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Data Quality in Urban Digital Twins: Challenges in the Virtualization of Florence's Historic Heritage

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Abstract

The increasing vulnerability of historic city centres to climate change and environmental risks demands the use of high-resolution digital tools for urban planning and heritage protection. In this context, the Digital City & River Twin (DiC&RT) framework is being tested in the historic centre of Florence to examine data quality and interoperability within Urban Digital Twins. The analysis focuses on the geometric and semantic representation of buildings, integrating MMS surveys and UAV photogrammetry. It addresses critical issues related to building density, visual occlusion, and data heterogeneity, proposing multi-technological solutions for more accurate modeling. The thematic component is geared toward multi-risk analysis, with particular emphasis on hydraulic and seismic scenarios, supported by controlled vocabularies and interoperable data structures such as CityGML. The case study highlights how data quality, consistency, and granularity are key requirements for the effective operation of urban Digital Twins in resilience management and heritage conservation.

1. Introduction

An Urban Digital Twin (UDT), defined as a dynamic digital replica of an urban environment, consists of multiple layers, geospatial data, interconnected devices that communicate with one another, and physical-mathematical models for forecasting and simulation. These tools are increasingly used in land management, supporting the study of various scenarios, including multi-risk analysis to enhance urban resilience (Riaz et al., 2023).

A common feature among different UDT proposals is the use of geomatic techniques to create the geometric layer. Numerous scientific studies have analyzed results obtained through aerial photogrammetry and Mobile Mapping Systems (MMS) (Kovanič et al., 2025). However, with the growing adoption of hybrid sensors and the integration of data from diverse sources, it becomes crucial to develop new approaches for the simultaneous evaluation of heterogeneous sources. Developing a UDT requires not only high geometric accuracy but also careful assessment of the quality and completeness of the acquired data.

While quantitative aspects - such as point cloud density or measurement precision - are essential for ensuring model accuracy, qualitative aspects are equally relevant for a faithful representation of the urban and architectural reality. Proper collection of thematic data is as critical as geometric data quality. Information on materials, functions, and conservation status must be appropriately structured to ensure a comprehensive and coherent representation of the urban fabric, also supporting the understanding and management of cultural heritage.

The Florence UDT project is characterized by its focus on data related to the historic urban fabric, widespread artistic heritage, and the relationship between the city and the Arno River that flows through it. These are fundamental themes for a city whose historic center is included in the UNESCO World Heritage list and whose economy is closely tied to tourism and cultural heritage valorization.

Engaging with cultural heritage means confronting its intrinsic fragility, increasingly threatened by natural and anthropic risks.

Traditionally, the conservation of built heritage has been addressed primarily at the scale of individual buildings, with interventions focused on protecting specific structures from a historical-artistic, architectural, and material standpoint, following an approach based on in-depth knowledge of their physical composition and degradation processes. In parallel, the prevention of environmental and human-induced risks - hydrogeological, seismic, climatic, and others - has historically been managed at the territorial scale through broad spatial models aimed at defining overarching planning policies. However, the increasing frequency and intensity of extreme climate events - often with localized but recurrent effects (as demonstrated, for example, by recent floods that have repeatedly affected certain Italian areas within the same year) - is forcing a reassessment of this dichotomy. An integrated perspective is now required, capable of accounting for the vulnerabilities of built heritage at both local and object-specific scales.

This evolution entails a shift toward more dynamic analytical and predictive models, enabling a downscaling of risk analysis, i.e., refining hazard and vulnerability assessments to the level of individual structures. This approach allows the identification of specific criticalities, supporting informed decisions regarding maintenance, mitigation, and intervention strategies (Bonazza & Sardella, 2023; Fiorini et al., 2024).

This requires the integration of heterogeneous expertise and is now concretely feasible due to the opportunities offered by the digital transition. Technologies such as artificial intelligence and Digital Twins, along with data from remote sensing and on-site Internet of Things (IoT) sensors, constitute advanced tools for the modeling, monitoring, and simulation of complex risk scenarios, enabling more effective forecasting and planning processes (Ministry of the Environment and Energy Security, 2024).

According to ISO Standard 31000:2018 (International Organization for Standardization, 2018), risk is defined as the effect of uncertainty on objectives. This effect can be either negative or positive, depending on the circumstances. However, when dealing with cultural heritage, the focus is primarily on preventing negative outcomes. Specifically, the aim is to avoid the so-called expected loss of value, a concept encompassing not only damage to the material aspects of the asset but also to the immaterial values that define its identity, meaning, and cultural function (Pedersoli Jr et al., 2016).

Addressing the specificities of the historic city requires that the UDT possess a level of granularity extending down to individual buildings. By incorporating information layers related to building characteristics - such as dimensions, structure, materials, functions, uses, historical data, etc. - it becomes possible to populate an information system that supports event simulation and intervention planning.

Currently in a pilot phase, the project aims to develop a modular UDT that can be used for management and simulation across multiple domains, including urban planning and the prevention of anthropic and natural risks.

Based on preliminary assessments from previous studies focused on quantitative data analysis (Tucci et al., 2025), this research seeks to further explore qualitative aspects. Among the UDT modules considered, this contribution focuses on two: one concerning the ability to accurately represent architectural details in the geometric layer, and the other on thematic data integration.

2. The Challenges of Surveying in Dense Historic Urban Areas

One of the objectives of the pilot project is linked to the interest of the Municipality of Florence in developing a UDT for managing fiscal and administrative aspects, such as street numbering, signage, traffic signs, the conservation state of building façades, and the condition of street pavements. These purposes introduce additional quality assessment criteria, as the required information must be clearly and accurately represented for the UDT to be effective and reliable in urban management and planning.

Figure 1. Lungarno degli Archibusieri, Palazzo de’ Girolami. Elements that are not distinguishable in the point cloud are highlighted in red.

Data acquisition was carried out using Mobile Mapping Systems (MMS) based on active sensors, following a methodology already tested in other UDT projects, such as the one developed for the Municipality of Milan (Franzini et al., 2024), and integrated with drone-based photogrammetry. This approach enabled broad spatial coverage and high-resolution acquisition of geometric data along riverbanks and streets in the historic center. However, in particular narrow streets - common in historic centers - the quality of data related to the upper parts of buildings is reduced. Although the acquired point cloud allows for the recognition and classification of façade materials, such as plaster, pietra forte, or rusticated stone, the data density does not always support detailed analysis of the conservation state, for example, in identifying instances of plaster detachment.

Another critical issue concerns information gaps caused by obstacles, strong radiometric variations, and shadows. Due to these factors, some architectural elements - such as coats of arms, bas-reliefs, or stone inscriptions - often located under balconies or in recessed niches, may be unrecognizable or entirely absent from the acquired point cloud (Figure 1).

In such cases, the integration of multiple geomatic techniques is necessary. Specifically, combining data from active sensors (static laser scanners or mobile mapping) with image-based methods (UAV and terrestrial photogrammetry, spherical panoramas) enhances the visibility of these details, contributing to a more complete representation of the architectural heritage even in the most complex areas.

3. Thematic Data Management for Multi-Risk Assessment

A second key aspect of the Urban Digital Twin (UDT) concerns multi-risk management of the historic center area traversed by the Arno River. As highlighted by numerous studies emphasizing the need for a multidisciplinary approach to water resource management and its interaction with historic heritage (ICOMOS, 2021), UDTs enable predictive analyses and simulations to assess hydraulic risks and support the conservation of urban water heritage.

The ongoing pilot project is thus designed as a framework for multi-risk analysis, including the assessment of hydrogeological risks (Ge & Qin, 2025) as well as seismic risks related to architectural structures and infrastructure, with particular reference to bridges (Habib et al., 2025).

To implement a model capable of monitoring the behavior of historic heritage, it is essential to define detailed information layers both at the scale of individual buildings and structures - incorporating data on typological and construction characteristics, crack patterns, structural displacements, and rotations - and at the urban and environmental scale, including climatic variations, temperature, humidity, and groundwater levels.

This contribution presents the criteria used to structure data to ensure a complete and integrated representation of the building and urban fabric. Among these criteria is the use of unique identification keys for buildings, organizing data such as names, cadastral identifiers, and other information necessary to guarantee a coherent and unambiguous arrangement of thematic data, aiming to support a robust and functional information model for urban management.

Architectural typologies must be identified and classified using standardized and controlled vocabularies suitable for cataloging cultural heritage. For example, the Getty Art & Architecture Thesaurus (AAT) (Getty Vocabulary, 2017) provides standard terms and definitions for the classification and description of historic architectural typologies (e.g., palaces, tower houses, churches).

The same principle applies to defining building typologies (e.g., single-family house, row building, block building, terrace) and identifying land uses. Additionally, appropriate criteria must be established for managing the temporal aspects of information - not only for data such as construction dates or past restoration and conservation interventions, but also to ensure accurate temporal references for all collected thematic data, including images, documents, surveys, and other essential sources for understanding the evolution of urban heritage.

Data quality and structuring are fundamental to ensuring the reliability of Urban Digital Twins applied to complex historic centers. The modular UDT approach, combined with proper acquisition and management of the information base, provides a more flexible tool for urban heritage planning and safety

management. This integrated approach considers diverse vulnerabilities and enables more precise formulation of risk scenarios and prevention strategies.
A significant example is the system developed by the Italian Institute for Conservation and Restoration in collaboration with ICCD and Sapienza University of Rome (Fiorani & Cacace, 2020), which, through the “Risk Map” (General Directorate for Cultural Heritage Security - MiC., 2024), enables multi-scale assessment of the conservation state of historic centers. The system is based on a model with six descriptive sheets, applicable to urban spaces, building units, and architectural aggregates, integrating vulnerability and hazard parameters to define risk levels and monitoring strategies.
Effective management of thematic data, based on structured criteria, shared vocabularies, and regulatory references, is thus the operational prerequisite for applying Urban Digital Twins in decision-making processes. In highly vulnerable historic contexts, such as Florence, only a coherent and integrable information base can enable reliable simulations and conservation strategies founded on multi-level analyses and objective evaluations.

4. Standards and 3D Models for the Semantic Representation of the Urban Environment

The evolution of urban Digital Twins involves not only the capacity to manage complex scenarios through the integration of data from heterogeneous sources but also the adoption of standardized data models capable of accurately and structurally representing the physical and semantic dimensions of the urban environment. The availability of interoperable 3D models proves crucial to ensure consistency in representation, facilitate information exchange between different platforms, and support advanced predictive simulations. In this context, standards such as CityGML (Kolbe et al., 2021) provide a formal framework for hierarchical spatial modeling, allowing the integration of geometry, semantics, and descriptive attributes into a coherent structure. The following section presents a review of significant international experiences that have adopted these standards as the foundation for the development of operational urban Digital Twins.

4.1 Integration and Applications of 3D CityGML Models in Urban Digital Twins

The integration of the third dimension in geographic data has become essential in the development of urban Digital Twins. Unlike two-dimensional or 2.5D representations, which are limited to planimetry and simplified height, 3D models provide a realistic and semantically enriched spatial description of cities, indispensable for advanced simulations and predictive analyses (Biljecki et al., 2015). Efficient management of these data requires the use of relational databases with spatial extensions, such as PostGIS, or specialized environments like 3DCityDB.
The most widespread standard formats for urban Digital Twins are CityGML, recently updated to version 3.0 (Kutzner et al., 2020), and CityJSON (Ledoux et al., 2019). CityGML, a standard of the Open Geospatial Consortium (OGC), is both a data model and an exchange format for storing 3D digital city models, enabling topological and semantic representation of urban objects. CityJSON, proposed by the same consortium, is a JSON-based exchange format for the CityGML data model and aims to simplify the management of 3D data.
CityGML supports urban modeling according to levels of detail (LoD 0-4), ranging from generic building volumes to the representation of interior spaces, making it an essential tool for Digital Twin-based applications.
Among the updates proposed in version 3.0 is greater integration with external modules, including the *Point Cloud* module, which allows direct management of georeferenced point clouds (Beil et al., 2021). This module enables the association of raw data from LiDAR or photogrammetric surveys with CityGML semantic models, allowing more flexible interaction between high-resolution geometries and structured urban objects. Integration of point clouds ensures higher spatial fidelity, useful for automatic feature extraction, anomaly detection, and monitoring the conservation status of buildings. In complex urban scenarios, the combined use of point clouds and semantic models enables multi-level analyses, improving the accuracy of simulations and the quality of decisions based on three-dimensional data.
Despite the standardization offered by CityGML, effective utilization of urban Digital Twins is hindered by fragmentation and heterogeneity among visualization and query platforms. Each city tends to develop vertical solutions based on specific technology stacks, limiting comparability and application interoperability. The absence of a coherent, shared software ecosystem has led to the adoption of heterogeneous tools: VC View, 3DCityDB WebClient, CesiumJS, ArcGIS Experience Builder, and custom WebGL viewers. These tools vary significantly in semantic support, performance, extensibility, management of LoD levels, and compatibility with complex attributes. Platform choice is therefore critical: availability of a CityGML-compliant 3D model does not automatically ensure operational data accessibility. A digital infrastructure capable of supporting queries, dynamic updates, and interoperability with BIM, GIS, energy, hydraulic, and environmental systems is necessary. Without this layer, the urban Digital Twin remains a passive representation rather than an active decision-making system.
Numerous cities have developed urban Digital Twins based on CityGML as the central data model, leveraging its semantic and hierarchical structure for coherent 3D urban environment representation. Rotterdam (Coumans, 2019) and Helsinki (Hämäläinen, 2021) adopted the VC View platform to manage and visualize their respective CityGML 3D models, accessible through public portals. These models support urban applications such as energy planning, shading analysis, urban green management, and climate scenario evaluation. Zurich (Schrotter & Hürzeler, 2020) provides access to its CityGML model via a geoportal based on ArcGIS Experience and interactive map services, facilitating integration with cadastral, infrastructural, and environmental data. Vienna (Lehner & Dorffner, 2020; Lehner et al., 2024) developed the “Digital geoTwin” project, creating a CityGML 2.0 semantic 3D model to meet municipal needs.
In Germany, beyond Ingolstadt (Beil et al., 2020), which developed a LoD3 urban 3D model focused on street space modeling applied to mobility, safety, and infrastructure analyses, municipalities including Berlin, Hamburg, Cologne, Düsseldorf, and Leverkusen use the CityGML application schema for implementing and exchanging 3D urban models, emphasizing interoperability and integration with advanced urban management systems (Kolbe et al., 2005). Dresden (Rubinowicz & Czyńska, 2015) adopts an integrated approach combining ArcGIS with CityGML data for its 3D Stadtmodell, available via an ESRI hub and used in urban simulations and sustainable urban development scenarios.
Other notable international cases include Singapore’s "Virtual Singapore" project (National Research Foundation, 2018), integrating CityGML with other standards for interoperable and dynamic urban fabric management. New York City (Beil et al., 2015) developed a CityGML LoD1/2 Digital Twin enriched with semantic attributes and publicly accessible, representing the most significant CityGML application at the U.S. scale.
Italian cities are also adopting urban Digital Twin solutions based on CityGML as the central data structure. In Turin (Yadav et al., 2024), the integration of multiscale geospatial data (LiDAR,

photogrammetry, technical maps) according to the CityGML standard is analyzed to produce a semantic and three-dimensional representation of the urban environment. The approach emphasizes modularity of levels of detail (LoD) and publication on webGIS platforms to support analysis and planned decision-making.

In the historic Marche towns of Morro d'Alba and San Ginesio (Di Stefano et al., 2024), a 3D geospatial database based on CityGML is proposed for cultural heritage management and urban planning. Using cartographic data and geomatic surveys, LoD1 and LoD2 3D models were developed, generating a 3D GIS with a relational database to organize and manage built environment information, enhancing the semantics and multidisciplinary aspects necessary for village management.

In Taranto (Pepe et al., 2020), CityGML models with multiple levels of detail (LoD1 and LoD3) were developed for historical and architectural representation of the city. A LoD1 model was created for the main urban epochs from the 19th century to today by integrating data from various formats and GIS sources. Additionally, a LoD3 model was developed for the historic "Ponte di Porta Napoli" through geomatic surveys, highlighting CityGML's role as a tool for sharing georeferenced territorial information and supporting urban heritage planning, conservation, and monitoring processes.

The geographic spread and variety of use cases confirm CityGML's effectiveness as a foundation for urban digital twins, due to its interoperability and support for integrated advanced analyses. The standard is extendable through regulated mechanisms allowing Application Domain Extensions (ADE), which expand the representation of urban objects and phenomena. These extensions increase CityGML's versatility, making it a robust platform for multi-risk analysis. CityGML supports urban energy simulation via tools like the Energy ADE, enabling integrated assessments of buildings and urban contexts (Agugiaro et al., 2018). Its semantic and hierarchical structure suits complex scenarios such as seismic vulnerability analysis (Sammartano et al., 2023).

In flood risk management, projects like LamPIT (Macchione et al., 2019; Costabile et al., 2021) investigated the integration of numerical hydraulic modeling with 3D semantic data structures based on CityGML. These methods were applied, for example, to simulate flooding of the Crati River crossing the historic center of Cosenza, demonstrating modeling potential for predictive analysis and risk management in complex urban contexts.

In digital conservation of historic centers (Lasorella & Cantatore, 2023) proposed an innovative approach combining CityGML 3D models with a technical decision support system (T-DSS). This system integrates specific Italian regulations, such as UNI 11182, UNI/CEN TS 17385:2019, and Italian Consolidated Law on Building, to define architectural intervention classes in historic centers. The method was validated in the Ascoli Satriano district (Puglia), providing a semi-automatic workflow that facilitates digital conservation planning and supports complex technical decisions in historic contexts.

These cases demonstrate how adopting semantic 3D models based on open standards like CityGML enables more integrated, interoperable, and informed urban transformation management, though it requires adequate digital infrastructures and coordinated strategies to ensure effective operational use in real-world applications.

5. Geographic Data Sources and Preliminary 3D Modeling Experiments

The geometric layer constitutes a foundational stratum of the Urban Digital Twin and is essential for integrating thematic information, assessing quality, and developing simulation scenarios. During the preliminary project phase, an analysis was conducted on the potential of the Topographic Database of the Municipality of Florence (DBT) (DBT2K, 2016) as the primary georeferenced base for structuring spatial information. Concurrently, a limited experiment on the automatic generation of semantic 3D models using open-source tools was performed. Although still at an early stage, these activities enabled testing of technical solutions for integrating 2D and 3D data, useful for evaluating approaches and tools for potential future developments.

5.1 Structure of the Topographic Database of the Municipality of Florence

The use of the Topographic Database of the Municipality of Florence (DBT) as the primary source for organizing thematic data addresses the need for a solid, coherent, and detailed information base for managing multi-risk analyses of the historic center. Based on the Regional Technical Map (CTR) at 1:2.000 scale (Figure 2), the DBT organizes data into a hierarchical multilayer vector structure compliant with INSPIRE standards (INSPIRE, 2007) and national DBT requirements. The database is divided into distinct thematic layers, including built environment, road networks, hydrography, contour lines, toponymy, land use, etc., each containing geometric entities (points, lines, polygons) linked to alphanumeric tables with standardized descriptive attributes.

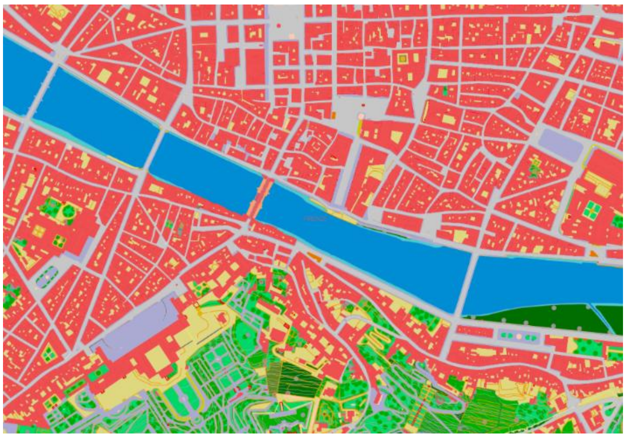

Figure 2. Topographic Database of the Municipality of Florence (DBT).

Unique feature identification is ensured by persistent ID codes, enabling traceability, interoperability, and incremental updating. This architecture allows stratified reading of the territory and urban fabric, facilitating correlation of morphological, infrastructural, and environmental dynamics with risk phenomena, thus providing a solid foundation for predictive simulations and vulnerability analysis.

5.2 Initial Testing of 3DFIER within the Urban Setting of Florence

The open-source software 3DFIER (Ledoux et al., 2021) was used as the initial test for integrating planimetric data with elevation information, generating automatic semantic 3D models in CityJSON format. Input 2D data originated from the Florence Municipality DBT, while elevation data came from a point cloud acquired via UAV photogrammetric survey, segmented according to standard ASPRS classes for LiDAR data (Figure 3). This data integration enabled automatic generation of LoD1 3D models, with geometries and semantic attributes derived from DBT entities (Figure 4). Although exploratory and limited, the test confirmed the potential of automated workflows to create interoperable datasets for future Urban Digital Twin population.

Systematic validation and normalization of input data remain necessary to meet reliability and detail requirements for more complex operational applications.

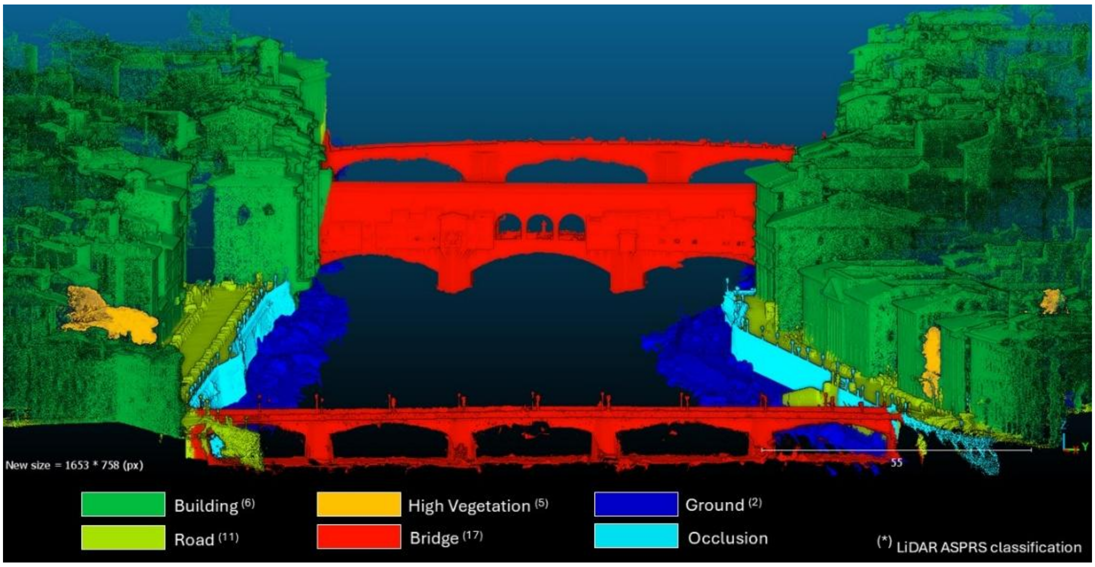

Figure 3. Point cloud acquired by drone and segmented according to the standard ASPRS classes for LiDAR data (classes used: Building, Road, High Vegetation, Bridge, Ground, Occlusion for the embankments of the Arno River).

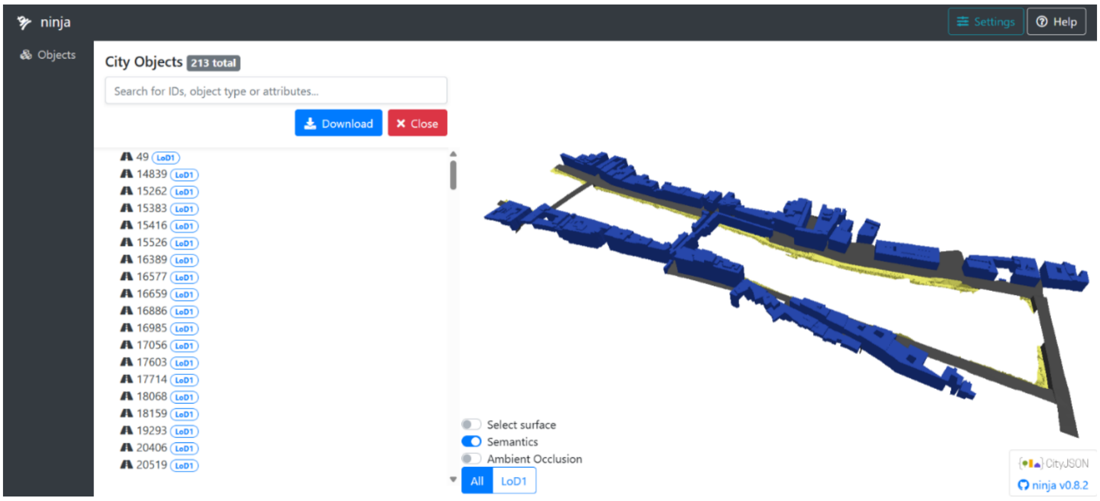

Figure 4. Test area implemented with 3dfier, visualized in CityJSON Ninja (https://ninja.cityjson.org/#).

6. Conclusions

The study preliminarily identified key challenges and opportunities in developing an Urban Digital Twin (UDT) for historically and morphologically complex contexts like Florence's centre, requiring an integrated approach balancing geometric quality and semantic data consistency. High building density, intricate architectural details, and adverse environmental data acquisition conditions pose significant obstacles, mitigated only through multi-sensor, multi-scale strategies. The thematic information layer, based on structured data, controlled vocabularies, and normative references, is essential for enabling effective, conservation-oriented risk analyses.
The experimental use of the open-source 3DFIER software for automatic generation of CityJSON LoD1 models, based on 2D data from the Florence Municipality Topographic Database (DBT) integrated with UAV-derived point cloud elevation data, represents an initial technical test. Although 3DFIER's automatic semantic modeling showed promise in creating coherent, interoperable datasets, this remains a preliminary phase aimed at feasibility assessment rather than producing fully operational models for advanced applications.
The project roadmap includes refining automatic extraction procedures and progressively integrating information layers within CityGML environments, focusing on interoperability with GIS and BIM systems and employing ADE extensions for multi-risk analysis. This will enable evolution toward a fully functional UDT, capable of supporting complex urban decision-making and sustainably enhancing Florence's cultural heritage.

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