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F. Maggioli, C. Romanengo, D. Cabiddu, and D. Giorgi (Editors)

Poster

Organising and Enriching Urban 3D Models for Digital Twin Applications

S. Pittaluga[1] and D. Cabiddu[1] and M. Mortara[1] and M. Spagnuolo[1]

[1]Istituto di Matematica Applicata e Tecnologie Informatiche, Consiglio Nazionale delle Ricerche (CNR-IMATI), 16149, Genova, Italy

Abstract

The creation of an urban digital twin for the city of Matera, including 3D geometric models of the city landscape and heterogeneous information coming from different data sources, highlighted the need for a graphical user interface capable of integrating complex 3D urban scenes with geo-referenced data and knowledge (e.g., from real-time sensors, administrative information systems, algorithmic analysis and simulation, manual annotation) and making them easily accessible to a range of users with different levels of expertise. From these requirements, a new tool Matera3D has been developed as a specialized software platform for visualizing, analyzing and documenting 3D urban models. The application integrates point cloud and triangle mesh management with interactive semantic annotation, CityGML compliant dictionaries, and basic morphological analyzes, such as shadow computation and street slope measurements, as an initial set of processing tools that will be extended in the future. The software organizes all project data, including geometry, annotations, metadata, and scalar fields embedded in the geometry, within a coherent folder structure to ensure interoperability and efficient sharing. The software can show data from different sources and of different types in an integrated 3D view to facilitate research and practical applications in urban planning, environmental assessment, and infrastructure management beyond the popular 2D (GIS) approach.

CCS Concepts
• ***Computing methodologies*** → ***Graphics systems and interfaces; Rendering;*** • ***Human-centered computing*** → ***Geographic visualization;***

1. Introduction

The increasing availability of high-resolution urban 3D datasets (acquired from LiDAR surveys, photogrammetry, and mobile mapping) has stimulated the development of numerous tools for visualization, processing, and analysis. These datasets are essential for creating urban digital twins, where the 3D representation of the city is not merely a visual output but a functional asset for morphological analysis, simulation, and infrastructure management. To fully exploit their potential, software solutions must integrate heterogeneous data sources, support semantic enrichment, and provide intuitive interfaces for both experts and non-specialist users.

Among open-source solutions, CloudCompare [clo] is widely used for processing point clouds and meshes, but lacks structured semantic annotation. Cesium [ces] excels in streaming large-scale urban datasets and supporting standard formats such as CityGML [Kol09], but does not allow direct creation or modification of annotations. The Urban Mesh Annotation Tool [GNBL21] from TU Delft adopts a semi-automatic approach to annotating urban meshes, useful for benchmark datasets but without interactive project management or CityGML integration. City3D [ZNW*22], also from TU Delft, focuses on the automatic reconstruction of LoD2 buildings from point clouds and footprints, but does not handle complex annotations or metadata. On the commercial side, ArcGIS [arc] offers plugins for semantic annotation of meshes, geometric model management, rendering, and exporting, providing a more integrated, though proprietary, workflow.

While these solutions collectively address important steps of the pipeline (such as preprocessing, visualization, or enrichment), there is no single open-source application that combines interactive annotation of 3D city models with standardized export in one environment. To address this gap, we developed `Matera3D`, a dedicated application for the visualization, annotation, and processing of urban 3D models. Its primary goal is to make complex urban datasets accessible to users with varying levels of expertise, supporting the creation of urban digital twins. By integrating semantic annotation, interactive exploration, and basic analysis in a unified workflow, `Matera3D` enables meaningful engagement with urban data while ensuring interoperability and practical applicability.

2. Software architecture and main features

`Matera3D` is a **Qt** [qt] desktop application with a **VTK** [SML06] graphics engine, designed to integrate within a single environment

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the visualization of point clouds, meshes, GIS layers, and hybrid views, with full support for coordinate reference systems.

The interface consists of a main area for 3D visualization and a sidebar that combines a project management tree view with a map view showing the spatial extent of the loaded geometric layers (see Figure 1). To meet the usability requirements of different user profiles, the application adopts a dual-level interaction paradigm: a basic mode that offers essential display and query functions for non-expert users, and an advanced mode that provides access to the full set of tools for displaying, editing, and semantic annotation of the models.

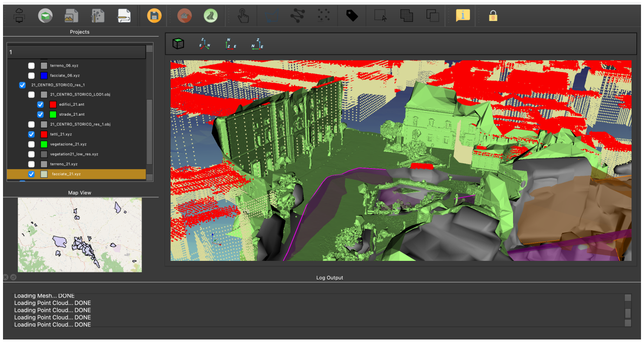

Figure 1: *Main window displaying heterogeneous urban datasets: segmented point cloud (façades and roofs) in yellow and red, low-resolution mesh in gray with draped GIS layer in purple, and high-resolution mesh in green.*

A distinctive feature of the software is its data management, structured around the concept of a project. A project serves as a container for heterogeneous datasets that collectively describe a target area. Ideally, it corresponds to a well-defined spatial unit, such as a neighborhood, a single building, or any semantically coherent portion of space, where different datasets contribute to both its geometric and semantic characterization.

On disk, a project is stored as a single folder containing geometries (both meshes and point clouds), annotations, scalar fields associated to the geometries, and metadata. This structure ensures ordered and consistent organization of information while preserving the semantic link between geometry and annotations. Projects can be compressed and shared as single files, simplifying transfer and reducing the risk of data loss or misalignment. Since each project represents a distinct portion of territory, multiple projects can be opened simultaneously in the application and explored seamlessly within the same environment.

The annotation system is designed as an integral part of the model: each annotation is tightly linked to the underlying geometry and can be created or modified interactively through the user interface by adding or removing elements. Annotations are organized into semantically coherent sets, each defined by a unique geometric type (point, line, or area) and a shared attribute schema. Individual attributes may remain empty; for example, a set may represent building annotations without requiring all attributes to be specified. These sets can be freely defined by the user or derived from CityGML-compatible dictionaries, ensuring interoperability and enabling direct export to standard formats that can be visualized in platforms such as Cesium.

Annotations are linked directly to mesh elements: area annotations are associated with faces, line annotations with edges, and point annotations with vertices, using element indices as references. While this approach makes annotations mesh-dependent, it significantly accelerates saving and loading operations compared to methods that maintain independent boundaries in global coordinates. In this way, there is no need to recompute the correspondence between annotated and non-annotated elements at each session, resulting in a more efficient workflow.

`Matera3D` can integrate geometry analysis modules that implement measuring, recognition, classification, characterization functionalities useful for urban digital twins. For example, `Matera3D` already includes the slope computation of street arcs and the shadow estimation at a specific date/time, computed intersecting sun rays with the occluding surrounding built and natural environment. These two functionalities are crucial ingredients for answering higher level questions of interest for citizens and administrations, concerning accessibility, personalised paths, perceived environmental comfort and even expected energy gain from photovoltaic installation at urban districts scale [RSC*25].

3. Conclusions and Future Work

`Matera3D` provides a set of functionalities that enable the integration of semantic and morphological information into 3D models, making them available for subsequent applications and ensuring compatibility with standard formats. Beyond its current implementation, the tool is conceived as a foundation for broader developments aimed at overcoming existing limitations and evolving into an open-source scan-to-model platform.

Several challenges remain open. Semantic annotation requires navigating the mesh to identify adjacencies, which in turn demands topologically clean geometries, free of self-intersections and other inconsistencies. More advanced tools for local analysis are also needed to reduce annotation failures when inconsistencies are present. Another issue of particular importance concerns the transfer of annotations from external sources that do not align precisely with the mesh structure. For example, a polygon from a GIS dataset may define an area whose boundary does not correspond to any mesh edge but instead cuts across elements. Different strategies can be adopted to address this problem, each with specific advantages and limitations, and further research is needed to identify the most effective solutions for seamless annotation transfer.

In conclusion, the current implementation represents the initial core of a system that will be progressively expanded to cover the entire workflow for the creation of semantically enriched 3D city models.

3.1. Acknowledgements

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