A Geodatabase Design for the Development of a Digital Twin for Urban Environments: A Case Study from Turin, Italy

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Abstract

3D City models are essential for urban planning, accurately visualizing, analyzing, and simulating urban environments. They find applications in various fields like AEC (Architecture and Construction), urban and transportation planning, development and conservation processes, energy systems monitoring, and many more. Extensive datasets for the 3D City Models need to be organized following international standards to make them reusable and sharable for different stakeholders. Designing a Geodatabase (GeoDB) for a 3D city model is crucial for data management as it is helpful in the streamlined visualization and analysis of the city's features and relations among its objects. Over the years, 3D city models have evolved into Urban Digital Twins, offering dynamic real-time simulations of cities and even better management and analysis of urban processes. This transition from 3D city models to UDTs enhances decision-making by providing detailed insights into the dynamics of urban systems, enabling better urban management and planning. This research concentrates on building a GeoDB to support the UDT. The paper discusses the data acquisition, processing, and integration methodologies.
Additionally, it highlights the significance of utilizing advanced remote sensing technologies such as aerial LiDAR and aerial photogrammetry to enhance the digital twin’s quality and richness in detail. The semantics of the built environment datasets are clarified and strictly defined for the most important UDT features, such as buildings, roads, trees, and other features. This will ensure everyone can interpret the data similarly, leading to better analysis and decision-making.

1. Introduction

3D City Models are essential for urban planning, accurately visualizing, analyzing, and simulating urban environments. They find applications in various fields like AEC (Architecture and Construction), urban and transportation planning, development and conservation processes, energy systems monitoring, and many more (Biljecki et al., 2015; Binyu Lei & Biljecki, 2023; Hu & Minner, 2023, Diakite et al. 2022, Xu et al. 2022, Diakite et al. 2022, Xu et al. 2022). The different datasets used to design the 3D City Models need to be organized and harmonized following international geographic standards to make them reusable and sharable for different stakeholders and in different fields of application. Designing a Geodatabase (GeoDB) for a 3D city model is crucial for data management as it is helpful in streamlined visualization and analysis of the city's features and relations among its objects (Yao et al., 2018; Li et al., 2020). Moreover, the geoDB design phase could also help in decision-making processes for urban planners and policymakers. Over the years, 3D city models have evolved into Urban Digital Twins, offering dynamic real-time simulations of cities and even better management and analysis of urban processes (Lehtola et al., 2022; Therias and Rafiee, 2023).

Urban Digital Twins (UDTs) are the virtual and digital representations of cities and the physical elements of the urban environment, integrating various data sources to offer comprehensive insights into urban dynamics (Yan et al., 2019; Zlatanova et al., 2020). These twins are developed by aggregating geospatial data from sources like satellite imagery, 3D geometric data acquisition (traditional, photogrammetric), remote sensing sensors, IoT sensors, urban infrastructure databases, and social media feeds. These data are then organized and managed within GeoDB, providing a structured foundation for UDTs. Through continuous data updates and advanced analytics, UDTs facilitate real-time monitoring, simulation, and optimization of urban systems, fostering smarter and more resilient cities (Ferré-Bigorra et al., 2022; Hämäläinen, 2021).

The development of Urban Digital Twins, integrating different spatial datasets, such as technical maps, 3D city models data, point clouds, Digital Elevation Model (DEM) and so on, represents a systematic and simplified approach in urban planning and asset management (Dimitrov and Petrova-Antonova, 2021; Jeddoub et al., 2023). This innovative approach connects state-of-the-art geospatial data technologies to create a detailed, dynamic, and interactive digital replica of urban environments. Using high-resolution 3D models, these Urban Digital Twins provide accurate geometric and spatial representations of urban built environments. Incorporating geodatabases ensures systematic and rigorous data management and accessibility, facilitating real-time analysis and decision-making for various urban planning applications like traffic management, emergency management and services, etc. (AlBalkhy et al., 2024; Piras et al., 2024). This integration of technologies and geodatabase offers significant potential for enhancing urban sustainability, resilience, and efficiency, putting up the Urban Digital Twins as a critical tool in modern urban research and development.

This transition from 3D city models to UDTs enhances decision-making by providing detailed insights into the dynamics of urban systems, enabling better urban management and planning. UDT integrate diverse data sources, facilitating stakeholder collaboration and sustainable development. UDT entitle policymakers and administrative units to offer real-time insights into urban dynamics, simulate various scenarios, and aid in evidence-based decision-making for urban planning, infrastructure development, and resource allocation (AlBalkhy et al., 2024; Charitonidou, 2022).

Despite significant technological advancements, extensive research and updates on geographic standards, spatial representation, and the development of 3D city models, the transition from 3D city models to 3D GIS (Geographic Information System) continues to encounter substantial implementation challenges. These challenges primarily stem from interoperability issues, which can be technical, geometric, and semantic. To address these ongoing gaps, this research aims to establish comprehensive operational and methodological foundations for creating a well-organized dataset within a geoDB. This dataset will be published on the web (webGIS) and is intended to serve as a foundational element for defining a complete urban digital twin. This effort seeks to bridge the gap between current 3D modelling practices (nowadays spread in open source and commercial solutions) and the seamless integration required for practical 3D GIS applications. This ultimately contributes to the realization of more sophisticated and functional urban digital environments.

1.1 Research objectives

The first aim of the research is to analyze the data availability of the selected Italian case study and then the data harmonization following the CityGML OGC standard, version 3 (https://www.ogc.org/standard/citygml/)and it Level of Details (LOD). Integrating spatial data, derived from 3D integrated metric surveys, including aerial LiDAR (Light Detection and Ranging) and UAV (unmanned aerial vehicle) photogrammetric point clouds, holds immense potential for automatically generating a comprehensive 3D city model. Leveraging these datasets allows for representing urban features with high accuracy and fidelity, essential for various applications such as urban planning, simulation, and analysis. z The GeoDB architecture accommodates heterogeneous data sources while ensuring interoperability and scalability. In this way, the digital twin is facilitated by seamless data integration. It also allows integration with existing AEC (Architecture Engineering Construction), GIS packages and a range of platforms from visualization, interaction and simulation, enabling proper data synchronization and collaboration among various stakeholders.

1.2 Gaps and Background of the research work

The development of comprehensive 3D city models in Italy has been relatively limited, leading to a lack of informative, comprehensive spatial data for urban planning and management. Learning from cities such as Rotterdam, Amsterdam, and Singapore which already have robust 3D city models (Ledoux et al., 2021) Italian cities are now taking steps to implement similar initiatives. The absence of widespread 3D city models hampers efforts to optimize infrastructure, address urban challenges, and highlight the need for accelerated development in this area to keep pace with global urban innovation (Billen et al., 2014).

The increasing complexity of urban environments necessitates advanced methodologies for effective management and planning. In this context, the concept of Urban Digital Twins has emerged as a pivotal innovation, providing a dynamic and interactive digital replica of urban areas. These digital twins are underpinned by highly detailed and reliable 3D models and detailed 3D point clouds, which offer precise spatial and geometric information. However, the real strength of Urban Digital Twins lies in integrating comprehensive geodatabases, which facilitate efficient data management, storage, and retrieval (Ketzler et al., 2020; Lehner and Dorffner, 2020). A well-designed geodatabase is the backbone for these digital twins, enabling the seamless integration and analysis of diverse datasets.

Hence, as mentioned before, this research focuses on the design and implementation of a geodatabase tailored for the development of an Urban Digital Twin for the urban environment of Torino, Italy, highlighting the potential of such systems in enhancing urban resilience and sustainability.

The city of Torino, with its rich historical heritage and complex urban built environment, presents a requiring case study for the development of an Urban Digital Twin. Implementing a geodatabase in this context requires thorough consideration of various factors, including data types, spatial relationships, and temporal dynamics (Breunig et al., 2010; Shahidinejad et al., 2024). By making the use of traditional and innovative GIS and geoDB management technologies, this research work aims to create a a comprehensive geodatabase framework that supports the intricate needs of an urban digital twin.

An historical part of Torino city will demonstrate the practical applications and benefits of this approach illustrating how a structured geodatabase implemented with energy information, can help urban planning, infrastructure management, and disaster response activities. Ultimately, this study seeks to contribute to the broader discussion on smart cities and urban informatics, offering insights and methodologies that can be replicated in other urban settings globally.

The paper discusses the data acquisition, processing, and integration methodologies. Additionally, it highlights the significance of employing advanced remote sensing technologies such as aerial LiDAR and aerial photogrammetry to enhance the digital quality and detail richness for the urban built environment features. The semantics of the built environment datasets are clarified and strictly defined for the most important UDT features, such as buildings, roads, trees and other features. This will ensure that any users can visualize and query the data leading to better analysis and decision-making. The research will investigate existing solutions for 3D data management, such as 3DCityDB (Yao et al., 2018). Ultimately, this research will create a reliable database to support UDTs. By combining geodatabase and webGIS, we aim to define a replicable method and a powerful tool for spatial data analysis and decision-making processes in various domains. This part of the methodology sets the basis for UDT development.

2. Study Area and Datasets

For the present research, we focused on studying a residential locality near Intesa Sanpalo Skyscraper, an area in Turin, Italy. It covers about 7 hectares and includes around 200 residential buildings. The locality of Intesssa Sanpaolo Skyscrapper in Torino, Italy, was undertaken as a study area, because it presents a mixed residential and small commerce use and because, within a small dimension, presents the most common building structure and size in the city, making it the perfect sample, comprising around 200 buildings. Another reason for selecting this area was the availability of the existing datasets and processed data products acquired for the Torino Digital Twins project (Boccardo et al., 2024) . Figure 1 represents the location of the area of interest under consideration for this research work.

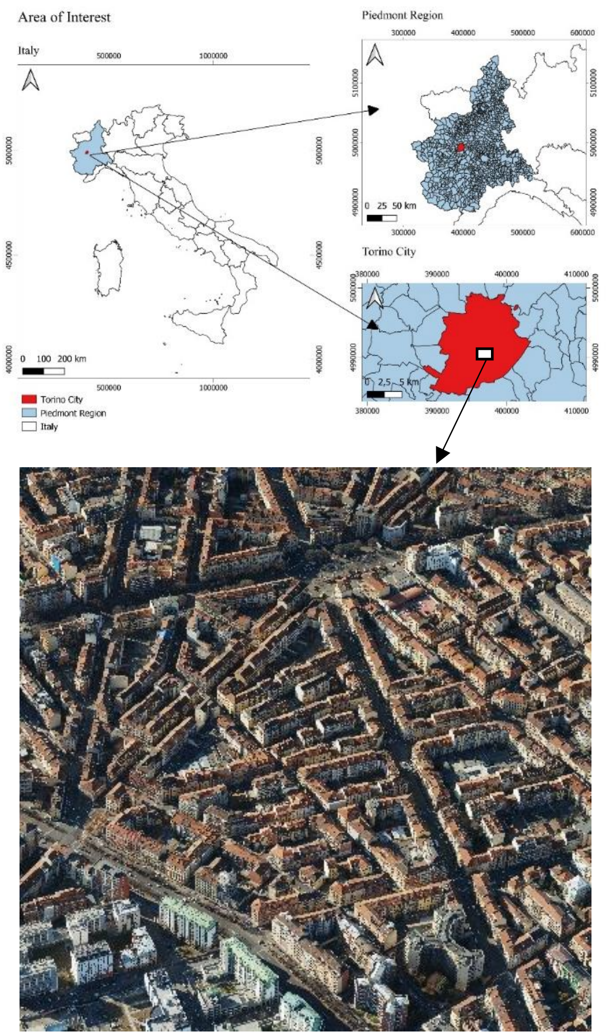

Figure 1: Location and aerial view of the study area under consideration.

The dataset used to model the Turin DT was acquired on January 28-29, 2022, using the new Leica City Mapper-2, a hybrid digital sensor onboard an aircraft that acquires optical images as well as LiDAR scans of the ground. For the optical imagery data collection, a total of 20,291 images were captured over the city of Turin from an approximate altitude of 1 km. Form this dataset, only 378 images have been used for the test site in this research work. Each capture location included one Nadir image and four oblique images to ensure the highest level of details from side perspectives as well. The photogrammetric image data were characterized by a Ground Sampling Distance (GSD) of 5 cm. The dataset exhibited a 60% overlap for lateral images and an 80% overlap for longitudinal images. First data is the point cloud from the photogrammetric data acquisition and processing of the images in the Agisoft Metashape software. Figure 1 shows the aerial photogrammetry point cloud of the study area with 7,44,3480 points. The LiDAR data were acquired concurrently with the imagery, exhibiting a point density ranging from 30- 40 points/m^2. The system utilized a 20° acquisition angle and featured a conical scanning pattern. This configuration facilitated the capture of vertical surfaces from multiple directions within the resultant point cloud. Figure 3 shows the point cloud acquired from the aerial LiDAR simultaneously with aerial photogrammetry, having 9,790,650 points.

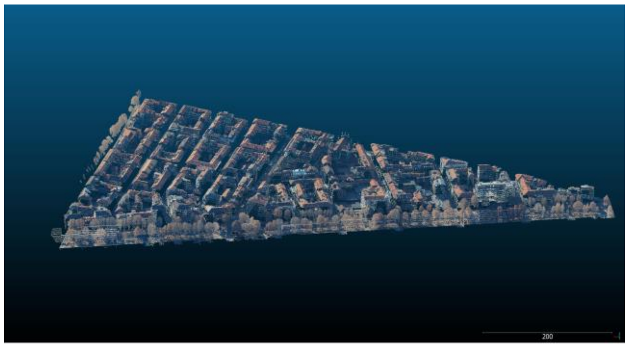

Figure 2. Point cloud of the test site post-processed from the aerial photogrammetry processing.

Figure 3. Point cloud of the test site resulted from the acquisition from aerial LiDAR.

Regarding the cartographic datasets, we have selected several resources to ensure comprehensive coverage and accuracy. Table 1 contains the summary of the datasets used in this research work.

Dataset	***Source***	***Data Format***	***Other information***
Point cloud	*Aerial Imagery*	.las	GDS: 5cm, Point density: 147 pts/ m^2
DSM	Aerial Imagery	.tif (raster)	0.5 m resolution
Point cloud	*Aerial LiDAR*	.las	33 pts/ m^2
Building footprints	*OSM*	.osm, .shp (vector)	Building shapefile
Buildings, roads, vegetation, railways, etc.	*Regional datasets from the regionalGeo portal (BDTRE 10k)*	Both vector and raster	Update every 6 months
Buildings, roads, vegetation, railways, etc.	*Torino technical map (1:1000)*	vector	Update every 6 months

Table 1. Dataset details for developing a GeoDB for Torino Digital Twins.

These include the technical Map of Turin city at a scale of 1:1000 and the BDTRE (Base di Dati Territoriale degli Enti Piemontesi) dataset available through the Geoportal Piedmont at a scale of 1:10000 (available in the Geoportal of Piedmont Region). Additionally, we have incorporated the DTM (resolution 5 m) from the ICE dataset. These layers encompass detailed information on buildings, building footprints, and vegetation. They are all organized into various levels of detail as defined by the CityGML standard. Furthermore, all data will be integrated and visualized within the geoDB in both 2D and 3D formats, facilitating advanced spatial analysis and enhanced urban management capabilities. This approach ensures that the dataset is comprehensive and detailed, readily accessible and usable for a wide range of applications.

3. Methodological workflow

One of the first steps of the methodology is the data harmonization of different semantically and geometrical datasets adapted to create a digital twin of an urban environment. This paper focuses on some preliminary methods for data harmonization, conceptual model development, GeoDB design and webGIS publication. The methodology initiates with data acquisition, where necessary data is collected for use throughout the project. Subsequent data harmonization aligns data from various sources for consistency and compatibility. This is followed by the development of conceptual and logical models that define the data's structure and interrelations. The models are then implemented into a Geographic Database (GeoDB) within a GIS environment, adhering to CityGML standards. Finally, data visualization in a web environment and sharing via a web application ensures that the processed data is comprehensible and accessible to users, thus facilitating practical applications in a web-based platform. The overall methodology of the research has several different phases summarised in the Figure 4 below.

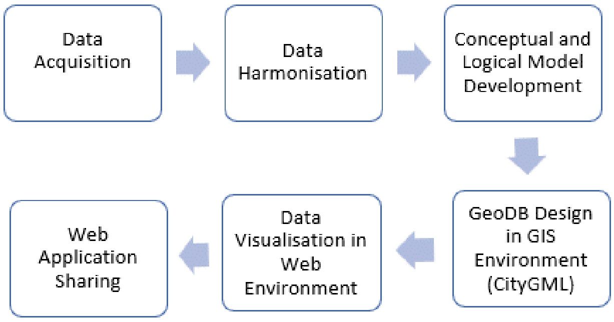

Figure 4. Methodological workflow of the research study.

3.1 Data collection

The datasets used in this research were acquired to facilitate the development of Digital Twins for the city of Torino. Aerial photogrammetry and aerial LiDAR datasets were acquired due to their complementary strengths in capturing the three-dimensional urban environment with higher details of geometric detail and texture information. These datasets provide enhanced detail for the various urban features, including buildings, trees, roads, vegetation, and terrain. This highly detailed 3D data is crucial for accurately representing the diverse elements of Torino's urban landscape in the Digital Twin environment. Integrating these datasets in a digital twin environment also ensures a more dynamic, precise, and detailed visualization, aiding in urban planning and management.

3.2 Data harmonization

In the subsequent data collection phase, the data harmonization stage ensures that the acquired and processed datasets are standardized and compatible for developing a geodatabase for an Urban Digital Twins. This involves converting data into a standard format, resolving discrepancies/ errors, and ensuring consistency across different data sources. This step is critical to facilitate smooth integration and usage of datasets in later stages of the development process.

3.3 Conceptual and logical model

With harmonized data, the next step in the development for UDT is designing a conceptual model. The conceptual model for developing Torino Energy Digital Twins provides a structured framework to represent various geospatial and building-related datasets. This model serves as a blueprint for the GeoDB, defining the data's structure, relationships, and constraints.

A well-designed database, which is a preliminary phase for constructing a GIS, must consider developing application-independent schemas and explicitly provide all useful information for future implementations or data interpretation. Databases offer various tools to retrieve and present stored data for communication purposes. These capabilities are extended to geodatabases by introducing the spatial aspect, adding additional potential. The presence of spatial attributes of managed objects defines a geographic data database. One of the main pieces of information that must be stored and managed in the database is the location of objects in a specific geographic space, regardless of how this information is formalized. Although structuring complex databases and related information systems can only be done by database experts, structuring simple territorial information systems requires some introductory knowledge, including defining a conceptual data model.

The information we want to store in a GIS is perceived by our minds and populated by objects (entities) and their static and dynamic characteristics, including data and the relationships between the data. This design process, therefore, involves modeling to describe the perceived reality in a computer-usable language through successive stages. These modelling phases, defined by the ANSI/X3/SPARC standard since 1975, include:

- External model: Describes the application domain model using natural language (high-level language) and analyses the relevant reality to be managed in the database.
- Conceptual model: Implementation-independent, formalizes the previous model by identifying concepts (entities or classes of entities) and their relationships.
- Logical model: Adapted for implementation, focusing on how the system will implement the conceptual model (system design). It schematizes the conceptual model into a data structure translatable into a computer-understandable language (relational model), including storage methods (numbers, strings, identifiers) and data linking.
- Internal model (or physical model): Describes the actual software and hardware implementation in a low-level language (system implementation). The final implementation will contain the system's self-description (encoding both data and data structure).

The most used formalism for creating the "conceptual model" is the Entity-Relationship model. It essentially perceives three elements: objects, their properties, and the relationships between such objects. This model uses these elements with specific names and meanings and can be graphically represented using a diagram. An entity represents a real-world object for which information is to be recorded. Entities are objects with properties called attributes, graphically represented within a rectangle with the entity's name and associated attributes listed below. The first attribute is the entity identifier, which is uniquely characterized. Relationships between entities are defined by associations, represented by diamonds and circles (for taxonomic relationships), with characters inside. The cardinalities of an association represent the number of times it can occur between linked entities, specifying the minimum and maximum possible occurrences for each entity.

For this work, the conceptual model development is guided by the requirements of the CityGML standard, ensuring that the database will be compatible with this widely recognized geospatial framework. Figure 5 represents the conceptual framework model for the development of Torino Energy Digital Twins. This model is designed to ensure comprehensive integration and accurate representation of energy-related information within the urban context of Torino. The model is organized into different Levels of Detail (LOD), each corresponding to a specific aspect of the geospatial data and its attributes. The conceptual model defines clear and explicit relationships and hierarchical structures among different datasets, ensuring unified integration and interoperability within the GIS environment. Using standardized data formats and maintaining detailed metadata for each dataset, the model supports effective data management and facilitates comprehensive energy analysis and digital twin development for Torino.

CityGML employs various Levels of Detail (LOD) to represent urban features with increasing complexity of the urban structures. The Torino Energy Digital Twins conceptual model complies with these LODs to systematically structure data from basic geospatial elements to detailed building and energy attributes.

Table 2 summarizes the different Geometrical features, LoDs and their associated attributes

Dataset/ Geometry	*LoD*	*Attributes*
Roads	LoD 0	Id, source, creator, scale, typology, and height.
Vegetation	LoD 0	Id, Source, creator, scale, and typology.
Building Footprints	LoD 1	Id, source, creator, scale of acquisition, height, and typology.
Building Roof	LoD 2	Id, Building roof structures, typology and acquisition details
Building Furnishings	LoD 3	Id. Building typology and acquisition scale.
Energy Data	LoD 4	Id, energy rating, energy year, energy consumption year, monthly energy consumption, energy solar potential, and heat transmissivity.

Table 2. Different Geometrical features, LoDs and associated attributes

3.4 GeoDB design and 3D visualization

The GeoDB is designed within a GIS environment specifically adapted to comply with CityGML standards. For this step, the GIS software ArcGIS Pro by ESRI was selected (version 3.0.3). This stage involves developing the database, implementing the logical and internal models from the previous step, and ensuring that all geospatial data is accurately represented. This step is

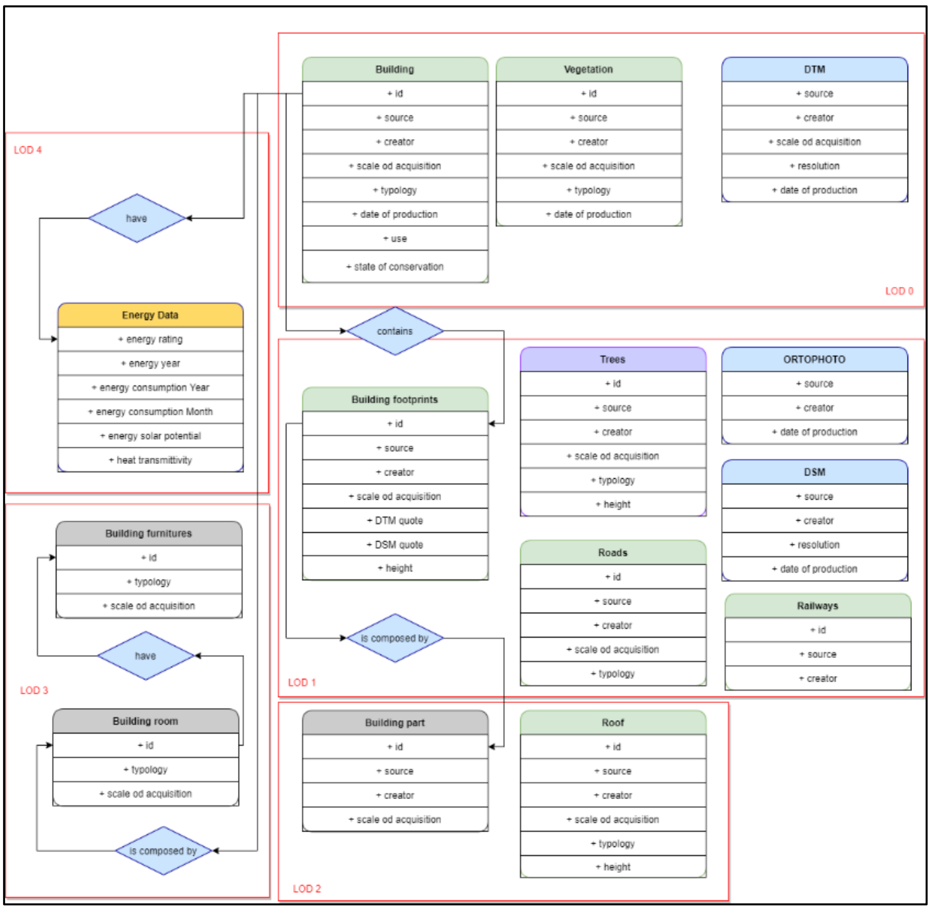

Figure 5. Conceptual model for the GeoDB creation.

Figure 7: ArcGIS Pro GeoDB layers organization and 3D visualization.

Figure 6: Aerial LiDAR point cloud classification in GIS environment.

essential for providing a robust and scalable database infrastructure.

After the data harmonization, the different 2D and 3D data have been added to the Local Scene in ArcGIS Pro, dividing all the datasets into LOD and 2D or 3D scenes as represented in Figure 6. Thanks to the "height" attribute of the building data from the technical map, it is possible to visualize the data in a 2,5 dimension.

Finally, point clouds of the data above described have been added to the GeoDB following the different Levels of detail of CityGML as represented in Figure 7. Moreover, they have been classified thanks to the available "classification" tool in ArcGIS Pro.

4. Preliminary results: the GeoDB in a 3D webGIS

After the GeoDB creation, the next phase is to share the database through a web application. For this step, we have employed ArcGIS Pro Online, specifically ArcGIS Experience, to publish and share data. This application allows users to access, visualize, and interact with the geospatial data remotely. The webGIS application is designed to be user-friendly and accessible, ensuring that a wide range of stakeholders can utilize the data.

This platform would facilitate the publication of web-based queries, providing valuable utility to stakeholders and offering substantial assistance to urban planners, municipal offices, and policymaker bodies. Generally, webGIS platforms are renowned for their user-friendliness, allowing easy navigation and interaction. Additionally, these platforms offer the capability to enrich and update the underlying database, ensuring that the information presented remains current and relevant to the users' needs. The design of this webGIS platform highlights ease of use and accessibility, making it possible for a diverse group of users to benefit from the geospatial data. By enabling remote access and interaction, the webGIS application supports various functions such as urban planning, decision-making, and policy development. The ability to publish web-based queries further enhances its utility, allowing stakeholders to obtain specific information efficiently. Continuous updates to the database ensure that users always have access to the latest data, which is crucial for effective urban management. The integration of ArcGIS Experience with ArcGIS Pro Online provides a robust solution for geospatial data sharing and visualization, illustrated by the interface shown in Figure 8.

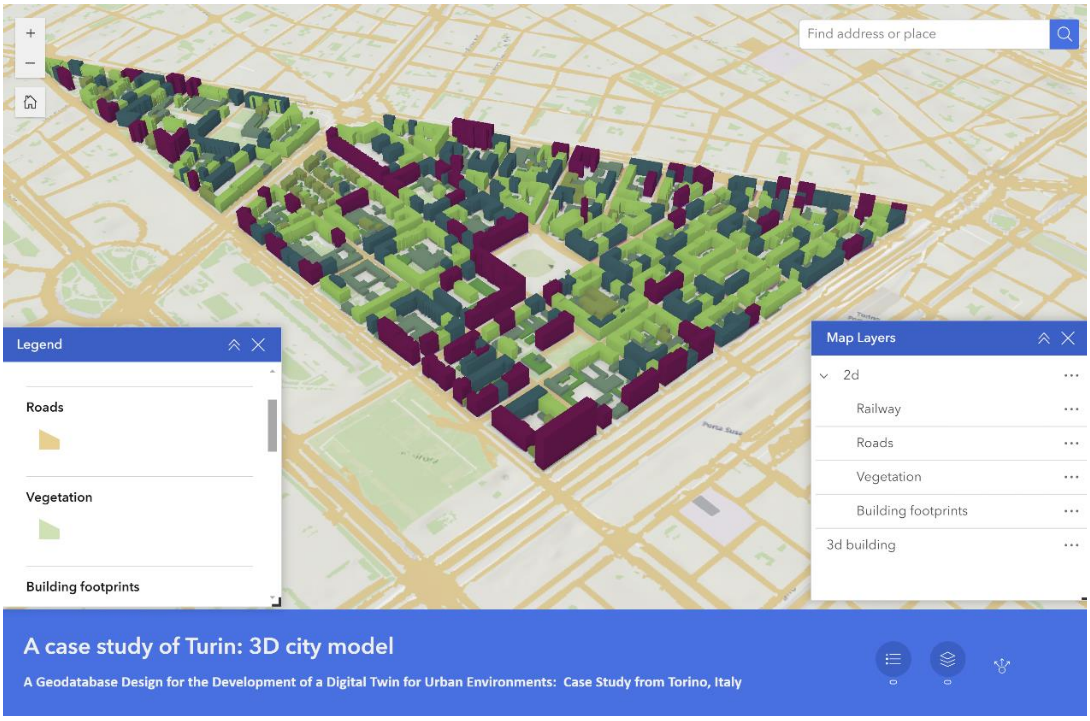

Figure 8: Visual representation of the WebGIS platform

5. Discussions & Conclusion

The research outlined above aimed to develop a geodatabase for the development of a digital twin for urban environments, with a specific focus on the city of Torino, Italy, highlights the influential role of a well-structured geospatial database in urban planning and management. The adoption of the CityGML standards in the geodatabase design has enabled a detailed representation of urban elements, effectively integrating spatial and non-spatial data to support a broad range of urban applications. This integration is necessary for enhancing the functional capabilities of urban systems and for providing a robust framework that supports the dynamic needs of urban planning.

The multi-level design of the geodatabase is particularly worth mentioning. It provides varying degrees of detail, encoded through the Levels of Detail (LOD) concept, which range from basic geospatial elements at LOD 0 to more complex representations involving building details and energy data at higher LODs. This LoD structuring is necessary for conducting precise simulations and analyses, thereby equipping urban planners with the tools to make informed decisions based on comprehensive, accurate data. The ability to view urban features at different complexities allows for both high-level and detailed investigations, facilitating a deeper understanding of urban dynamics.

However, developing such a geodatabase for developing a digital twins is not without its challenges. One of the primary difficulties encountered in this research work was related to data harmonization and integration. The variations in data formats and standards across different sources necessitated extensive pre-processing efforts to ensure data consistency and interoperability. This part of geodatabase development is critical as it affects the usability and reliability of the data in the practical real-world applications.

To address these challenges, future research could focus on the enhancement of data harmonization techniques. There is a persistent need to develop more efficient methodologies that can minimize the manual effort required in data integration processes. Additionally, exploring the potential of automated tools to facilitate these tasks could significantly streamline the development of geodatabases. Such advancements would improve the efficiency of geodatabase constructions and enhance their accuracy and applicability in urban planning scenarios. While the geodatabase designed for Torino has demonstrated significant potential in supporting urban management and planning, it also highlights the complexity involved in its operational and practical implementation. Continued research and development in this field are essential to overcoming these challenges and maximizing the utility of urban digital twins in urban planning and development processes.

6. Future Perspectives and Developments

Future research on developing a geodatabase for digital twins of urban environments, like the case study in Torino, Italy, should focus on better data integration, real-time data processing, and the implementation and operational scalability. Combining different data sources, such as IoT devices, remote sensing, and crowd-sourced information, will be essential for creating detailed and dynamic models. Another opportunity could be to simultaneously visualize the multi-source point cloud datasets in a webGIS platform. Key areas for the development of Urban Digital Twins include making it easier to combine different 3D data sources, including point clouds and mesh models to create more accurate CityGML models. Enhancing real-time visualization and interaction on webGIS platforms can improve analysis and decision-making. Advancements in data compression, streaming, and rendering technologies are crucial for efficiently managing and displaying large point cloud datasets, making web-based urban environments more dynamic and user-friendly. A key point will be the conversion of the 3D city model implemented into the GeoDB in CityGML data format (CityJSON).

These improvements can help stakeholders better understand urban landscapes, promoting sustainable development and smarter resource management. Moreover, machine learning and artificial intelligence improvements can enhance predictive abilities and automate data management. Ensuring that these systems have user-friendly interfaces and can work well with other urban management tools will make digital twins more useful for city planners, policymakers, and other stakeholders, leading to smarter and more resilient urban development.

Once the GeoDB is established, the next step could be the integration of Building Information Modeling (BIM) and point cloud data in the geodatabase. This integration enhances the usability of the database in an Urban Digital Twins with detailed architectural and structural information, providing a comprehensive geospatial dataset that combines both geographic and building-specific data. This would be crucial for applications that require detailed 3D models and geospatial analysis.

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