Fast Urban Digital Twin Prototyping Based on Open Data

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Abstract

As cities experience the digital transformation of the information era, informed decision-making becomes a first-hand necessity. Urban Digital Twins (UDTs), as the natural evolution of the smart city, are digital replicas of urban environments that model their structural and functional elements. However, their implementation is often hindered by technical complexity, data requirements, and resource demands. This paper proposes a globally applicable framework for prototyping UDTs by leveraging open-source software and global open data. Based on recent UDT implementations, essential system components and fundamental data typologies are identified to establish a minimal baseline for UDT prototypes. From the identified system components, a novel modular and automated UDT prototyping platform, UrbanDT, is developed and documented, integrating processing capabilities, data management, and interactive 2D and 3D visualisation. A fully automated workflow is presented for assembling UDT prototypes, encompassing baseline data acquisition, processing, and system configuration. The framework is validated through a UDT prototype for Bologna, Italy, demonstrating its applicability for data exploration and mobility-related street network analyses. Results indicate that the proposed framework enables reproducible and extensible UDT prototyping, offering a practical approach for cities and researchers to explore UDT concepts before committing to full-scale implementations.

1. Introduction

In recent years, the paradigm of the smart city has evolved towards the concept of Urban Digital Twin (UDT) or the Digital Twin City. As cities evolve from gathering information to using information, Urban Digital Twins emerge as cornerstones in the development of smart cities, providing tools for city planners to model and simulate urban areas and implement changes (Martella et al., 2023). Nevertheless, the implementation of fully functional UDTs are usually expensive and complex enterprises, as they involve the interaction of multiple systems and the integration of a variety of data sources.

As smart cities evolve, the implementation of UDTs presents significant technological, economic, and data-related challenges (Ferré-Bigorra et al., 2022). Technologically, UDTs require the integration of heterogeneous systems and data sources, such as GIS, sensor networks, and 3D visualisation platforms, supported by robust digital infrastructure and interdisciplinary expertise. Economically, full-scale UDTs demand substantial investments in high-quality datasets, software, and continuous system maintenance, requiring long-term collaboration among public institutions, private stakeholders, and research organisations. Data heterogeneity, quality assurance, accessibility, and security further complicate the implementation UDTs. In this context, UDT prototypes provide a minimal yet functional entry point, enabling cities to experiment with technologies, test data workflows, and assess potential applications before committing to large-scale systems, supporting their widespread adoption.

This paper first analyses, from a technological perspective, the concept of Urban Digital Twin, its system components, and recurrent data associated, deriving a minimal baseline for the creation of UDT prototypes. Then, by leveraging open-source software and global open data, it documents a modular platform for the deployment of UDTs and an automated pipeline for the creation of UDT prototypes from anywhere in the world, delving into global open datasets as baseline data for UDT prototypes. Finally, a case study featuring the implementation of a UDT prototype for the city of Bologna, Italy is illustrated to validate the proposed UDT prototyping framework, showcasing the platform visualisation and processing capabilities.

2. Literature Review

As UDTs gain increased popularity, its concept transcends from the mere digital representation of objects, to a digitally-enabled system of systems framework that actively integrates multiple urban processes. In order to correctly identify the literature related to UDTs, its definition must be addressed, indicating what an UDT actually is. The overarching concept of Digital Twin has been previously explored under many different perspectives, including the work of Abdelrahman et. al. (Abdelrahman et al., 2025), where the authors reviewed a large number of papers to derive definitions of Digital Twins in various domains, including urban. They defined the Urban Digital Twin as: *"... a spatial–temporal virtual representation of a real-world urban area or city, mirroring its states during its lifecycle through IoT sensors. It is used to monitor and analyse urban systems across different time spans to aid in decision-making and can be extended to simulate and predict various states and scenarios"*.

From this definition, conceptually, the UDT is defined as a virtual representation of a real-world urban environment, which is constantly being updated through data streams (e.g., IoT networks), and that enables processes and analyses, such as forecasts and simulations. It also highlights the use of multi-temporal geospatial data. The label of "Urban Digital Twin" is then used as an overarching framework: digital representations of urban areas, that posses certain characteristics like visualisation capabilities, 3D support, data management and integration, and data processing (Fuller et al., 2020).

From documented recent UDT implementations from cities like Florence (Italy) (Adreani et al., 2024), Sofia (Bulgaria) (Vitanova et al., 2025), or Helsinki (Finland) (Hämäläinen, 2021) certain components arise as fundamental for the development of UDTs. Primarily, data visualisation and 3D support was the most important system requirement for UDT implementations. Other data visualisation strategies like dashboards were also common.

In addition to visualisation, data processing was also deemed fundamental for the implementation of UDTs. Processing modules (referred also in the literature to as core modules, analysis modules, or simulation engines), enable the manipulation and processing of data within an UDT. Processing modules benefit from server-side technology and cloud computing, enabling the decoupling of visualisation and processing, especially for web-based tools.

Data is the single most important element of the UDT. Without data, neither visualisation nor processing is possible, as there would be nothing to see and nothing to process. Data storage in UDTs is mostly performed by database management systems and data lakes, which are used for storing base geospatial data such as 3D city models, street networks, building footprints, and land use and land cover.

Complementing data storage, UDT implementations require certain data typologies to correctly reflect urban processes and scenarios. From documented UDT implementations data typologies like 3D city models, building footprints, land cover data, street networks, traffic and mobility, air quality, environmental information, elevation, and socioeconomic data were commonly found in UDT implementations.

3. Urban Digital Twin Platform

The implementation of an Urban Digital Twin (UDT) is a massive undertaking that involves technical expertise and resources. As open data enables global applicability, platforms that leverage automated workflows, processing capabilities, and data interoperability are essential. Based on the identified system components previously described, UrbanDT, a novel UDT prototyping platform, is proposed by leveraging open source software as UDT components and containerisation technology. Figure 1 depicts the proposed system structure, specifying the underlying software technologies that compose the platform modules, the data flow, and the connections between them.

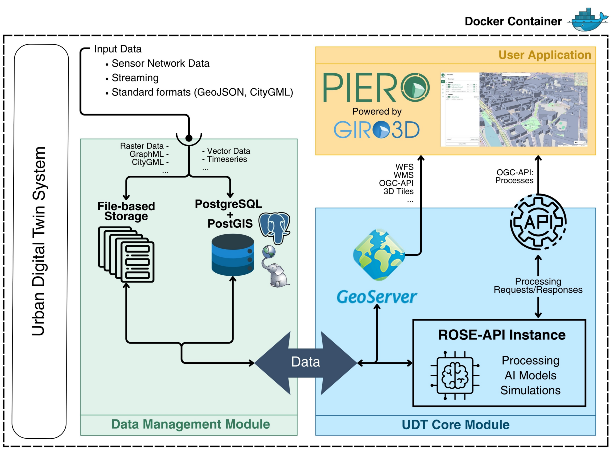

Figure 1. UrbanDT platform system structure.

The UrbanDT platform is composed by three main modules, namely the core module, which handles data sharing and processing capabilities; the data management module, which handles data input and storage, and the user application module, which enables user interaction with the UDT system and data visualisation. The UrbanDT platform is published as open-source software in a GitHub repository (Duque Ordonez, 2025). Each module is further described in the following subsections.

3.1 Core Module

The UDT core module is responsible for providing processing and data sharing capabilities to the entire system, serving as a bridge between information and user applications. To fulfil these roles, two specific software components are integrated within this module. The first is the open-source application ROSE-API which provides processing and OGC API-based data sharing capabilities. The second is the well-established GIS Server GeoServer, which provides data sharing capabilities through various OGC standards.

3.1.1 ROSE-API as Processing Engine: ROSE-API (Duque et al., 2024) is a server-side web platform for managing, processing, and sharing geospatial data through multiple OGC API standards. Designed with reusability in mind, ROSE-API incorporates dynamic components and offers a high degree of configurability. Two key features enable this open-source software to be integrated within the core module, namely its processing capabilities provided through OGC API - Processes standardised interfaces and functionalities; and its standardised REST API which is primarily used to deliver processing services.

Processes in ROSE-API are custom Python scripts with a specific structure. Each processing script consists of metadata related to the process such as input and output schemas, description or title, and a function to be executed. By enabling the creation of custom Python code, even during runtime, ROSE-API enables an extensible way to create processing pipelines within the system. In addition, processes may be executed asynchronously, enabling cloud-like execution of time-consuming computations without blocking user interactivity.

3.1.2 GeoServer as Data Sharing Service: GIS Servers, as tools for sharing and managing geospatial data, are beneficial for UDT implementations as they foster interoperability through standardised interfaces for data access and manipulation. In the context of UrbanDT, GeoServer is used as a mediator between the data management module, which handles data storage and acquisition, and user applications, which manage visualisation and user interaction.

As a complement of the processing capabilities of the ROSE-API platform, the open-source GIS server application GeoServer (GeoServer Development Team, 2025) is included within the core module to handle data sharing and interoperability. It supports multiple standardised interfaces for data access and management, such as the OGC Web Services family (e.g., WMS and WFS), and the OGC API - Features standard. Such standards allow data exchange between heterogeneous systems in consistent and interoperable data formats.

GeoServer ensures the data integration of various data sources such as 3D city models, environmental information or mobility networks within the UDT system. It also supports layer reprojection, 2D vector and raster tiling, layer styling, geospatial web cache for large datasets, support for rendering both vector and rasters as images through the WMS standard, multiformat output capabilities, and a user-friendly web administration application interface.

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3.2 Data Management Module

Complementing the data-sharing capabilities and data interoperability offered by the core module, the data management module handles data storage and data input to provide reliable and accessible storage capacity for the UDT system. The data storage and input strategies of the data management module facilitates maintenance, timely update, and seamless addition of data to the UDT system. The data management module leverages both structured and unstructured data storage for spatial and non-spatial information.

3.2.1 PostgreSQL and PostGIS for Structured and Geospatial Data: Structured data are managed through multiple PostgreSQL databases enhanced with the PostGIS extension, which provides support for geospatial data. These databases serve as the primary storage solution for both the UDT system and the ROSE-API application.

PostgreSQL (PostgreSQL Global Development Group, 2025) is an open-source relational database management system that serves as the main component of the data management module within the UDT platform for the storage of structured spatial and non-spatial feature data. It allows efficient handling of large, complex datasets, which are typical of urban environments, where multiple data types, such as sensor readings, administrative boundaries, mobility records, and environmental indicators, must coexist and interact. It also supports various indexing methods, query optimisation, and a transaction management system, making it highly suitable for applications that require high performance and data integrity, such as UDTs. The PostGIS (PostGIS Project Steering Committee, 2023) extension provides geospatial capabilities to PostgreSQL by adding spatial data types, spatial functions and a specialised spatial index, transforming it into a spatial database. Furthermore, PostGIS supports three-dimensional geometries and temporal properties, which are essential for modelling dynamic urban environments and representing elements such as buildings, networks, and mobility patterns within UDTs.

By default in UrbanDT two databases are available: one dedicated to the configuration and data management of the ROSE-API application; and a second database for managing the configuration of the UDT system, providing structured data storage for vector datasets, and storing metadata details for its subsequent access and use. The UDT system database streamlines vector-based geospatial data between the data management module and the visualisation module, using GeoServer as a proxy. Both databases are made available outside the Docker container through a dedicated port for its further use by expert users and system administrators.

3.2.2 Raw File-Based Storage and Input Data Support: In addition to database storage, raw data is persisted in their native formats as unstructured data using the file system. The storage of raw, original data enables their usage for direct analyses and processing, as well as facilitates the implementation of cloud-based sharing strategies for cloud-optimised data formats like Cloud-optimized GeoTiff (COG), ZARR, or GeoParquet.

This file-based storage strategy also provides the system with flexibility for the addition of new datasets. Using shared folders, system administrators may add new data to the system. Metadata records allow the in-disk stored data to be utilised by the core module for data sharing through GeoServer, for analytical processes, as well as for cataloguing purposes. This enables also data from continuous monitoring sources to be integrated into the platform by directly inserting data from observations into the database, or by constantly storing and publishing new datasets as they are generated.

3.3 User Application Module

The final component of the system addresses the visualisation capabilities and user interactivity of the UDT platform. The user application module consists of a web application with 2D and 3D data visualisation support, built upon the open-source web application Piero (Giro3D Development Team, 2025b) and the 3D web engine Giro3D (Giro3D Development Team, 2025a).

The user application enables user interactivity with the system and connects users with data and processes, provided mostly by the core module through OGC standardised interfaces. By leveraging geospatial information standards for data sharing, the user application module displays interactive maps that enable users to explore and analyse urban data. Furthermore, data analysis capabilities are provided by the core module through OGC API – Processes interfaces. The user application also supports dynamic layer configuration, which means that the addition, removal, or modification of geospatial layers shown within the user application can be performed at runtime without the need of redeploying the application.

4. Data Baseline for Urban Digital Twin Prototypes

To construct UDT prototypes, in addition to a supporting platform that can manage data, visualisation, and processing capabilities, a robust and diverse data foundation is necessary. The utilisation of global open data is fundamental for constructing such data baseline, as it enables free access to information with reasonable quality, specially in global contexts. The use of global open data also makes UDT prototypes generalisable and reproducible to any urban area around the world.

4.1 Base Data Requirements

From the description of various UDT implementations in academic literature, five data typologies were identified as fundamental for the implementation of UDTs. These include 3D city models that enable three-dimensional support for visualisation and analyses; the street network, which is a fundamental part of the urban fabric and determines the movement of people and vehicles; Digital Elevation Models (DEMs) which provide elevation data that enriches existing information and serve as a base layers for 3D representations; land cover information which complement city models and provide further context to urban areas; and finally population, which enables social and demographic spatial analyses.

Despite the importance of real-time monitoring data for UDTs, as these kind of information is oddly specific and not always provided open, the provision and usage of real-time data is out of the scope of this research. However, it is worth mentioning that the UrbanDT platform supports the integration of constant monitoring and real-time data.

4.1.1 3D City Model from Building Footprints: 3D city models, together with other modelling approaches like BIM (Building Information Modelling) or CIM (City Information Model), form the foundation for both visualisation and utilisation of UDT systems (Lehtola et al., 2022). Building high-resolution 3D city models is a complex and expensive task, as it usually requires surveys to extract high-resolution Digital Surface Models (DSM), large-scale 3D reconstructions, and texturing. Due to its elevated cost, there are no globally available open 3D city models, at the moment, that can be used for building general UDT prototypes. However, to overcome this limitation, research shows that in practice it is possible construct fast and general 3D city model representations from 2D data. A process called extrusion is generally utilised to transform 2D building footprints into 3D representations of city infrastructure, by leveraging the 2D polygons representing the building locations, and building height information (Ohori et al., 2015).

Global open data for 2D building footprints is in fact available, but they must possess building height information to construct 3D city models. Considering this limitation, two datasets of building footprints were selected for the construction of 3D city models due to their global coverage, convenient download procedures, and their particular focus towards 3D modelling. These datasets are the 3D Global Building Footprints dataset (3D-GloBFP) (Che et al., 2025), and the Bing Maps' Global ML Building Footprints dataset (Microsoft / Bing Maps AI, 2025).

4.1.2 Street Networks: Street networks are a fundamental part of the urban environment, as they represent the way in which the roads and paths of an urban area are arranged and how they are connected. Street networks model the streets where cars and other motorised vehicles circulate, the infrastructure that pedestrians and cyclists use, and the network of public transport around urban areas. The study and analysis of the street networks of multiple means of transportation provide a holistic view of cities and urban areas, and help characterise all kinds of urban mobility (Klinger, 2017).

The global dataset selected for representing the street network is OpenStreetMap (OSM) (OpenStreetMap contributors, 2017). This crowdsourced, free, and open sourced map of the entire world is widely used by the academic and open-source software community for its reasonable accuracy and worldwide coverage (Barrington-Leigh and Millard-Ball, 2017). Due to its global coverage, OSM is used as the data source of street network information for UDT prototypes, providing baseline data for road, pedestrian, cycling, and public transport street networks and infrastructure. The specific download and processing procedures for each street network type are further described in (Duque and Brovelli, 2025) .

4.1.3 Digital Elevation Model: DEMs are used in the context of UDTs to provide terrain and elevation features. This dataset fulfils two roles: i) providing elevation information to enrich other data sources, such as the street networks; and ii) provide the 3D topology and elevation for visualisation and spatial processing.

For this purpose, the NASADEM (NASA JPL, 2020) dataset was selected as the source of global open elevation data. This dataset is a digital elevation model produced by reprocessing and enhancing data from the Shuttle Radar Topography Mission (SRTM). According to its documentation, NASADEM provides topographic data (i.e., terrain) at 1 arc-second resolution (approximately 30 metres) with a near-global coverage, between 56°S and 60°N. It combines original SRTM radar measurements with additional elevation sources, refined algorithms, and void-filling techniques to improve accuracy.

4.1.4 Land Cover: Land cover information in UDT systems contextualise the urban environment to enable different analyses. Three datasets were selected as alternative sources of land cover information, namely the Copernicus-based CGLS-LC100 global land cover (Buchhorn et al., 2020), the Google's Dynamic World v1 (Pesaresi and Politis, 2023), and the GHSL Global Settlement characteristics dataset (Brown et al., 2022), all available with open licenses and provided in global extents. Each of the selected datasets represent different characteristics of the urban area.

The CGLS-100 dataset provides broad 100-metre resolution global land cover data over 23 thematic classes, ideal for covering large urban areas. The Dynamic World v1 dataset provides near-real-time land cover information with high resolution, but has limitations in its coverage as it depends on Copernicus satellite imagery. Finally, the GHS-BUILT-C dataset provides high resolution data and granularity of urban-specific thematic categories, including various typologies of vegetation and built-up areas, ideal for detailed land cover urban analyses.

4.1.5 Population: Other data typology that was identified as fundamental for the realisation of UDTs is demographic data, particularly population. The analysis of population with respect to other urban factors and indicators constitute an important use case for the UDT.

The dataset selected as the source of population data is the Global Human Settlement multitemporal population grid (GHS-POP) in its 2023 revision (R2023A) (Cariolia et al., 2023). It is a global population grid with a spatial resolution of 100 metres that represents the estimated residential population count per cell over multiple epochs. Its data spans from historical to projected, covering the years 1975 to 2030 at 5-year intervals. It transforms census and/or administrative unit counts into grid cells using ancillary built-up surface, volume, and settlement data from other GHSL products (Pesaresi et al., 2024). It was selected due to its global spatial coverage, temporal coverage, and overall accuracy with respect to other similar datasets (Bustos et al., 2020).

4.2 Automated UDT Data Download Workflow

In addition to unparallel availability, global open data is convenient for automated data workflows. For instance, Figure 2 illustrates the automated data workflow utilised for downloading UDT baseline data based on the previously described global open datasets.

This workflow is enclosed within a Docker container, ensuring a stable processing environment with customisation capabilities. Inside the container, a set of scripts are in charge of downloading and processing data related to various data typologies, which compose the UDT baseline data. This automated workflow is intended to work as a one-click procedure for the assembly, data provision, and configuration of UDT prototypes.

The initial step of the workflow is to define an area of interest. The area of interest is represented by a polygon and defines the physical location that the UDT models. The selection of the area of interest triggers three download procedures: first, extracting raster-based data related to land cover, elevation, and population; second, extracting the driving, pedestrian, and cycling street networks, as well as the public transport network and infrastructure; and third, the creation of a city 3D model as the extrusions of 2D building footprints.

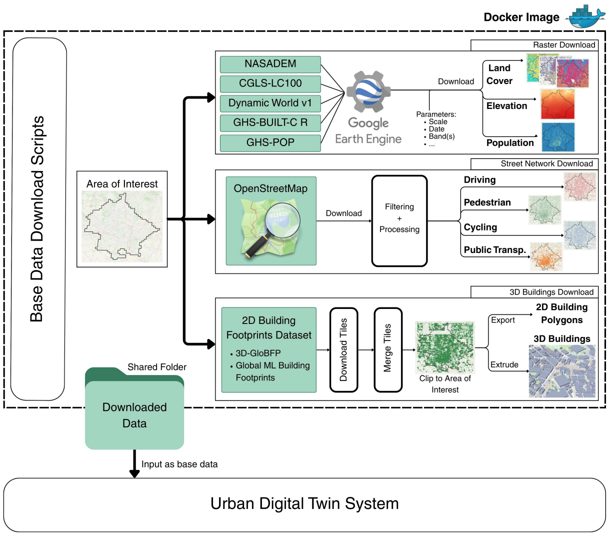

Figure 2. UDT base data download workflow.

This automated workflow serves as the foundation for populating UDT prototypes with baseline data. However, to achieve a more comprehensive and reliable Digital Twin, authoritative data is needed. As the UrbanDT platform enables data extension mechanisms, default global open data can be substituted with higher-quality and authoritative information, while new datasets can be added to support custom UDT utilisation. These two capabilities ultimately strengthen the UDT's role in urban planning and decision-making processes.

5. Case Study

Demonstrating the global applicability of the proposed automated UDT prototyping framework, a use case is implemented as a proof of concept to explore the visualisation, processing, and extensibility capabilities of the UrbanDT platform and the global applicability of the automated download pipeline. This use case consists of the implementation of a UDT prototype for the city of Bologna, Italy, focused on urban mobility. Making use of global open data, exploration of various data typologies is performed. In addition, processing capabilities are demonstrated by a custom process that assess mobility conditions through the calculation of street network indices at the city level.

5.1 Automated UDT Prototype Construction Pipeline

The first step of the case study contemplates the construction of the UDT prototype for the city of Bologna, Italy. By leveraging containerisation technology and automation, the implementation of the UDT prototype is delegated to an automated pipeline for the creation of UDT infrastructure and base data download. This automated pipeline, depicted in Figure 3, utilises Docker compose for the definition of a multi-container application, which creates and connects the different components of the UrbanDT platform and provision it with base data. Furthermore, the resulting UDT prototype can be configured based on configuration parameters, provided as an environment file.

After the UDT platform is fully deployed, a new container starts the data download procedure. Base data is then stored in a shared folder, accessible to each container of the application. After the download procedure is finalised, the GeoServer instance is configured to share the various downloaded datasets.

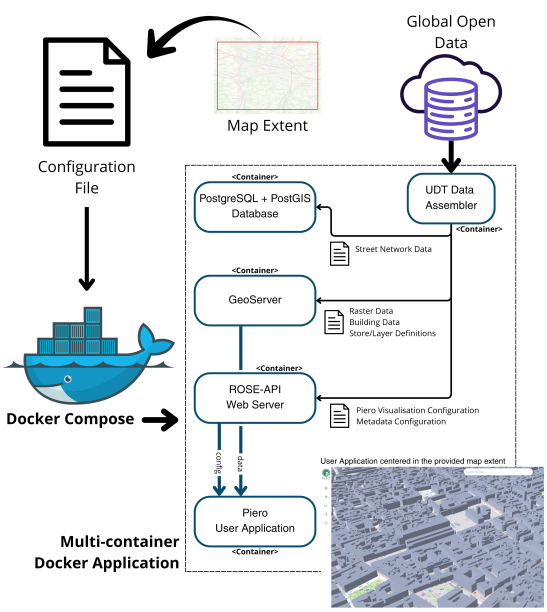

Figure 3. Urban Digital Twin automated construction pipeline.

By utilising the GeoServer REST API, the layers corresponding to the pedestrian, cycling and road street networks, public transport infrastructure, Digital Elevation Model (DEM), various land cover layers (Copernicus, Global Human Settlements, and Dynamic World v1), and population counts are configured. Finally, metadata files for each of the downloaded datasets are created and a dynamic configuration for the user application is built, which specifies the visualisation parameters of the Piero-based user application and the available geospatial layers.

The final result is a fully-functional UDT prototype for the city of Bologna, with localised data from global open data sources, processing capabilities, 2D, and 3D data support. The next subsections further showcase the data visualisation and processing capabilities of the UrbanDT platform.

5.2 Data Exploration, 2D, and 3D Visualisation

An initial data exploration allows the visual inspection of available data to demonstrate the 2D and 3D visualisation capabilities of the UrbanDT platform, as visualisation of 3D data is a common Digital Twin functionality.

The UrbanDT platform supports the storage, sharing, and visualisation of 3D data with 2D, 3D, aerial view and street-level visualisation and controls. Figure 4 shows the 3D city model of Bologna, generated from extruded building footprints, from a 3D aerial view as observed within the the UrbanDT's user application.

The 3D city model generated for this use case unravels a limitation with respect to the usage of open data, which is its low quality when compared to authoritative data. In addition, the usage of extruded 2D building footprints as a 3D city model might look like an oversimplification. Nevertheless, using extruded 2D building footprints is a widely adopted practice for prototyping 3D city models at the level of detail 1 (LOD1). These models, despite their simplicity, are adopted for multiple applications like shadow estimation, solar power potential, urban air flow analyses, sky view factor, or flood simulations (Biljecki et al., 2017).

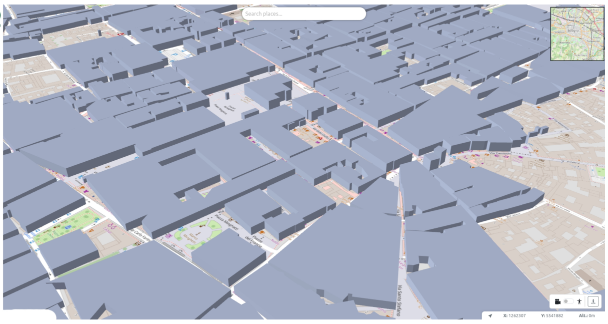

Figure 4. 3D city model from extruded 2D building footprints.

For raster data, visualisation is rendered in the user application web map using the WMS (Web Map Service) standard. WMS provides rendered data, which means that it is not the original raster information but a styled representation of it. As rendered data, styles are applied through GeoServer, leveraging the SLD (Styled Layer Descriptor) standard. Figures 5, 6, and 7 illustrate how the DEM, population, and GHS Urban Characteristics land cover dataset look like from the UrbanDT platform, respectively.

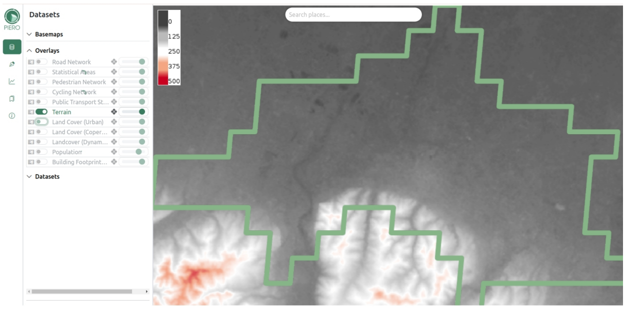

Figure 5. Digital Elevation Model data visualised in the UrbanDT platform user application.

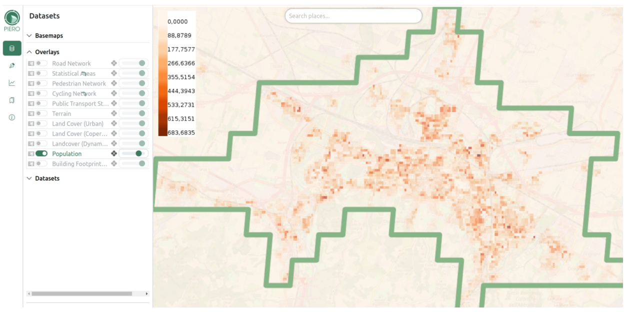

Figure 6. Population data visualised in the UrbanDT platform user application.

From the visualisation of elevation data (Figure 5) it is possible to observe that most of the city is flat, except for a hilly region south to the city. This region, ranging in elevation from 250 and 500 metres above sea level, corresponds to a portion of the Apennines mountain range, which is located south of Bologna. With respect to population (Figure 6), the dataset shows that most of the population of Bologna is concentrated towards the centre and the south-east part of the city. According to the Eurostat degree of urbanisation manual (Eurostat, 2021), and based on the value ranges of the population distribution (with a maximum value of around 700 people per squared kilometre), Bologna can be classified as either a low-density or a semi-dense urban area.

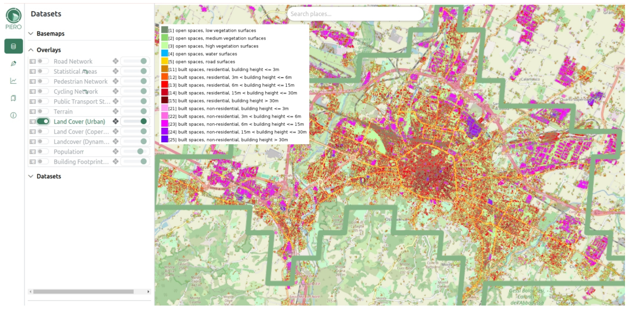

Figure 7. Land cover (GHS Urban Characteristics) data visualised in the UrbanDT platform user application.

Finally, street network data showcases how vector data is visualised. The exploration of the various street network types illustrates the prominence of active mobility within Bologna's old town. Figure 8 depicts the pedestrian (green) and cycling (blue) networks overlapped by the road network, which represent areas designated for vehicular traffic. From the figure, the significant presence of pedestrian and cycling-only infrastructure, indicated by green and blue-only segments, reflect the municipal emphasis on promoting active mobility. This trend is particularly evident in the centre-most parts of the city's old town where pedestrian infrastructure dominates the urban fabric.

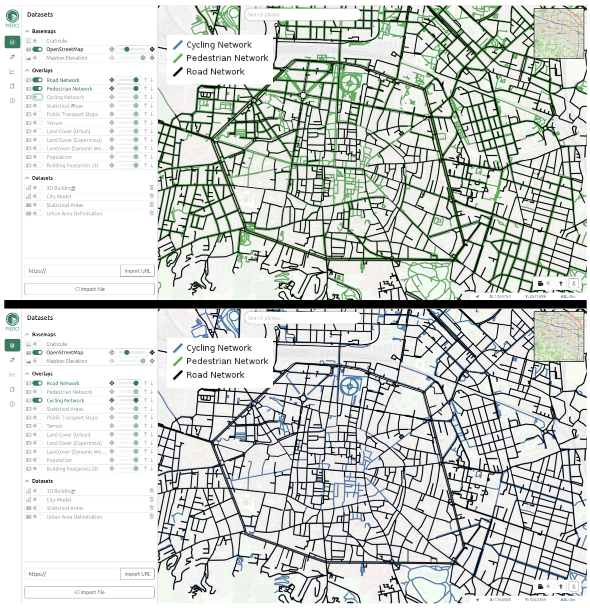

Figure 8. Pedestrian and cycling street networks (green and blue, respectively) with respect to the road network (black).

5.3 Processing Capabilities and Street Network Analysis

The UrbanDT platform enables processing capabilities through OGC API - Processes interfaces and custom Python scripts. For this use case, a script to calculate street network indices, based on previous work (Duque and Brovelli, 2025), was implemented and executed over the street networks of Bologna. An example of the usage of processes in the UrbanDT plaform is depicted in Figure 9.

The analysis of the urban street network comprises the calculation of street network indices for the pedestrian, cycling, and road networks for the entire urban area of Bologna at the city

Figure 9. Example of street network analysis process execution and results from the UrbanDT platform.

scale. A subset of the calculated street network indices is reported in Table 1 including average proximity to points of interest (POIs), circuity, average street length, street density, Link-Node ratio, intersection density, average proximity to public transport (for the pedestrian network only), average slope (for the cycling network only), and orientation entropy (for the driving network only). Each indicator represent different characteristics of the urban area with respect to mobility like compactness, connectivity, functionality, or efficiency.

Indicator	Pedestrian	Cycling	Road
Avg. Proximity to POIs	27.4	39.9	48.1
Circuity	1.110	1.095	1.089
Avg. Street Length	65.46	75.45	92.42
Street Density	17,119	24,230	17,864
Link-Node Ratio	1.129	1.065	1.033
Intersection Density	236.4	135.6	79.6
Avg. Proximity to Public Transport	5.7	–	–
Avg. Slope	–	0.032	–
Orientation Entropy	–	–	3.4523

Table 1. Urban street network indicators for the pedestrian, cycling, and road networks at the city scale for Bologna.

From the results it is observed that the urban area of the city of Bologna presents good conditions for active mobility (i.e., walking and cycling) with low average slope which represents cycling comfort, a consistent value of proximity to POIs which is a measurement of functionality and accessibility, and short average street lengths which indicates high network connectivity (Duque and Brovelli, 2025).

Other values that indicate ideal conditions for urban mobility are an average street length of 65.46 metres for the pedestrian network and of 75.45 metres for the cycling network, which aligns with ideal experimental values of walkability. With respect to connectivity and compactness, Bologna presents better conditions for pedestrians than for motorised traffic with Link-Node ratio values of 1.129 and 1.033, respectively. The Link-Node ratio value for the pedestrian network, while still low, aligns with common values for urban areas; while for the road network is below the expected value of 1.1. For cyclists, the analysis exhibits a low average slope of 3.2%, which is just above the edge of the theoretical value of high comfort. Also, a higher value of street density with respect to both the pedestrian and road networks correspond to a better coverage and connectivity of the cycling network than their counterparts. Furthermore, it is worth mentioning that differences in magnitude between the indicators of each network highlight the need for mode-specific analyses.

Finally, with respect to functional aspects of the analysed networks, the values of proximity to POIs are increasingly higher for pedestrian, cycling, and road networks, respectively, as each mobility option may cover increasingly larger portions of the urban area. Consequently, proximity values are more useful for doing comparisons between different urban areas than for characterising specific mobility behaviours.

6. Conclusion

This work introduced an automated and generalisable framework for constructing Urban Digital Twin (UDT) prototypes by combining open-source technologies, containerisation, and global open data. A minimal baseline for UDT prototyping was established based on identified system components and data typologies recurrent in documented UDT implementations. From this baseline, a novel UDT prototyping platform, UrbanDT, was implemented and documented. The platform integrates processing capabilities, data management strategies, and interactive 2D and 3D visualisation through OGC-compliant interfaces, enabling the deployment of functional UDT prototypes with minimal configuration. An automated data download and configuration workflow further facilitates the creation of reproducible, globally applicable prototypes by providing baseline datasets and system configuration in a single, unified procedure.

Through the implementation of a UDT prototype for Bologna, Italy we further demonstrated the applicability of the proposed framework and platform, showcasing its ability to support data exploration, 3D visualisation, and custom processing workflows. Overall, the proposed framework supports an incremental, scalable, and accessible approach to UDT implementation, contributing to the wider adoption of Digital Twin technologies in urban research and planning. From the analysis of urban street networks of the use case, it was concluded that Bologna presents optimal conditions for active mobility, characterised by outstanding values of street and intersection densities, street length, link-node ratio, and average proximity to points of interest.

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