Digital Twins (Bacher, 2022, Döllner, 2020, Lehner and Dorffner, 2020)). The data semantics, the structure and the storage methods also need to be taken into account (Noardo, 2022). Digital Twins need to integrate multi-source data within common systems, and for each use case (mobility, flooding, air pollution, etc.), the data to be used in Digital Twins must fit the specific end requirements.

In the geoinformatics field, data integration was approached by extending the existing standard CityGML[2] for integrating urban geodata for various applications in the context of Smart Cities (SCs) (Jeddoub et al., 2023). An example of the data integration model is a study (established by Chaturvedi, 2021) that introduced the concept of “Dynamizers” to model, store and exchange the dynamic variations of properties and time-series data implemented as Application Domain Extensions (ADEs) for CityGML 2.0. The initial Dynamizer module was developed to enhance the usability and the integration of highly dynamic properties variations, whether provided from simulations or derived from sensors or Internet of Things (IoT) devices. The more recent Dynamizer module allows the creation of an explicit link between sensor/observation data and the respective city object properties within a 3D city model (3DCM) being measured. In this sense, the Dynamizer concept provides a method to handle the dynamic properties of city objects with respect to the application requirements.

Furthermore, the CityThings concept explains how to handle sensor data stored in separate databases and associated with a 3DCM using SensorThings API[3] and CityGML standards (Santhanavanich and Coors, 2021). The virtual model can be updated according to real-time updates based on IoT technologies.
Nevertheless, the integration of sensor data in the Digital Twins’ applications is part of the vast amounts of available and existing datasets (from Geographic Information System (GIS), organisation databases, etc.) that can bring the virtual replica of the city closer to its physical counterpart (Jeddoub et al., 2023).

[2] https://www.ogc.org/standard/citygml/0/
[3] https://www.ogc.org/standard/sensorthings/

Jeddoub et al. (2023) also pointed out that various initiatives now address data interoperability and data integration challenges in the urban environment in the SC domains. For example, the FIWARE smart data model[4] has shown its capabilities in harmonising SC data, namely sensor streams, for more than 200 cities worldwide (Bauer et al., 2021a). Data interoperability is the core challenge of the Open Geospatial Consortium (OGC) community, which focuses on ensuring clear semantics, fostering data modelling, and developing APIs to support application web development and facilitate data access and exchange. Thus, based on the review of OGC initiatives and standards, an overall reference architecture has been defined to create an open and interoperable system of systems to make SCs and Digital Twins a concrete reality (Atkinson et al., 2022).

As an example of a Digital Twin approach, innovation project DUET is described which took place between 2019 and 2022. DUET was designed to leverage the advanced capabilities of new data and computing technology to evolve the traditional public policy-making cycle using large open data sources. The aim was to help public sector decision-making become more democratic and effective, both in the short and long term, through developing and using Digital Twins for policy impact exploration and experimentation in entire cities and regions. These digital replicas of a city system could:

- (a) Enhance day-to-day city management by helping city managers react quickly to real-time events through rapid experimentation of different decision impacts, and
- (b) Enable city managers from different units to explore and discuss city issues with citizens and businesses in a visual, easy-to-digest way via a common view to ensure longer-term policy decisions are more effective and trusted.

Thanks to the 3D interface, public administrations can, for the first time, more easily harness the collective intelligence of all policy stakeholders to tackle complex, systemic policy problems that require innovative thinking from multi-sectors to develop transformative solutions. The DUET Digital Twin prototype was developed and tested in cities and regions at different points in their digital transformation journeys. Digital Twin prototypes have been created in the Flanders region (Belgium), the city of Ghent (Belgium), the City of Athens (Greece), and the City of Pilsen (Czech Republic). DUET created the concept of Policy-Ready-Data-as-a-Service and ensured all cities across Europe would be able to create their own Digital Twins that address ethical considerations around data use whilst also complying with Europe’s stringent privacy and security regulations.

It is common for Digital Twins to use data acquired by sensors whose performance, accuracy, and reliability have been thoroughly tested, verified, and confirmed through rigorous scientific or technical methods. On the other hand, citizen science initiatives commonly use low-cost sensors which are affordable and can be deployed in large numbers that allow measurements with high spatial resolution. The limitation is that the sensors are typically manufactured using cost-effective materials and production techniques which allow them to be produced in large quantities at relatively low prices, but their output can be less accurate and reliable than higher end sensors.

In this deliverable, we combine the efforts of the H2020 DUET project in the development of local Digital Twins and the COMPAIR project in collecting standardised, calibrated CS data that can be used as input to a Digital Twin. Section 2 describes the citizen science data

[4] https://www.fiware.org/smart-data-models/

acquired during COMPAIR using different types of sensors. Section 3 covers the sensor data standardisation and calibration to enable data from CS sensors to be integrated into a Digital Twin. In section 4, integration of CS data in the DUET project is described, and the results and examples of the Digital Twin implementation are found in section 5.

# 2. Sensor Data in COMPAIR

## 2.1 Traffic Counter Sensors

Telraam v2 traffic counter sensors deployed in the COMPAIR project monitor a street from a citizen's window and output the traffic volumes of different modes of transport, including pedestrians, bicycles, cars and heavy traffic. During the COMPAIR project, 115 Telraam sensors were delivered to Flanders, Athens, Plovdiv, Sofia and Berlin pilot areas. Fifty sensors that were delivered to the Flanders region are integrated into the Digital Twin in Flanders.

## 2.2 Air Quality Sensors

In addition to the traffic sensors, several air quality sensors are deployed in the COMPAIR project:

- SODAQ Air mobile sensors and sensor.community static sensors measuring particulate matter (PM), temperature and humidity;
- OnePlanet sensors measuring nitrogen dioxide (NO2), which is an air pollutant linked to traffic;
- bcmeter sensors measuring black carbon (BC), which are emitted from diesel engines and stove heaters.

Their output and relevant metadata are standardised according to the Open Geospatial Consortium (OGC) SensorThingsAPI data model (see section 3) and available through the COMPAIR API for potential integration into a Digital Twin.

All the measured air quality pollutants are linked to human activities and thus tend to be elevated in urban environments, and they are subjected to applicable limits in international air quality standards with limit values. D5.1: Guide to Air Quality Monitoring provides a deeper dive into air quality pollutants and sensors used in COMPAIR. Given that the sensors provide measurement data with acceptable accuracy, integrating such sensors in a Digital Twin model would enable insight into the spatially-resolved air quality mapping of regions that may not be accurately modelled due to the complex topography of the urban landscape (e.g. street canyons). It would also facilitate data-driven decision-making to improve the overall population's health, and promote sustainable practices, ultimately contributing to healthier and more livable communities.

# 3. Data Standardisation and Calibration

Digital Twins integrate and use several data sources to enable the modelling of complex scenarios. The input data may be generated by different sensors owned by respective partners, can vary in format, and needs to be accompanied by relevant metadata to enable the correct interpretation. Therefore, interoperability of the input data is key to effortless creation of a Digital Twin.

In COMPAIR, we use the OGC SensorThings API (OGC-STA) data model to address the interoperability challenge. The modal provides an open, geospatial-enabled, unified way to interconnect Internet-of-Things (IoT) devices, data and applications. OGC-STA covers two main modules: sensing and tasking. The sensing module provides a standard way to manage and retrieve observations (sensor measurements) and metadata from differently configured IoT sensor systems. Additionally, the tasking module can be used for parameterizing sensors IoT and actuators that can be triggered.

By making use of the OGC-STA data model air quality sensor measurements in the project, we ensure that the sensor data, regardless of the type of the measurement device (“Thing”) is accompanied by relevant metadata (e.g. measurement unit and its description) in a known format, is stored in a container (FROST server) where the data access options are extensive, unified and well-documented.

Using such a standard enables the data to be unified so that the integration of different types of devices into the Digital Twin becomes effortless. In the table below, you can see an example of two queries and the resulting response, which demonstrates the similarity of the data structure.

*Table 1: Examples of two queries to access the latest sensor observations from two different types of sensors measuring unique air quality parameters using the OGC-STA standard.*

| Thing | OnePlanet NO2 | SODAQ PM |
|---|---|---|
| Query | https://services.dev.wecompair.eu/receiver/sensors/Things?$filter=startswith(id,%27op%27)&$select=id,name&$expand=Datastreams | https://services.dev.wecompair.eu/receiver/sensors/Things?$filter=startswith(id,%27sodaq%27)&$select=id,name&$expand=Datastreams |
| Response | {<br>"@iot.count": 7,<br>"value": [<br>{<br>"@iot.id": "op_04B5E12850553441302E3120FF051D38",<br>"name": "Athens 2",<br>"Datastreams@iot.count": 2,<br>"Datastreams": [<br>{<br>"@iot.selfLink": "https://sensorthings.wecompair.eu/receiver/s | {<br>"@iot.count": 230,<br>"value": [<br>{<br>"@iot.id": "sodaq-350457790904377",<br>"name": "350457790904377",<br>"Datastreams@iot.count": 5,<br>"Datastreams": [<br>{<br>"@iot.selfLink": "https://sensorthings.wecompair.eu/receiver/sensors/Datastreams('sodaq-350457790904377_1')", |

| | | |
|---|---|---|
| | ensors/Datastreams('7295bc26-6e61-11ee-b5ce-6ffe362c63a2')",<br>"@iot.id":<br>"7295bc26-6e61-11ee-b5ce-6ffe362c63a2",<br>"name": "NO2 1",<br>"description": "NO2 electrochemical gas sensor signal",<br>"observationType":<br>"http://www.opengis.net/def/observationType/OGC-OM/2.0/OM_Measurement",<br>"unitOfMeasurement": {<br>"name": "Micrograms per cubic meter",<br>"symbol": "µg/m3",<br>"definition":<br>"http://dd.eionet.europa.eu/vocabulary/uom/concentration/ug.m-3"<br>},<br>"observedArea": {<br>"type": "Point",<br>"coordinates": [<br>23.722755,<br>37.957225<br>]<br>},<br><br>… | "@iot.id":<br>"sodaq-350457790904377_1",<br>"name": "PM1.0",<br>"description": "Raw sensor output of sensor for various bins of particulate matter",<br>"observationType":<br>"http://www.opengis.net/def/observationType/OGC-OM/2.0/OM_Measurement",<br>"unitOfMeasurement": {<br>"name": "Microgram per cubic meter",<br>"symbol": "µg/m3",<br>"definition":<br>"https://qudt.org/vocab/unit/MicroGM-PER-M3"<br>},<br>"observedArea": {<br>"type": "Point",<br>"coordinates": [<br>0,<br>0<br>]<br>},<br><br>… |

* *Differences in the queries are highlighted in red, and some of the similarities in the responses are highlighted in blue for ease of visibility.*

Table 1 shows that despite the fact that sensor data is sent from different types of devices that are owned by different sensor suppliers, little effort is needed to integrate data into a Digital Twin from various sources when such a standard is used.

In addition to data standardisation, COMPAIR also implements a cloud-based online sensor data calibration approach where data from high-end reference stations are combined with low-cost local sensor data to increase the data of air quality sensors. The details and validation of this approach are found in D3.5: Data Processing and Data Calibration of Air Quality Sensors. Increasing sensor data's accuracy and reliability enables low-cost sensor data to be inputted to a Digital Twin. In the following section, we outline an integration approach from the DUET project where data from various sources, including but not limited to CS sensors, are integrated into the developed Flanders and Athens Digital Twins.

# 4. Citizen Science Data Integration

In the context of the DUET project, the Flanders and Athens Digital Twins[5] were developed, which involved a 2D/3D map visualising information such as open-source or simulated (from models) air quality and traffic data, public transport data, landmarks, etc.

When combining data from heterogeneous sources, the data which is supplied by different providers may include personal data including but not limited to unexplicit personal data such as or licence plates of vehicles or cell tower data. Such data has to be depersonalised in order to comply with General Data Protection Regulation (GDPR) regulations of the EU. One important learning from DUET was that responsibility of data depersonalization should fall with the individual upstream data providers since these providers have optimum awareness of which aspects of the data can be considered personal. Therefore in DUET, input data was ensured to be depersonalised before integration into the Digital Twin.

Once the data is ready to integrate, specific software components are involved in integrating any data source of interest into these Digital Twins. These components are the following:

- The Message Streaming Platform allows different components to communicate and exchange data in an asynchronous way through messages in specified channels (topics). It is realised with Apache Kafka;
- The Message Broker controls the data flow from/to them and the Message Streaming Platform. Part of the Message Broker is also a web sockets server, transforming the communication messages to be more easily available to UI components;
- The Asset Catalog allows users to register, update, delete, and search for information about data sources and models that can be used in the Digital Twins;
- The Data Connectors enable access to internal and external assets through REST APIs, Blob storage, and Linked Data Event Streams. Data connectors offer a universal way of retrieving data from 3rd party REST APIs or the capability to implement adapters for more specialised interfaces;
- The Map Visualiser encapsulates the business and presentation logic of the 2D/3D visualisations. It integrates various data sources, such as geographical data, air pollution data, noise quality data, traffic data, etc., and presents them to the user in the form of 2D and 3D maps.

In order for new data sources to be integrated into the Digital Twins (also followed for the Telraam data as presented in the previous section), the steps are the following:

- A registered data provider inserts the relevant data source metadata in the Asset Catalog (Figure 1);
- The Asset Catalog notifies the Data Connectors and Message Broker components upon registration;
- The Message Broker creates a new topic in Kafka and updates the web sockets list;

[5] https://platform.citytwin.eu/app/map

- The Data Connectors attempt to automatically register and expose the new data source generically. If this fails, further manual configuration is necessary to incorporate the new data;
- Once the data source and the relevant topics are ready in the Map Visualiser, the proper UI adjustments/configurations need to be made so that the data can be visualised in the best possible way for users.

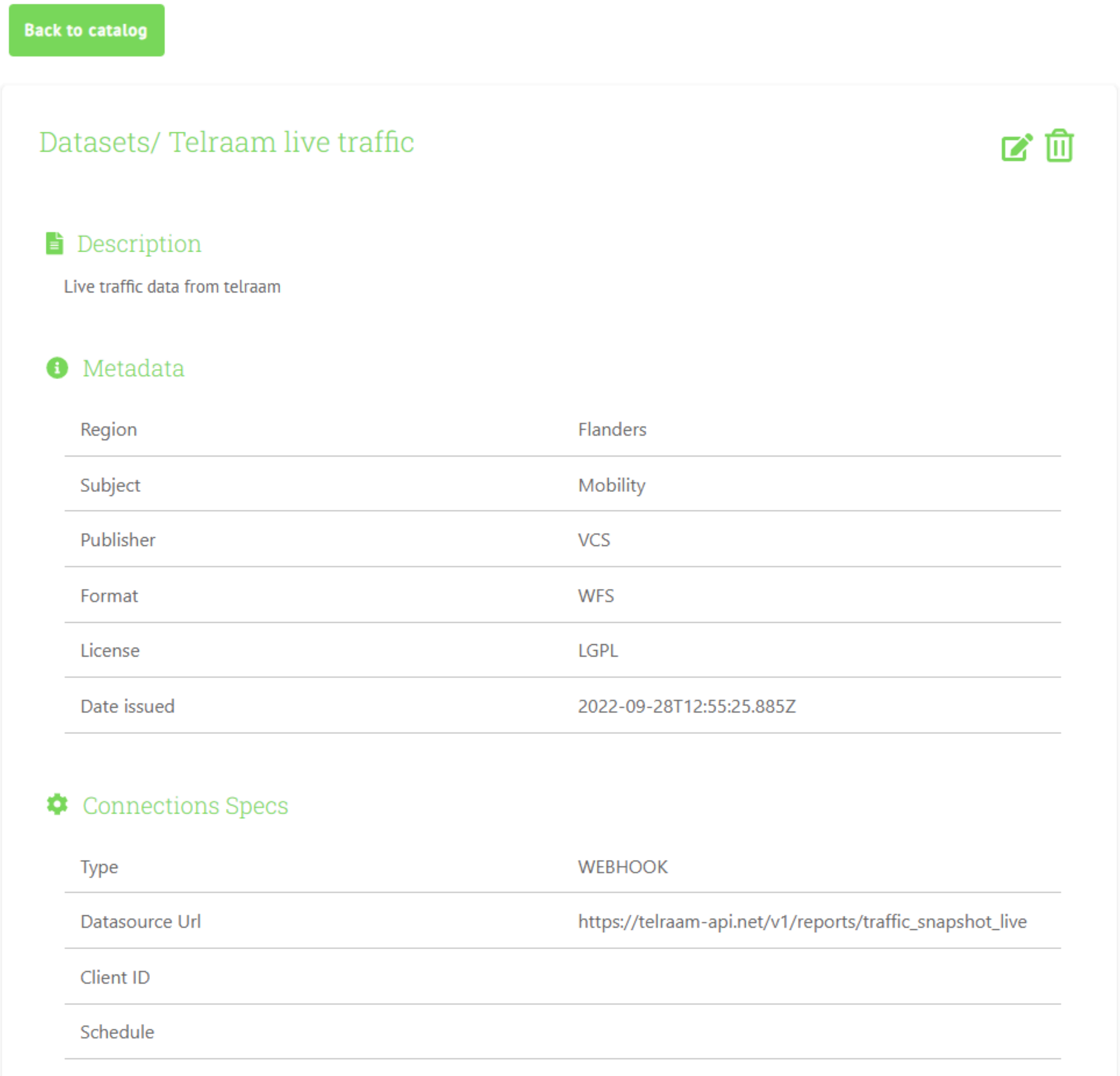


*Figure 1: The Telraam metadata in the Asset Catalog*

The next chapter 5 shows concrete results of this integration.

# 5. Results of Citizen Science Data Integration into Digital Twins

The DUET Digital Twin prototypes in Athens, Flanders (City of Ghent) and Pilsen make use of a combination of local and regional/national GIS data (terrain data, 3D building data, network data about roads, waterways and public transport, and even data about urban greenery likes trees are integrated. Also, air quality data and traffic count IoT sensor data are integrated to create a 'living' virtual city replica to, e.g. address the complex interrelation between systems (traffic, noise, air quality) and understand the effects, using simulation models.

The Cesium visualisation platform[6] was used with a so-called T-Cell[7] open architecture integrating a Kafka Databroker[8] and asset registry to visualise simulation models and depict the latest status of IoT sensor data. The DUET Digital Twin allows stacked simulations, starting with traffic modelling. Air quality and noise simulations can be made based on the outcomes of the traffic model and can be jointly visualised in the Digital Twin visualisation platform.

In COMPAIR, the data sources include data from reference stations that measure air quality and weather and data from IoT devices equipped with sensors that measure air quality through pollutant measurements such as Particulate Matter (PM), Nitrogen Dioxide (NO2), and Black Carbon (BC), and traffic counting sensors that measure traffic intensity. The data from these sources follow the OGC SensorThingsAPI standard, which helps overcome the cost of data integration from these sources and increase their usability. The availability of standardised services enables the integration into Digital Twins like DUET. COMPAIR and DUET show the advantages of standardised services as part of a data space, similar to the EU common dataspaces concept. Below, you can find two different Digital Twin case approaches, applied in Flanders and Athens, about how a Digital Twin can contribute to using Citizen Science data and involve citizens in the urban planning process.

*Digital Twin Case 1: Flanders pilot*

**Goal**: Integrating Citizen Science APIs into a Digital Twin to visualise the most recent measurement data and to provide a view of the historical data.

**Integration**: During the COMPAIR project, the Telraam API was adapted to deliver results every 15-minutes instead of hourly results to improve its applicability for policy-making purposes. The metadata was also changed to fit into standardised metadata standards like DCAT-AP and ISO 19115. The Telraam data has been integrated into the DUET catalogue and asset registry.

**Visualisation**: Figure 1 depicts the Telraam traffic count sensor road segments. The line colour shows the measured traffic volume, and the graph visualises traffic categories (pedestrians, cyclists, cars and heavy vehicles) over a selected period. Also, the official counting loop data

[6] https://cesium.com/
[7] https://www.digitalurbantwins.com/technical-approach
[8] https://kafka.apache.org/

usually installed on the highway exits and primary roads is integrated into the DUET Digital Twin. Both datasets complement each other and respectively provide a view of traffic on the main traffic axes and the local underlying road network. Figure 2 depicts the result of a local citizen science air quality sensor using the sensor.community API[9]. The sensor location, status and most recent measurements are combined in a single view.

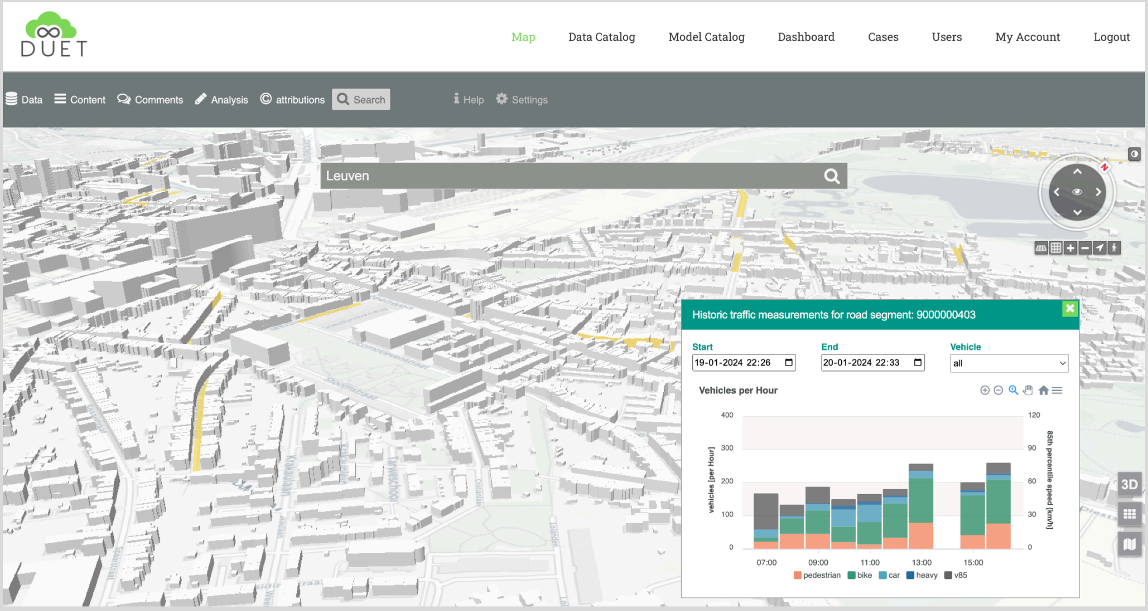


*Figure 2: The integration of Telraam Traffic Count data into the Flanders Digital Twin*

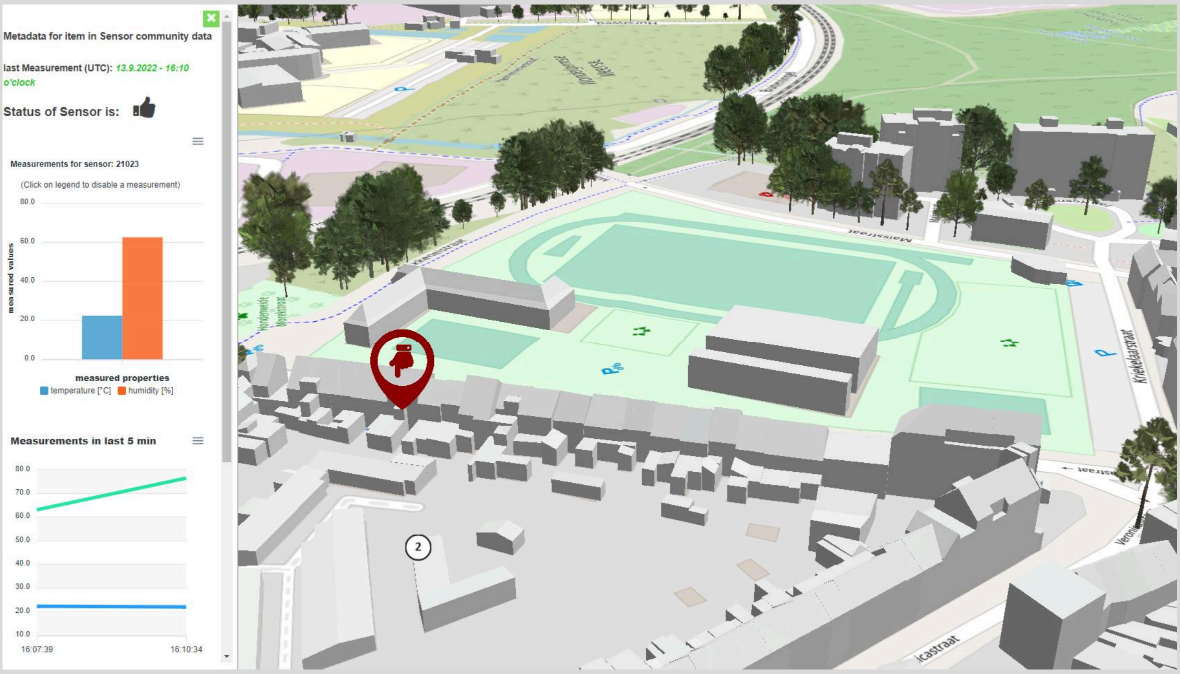


*Figure 3: The integration of Citizen Science Air Quality data into the Flanders Digital Twin*

## *Digital Twin Case 2: Athens pilot*

**Goal**: Evaluating the impact of implementing green routing in Athens Stadiou Street, allowing only pedestrians and cyclists, including evaluating citizen feedback and impact on daily mobility using

[9] https://sensor.community/en/

traffic modelling.
**Integration**: An open street map-based traffic model of Athens integrating road capacity data and a limited set of census data was used to calculate a basic traffic model of the entire city. The DUET Digital Twin provides an interface to change the road capacity in both directions. Reducing the capacity to 0% simulates a close-down for all motorised traffic (cars and heavy vehicles).

**Visualisation**: Figure 1 depicts the Athens Digital Twin cases, including the Green Routing case of Stadiou Street. Figure 2 provides detailed information about the Stadiou green route simulation, explaining how to browse the traffic model and how to add comments using geo-tagging. Figure 3 depicts the result of the road closure and shows the changes in road use (Green to Red) and the nearest public transport stops, including bus and metro.

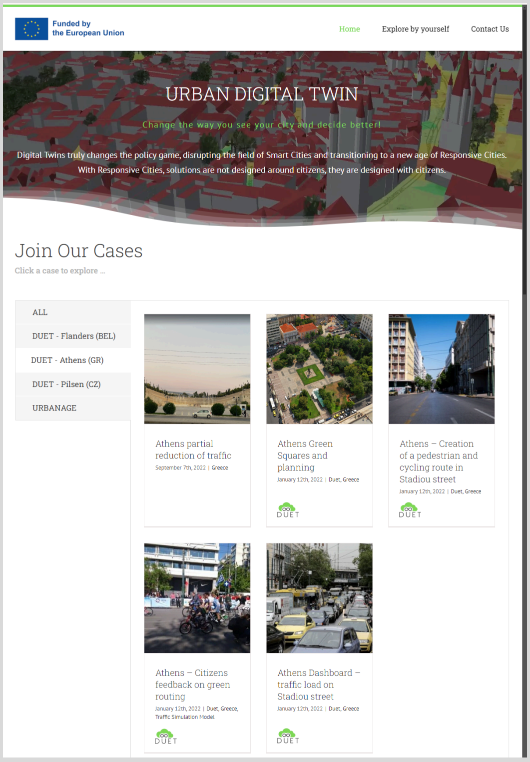


Figure 4: Athens Digital Twin cases overview

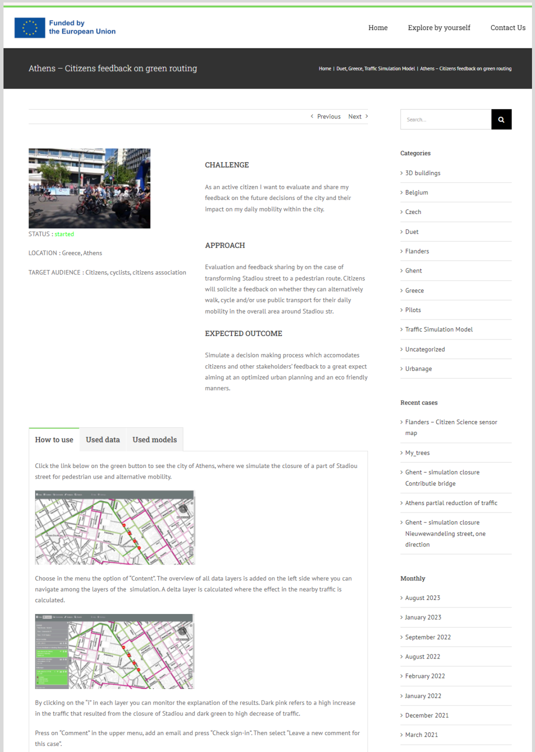


Figure 5: Use of a Digital Twin for Citizen Involvement in Athens - The Citizen Feedback on Green Routing case

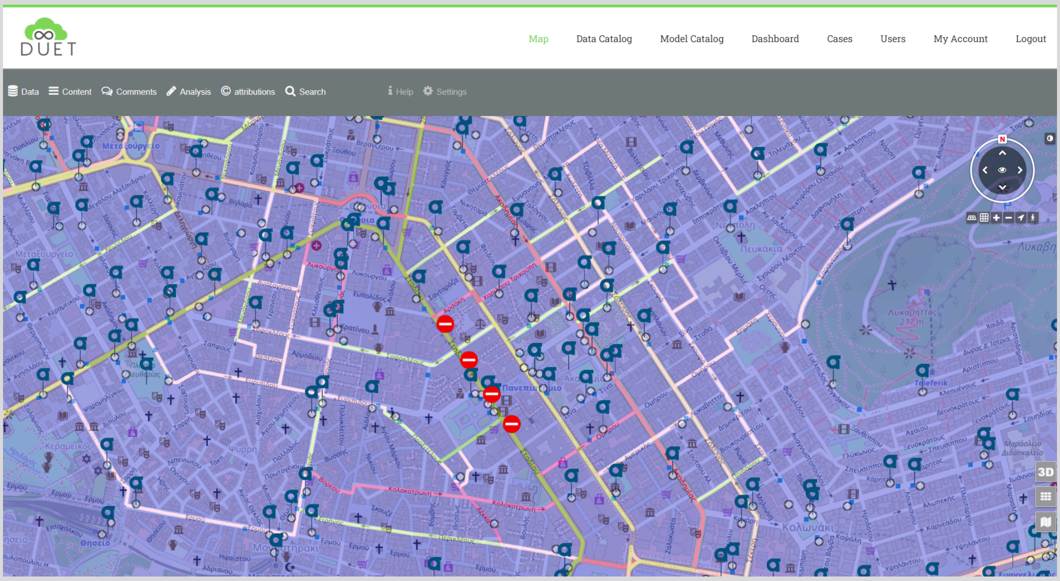


*Figure 6: The Green Routing road closure effect on the surrounding streets using a traffic model.*

The Flanders and Athens Digital Twin pilot cases show how a Digital Twin can support evidence-informed policy-making by integrating Citizen Science data and how a Digital Twin, including complex traffic modelling, can involve citizens by allowing geo-tagged feedback to optimise decision-making in the smart city and urban planning field.

# 6. Conclusions

Citizen science data can significantly enhance the creation and maintenance of Digital Twins of cities by providing additional spatial coverage granularity and validation capabilities, ultimately leading to more accurate, comprehensive, and responsive urban Digital Twins. In this deliverable, we describe the different types of CS sensor data collected in project COMPAIR and how the data is standardised and calibrated, which would greatly facilitate the integration of the CS data into a Digital Twin. Section 4 outlines the integration approach used in the DUET project, which integrates similar types of sensor data into Flanders and Athens Digital Twins. Section 5 shows results and examples from the developed Digital Twins. These examples from COMPAIR and DUET demonstrate that CS data can be combined with various data sources and integrated into a Digital Twin to support evidence-based decision-making.

The decision-making process in urban planning is a collaborative effort, often involving city officials, urban planners, and citizen science initiatives. A potential scenario could start with a city official or urban planner who aims to address air pollution by restricting traffic on a busy road segment. In this scenario, they can collaborate with citizen science initiatives, which enable comprehensive monitoring of the region via air quality and traffic sensors. The data output from these sensors can then be fed into the developed urban Digital Twin. The Digital Twin can be used to simulate several restriction scenarios and their potential impact on air quality and traffic flow. A decision can then be made and implemented in a small-scale, and its effects on the local and surrounding environments can be monitored using the same sensors that are used to further improve the Digital Twin.

New EU initiatives, like the URBREATH project which started in 2024, will further integrate Digital Twin, citizen involvement, and CS initiatives to support nature-based solutions in nine EU cities, including the three DUET pilots of Flanders, Athens and Pilsen.

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