Research report

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Project: *Digitalizzazione e transizione energetica nel progetto dei Positive Energy Districts (PEDs)*
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Abstract

This paper presents the ongoing work of the author, conducted as part of the Rome Technopole *and* MakingPEDs - Decision-Making Digital Twins for Climate Neutral PEDs *research initiatives. The research focuses on designing and implementing a geospatial database and management system, based on the open standard CityGML, to model urban areas and support energy performance analysis and simulations at a district scale. A local instance of 3DCityDB was established to manage CityGML data from various sources, including energy metrics linked to building geometries. Initial results demonstrated successful data integration and visualization. Ongoing work will focus on processing more diverse energy datasets, refining interoperability, and expanding interactive visualization capabilities to support comprehensive decision-making. The research contributes to the scalability of urban regeneration tools and the replicability of results across diverse urban contexts.*

Introduction

The project involves two major research initiatives: *Rome Technopole* (ECS 0000024, CUP F83B22000040006 - PNRR Missione 4, Componente 2, Investimento 1.5, funded by the European Union - NextGenerationEU) and *MakingPEDs - Decision-Making Digital Twins for Climate Neutral PEDs* (co-financed under the international DUT 2022 call, Positive Energy Districts Pathway). Rome Technopole aims to create a regional innovation ecosystem in Lazio, focusing on sustainable development, 'smart specialization', and the revitalization of the industrial sector. It includes the Flagship Project 2, which is centered on applying digital and green technologies for urban regeneration and sustainable construction, promoting ecological quality as a strategic priority for sustainability and resilience. The MakingPEDs initiative aims to create a geospatial database and management system for the effective design and measurement of PEDs. PEDs are urban areas with a net-positive energy balance, focusing on renewable energy production, efficiency, and advanced energy management. The aim is to develop tools that will be instrumental for the scalability and replicability of results from pilot cases in both the Rome Technopole and MakingPEDs projects.

Given the shared emphasis of both initiatives on urban regeneration through digital innovation, this project contributes to exploring key aspects of the *digital twin* paradigm applied to cities. The concept of a digital twin originated in manufacturing engineering to add life cycle assessment information to three-dimensional graphical representations and has since been adopted by a growing number of urban administrators and corporate services for urban management (Grieves and Vickers, 2017; Kritzinger et al., 2018). An urban digital twin is a virtual replica of the city with a bidirectional connection to the real space. This connection requires continuous data flow to document physical states and phenomena, as well as interfaces to guide decision-making processes and perform transformative actions. Urban digital twins allow for enhanced monitoring, simulation, and optimization of city operations. They support informed decision-making by offering predictive analytics, scenario planning, and efficient resource management (Bolton et al., 2018, Civiero et al. 2021). Recent advancements in cloud computing and artificial intelligence (AI) enhance these capabilities significantly, particularly in aggregating and correlating diverse data sources, identifying patterns, and creating predictive models, which further supports integrated urban management (Wan et al., 2019; Fuller et al. 2020).

The primary objective of the project is to build a system for managing a geospatial database that:

- collects and consolidates territorial data from various sources;
- processes the information using original algorithms and shares data with other analysis frameworks using interoperable formats.

The data collection will consider the availability of datasets and new data collection opportunities, such as:

- open data by the public administration;
- datasets from stakeholders and partner institutions;
- crowdsourced and sensor data from pilot cases.

The definition of the geospatial knowledge framework includes geometric, thermal, environmental impact, energy, socioeconomic, and building consistency characterization elements. The database will be designed to host and process data related to energy production and consumption, life cycle assessment of urban regeneration solutions, and cost analysis.

The geospatial database will feature the following characteristics and functions:

- schemas based on standards for geographic information exchange, particularly those proposed by the Open Geospatial Consortium (OGC);
- fields for recording references to data sources and acquisition protocols;
- application programming interfaces (APIs) or other services for data integration, retrieval, and processing;
- integrations with models and functions for energy and economic evaluation;
- data query tools;
- data visualization tools for both collected data and transformation scenario results using dashboards or three-dimensional interfaces.

This research report outlines the methodological framework, the tools and technologies used, and the results achieved so far in designing, building, and populating the geospatial information system. It regards the work of Valerio Palma (research fellow — *assegno di ricerca*) executed in the first 11 months of work on the project (January to November).

Methodology

The methodology adopted for this project encompasses the following main aspects.

1. *Definition of the level of detail of the model and selection of CityGML classes.* The research activities from both the Technopole and MakingPEDs initiatives, along with the various case studies (specifically, the Ostiense area in Rome for Technopole [fig. 9] and a set of buildings in Civitavecchia for MakingPEDs [fig.15]), were thoroughly examined alongside the CityGML 2.0 specification [1]. This helped define the level of detail and the appropriate classes to align model construction with the project scope and intended application, establishing a common and precise framework. The modular nature of CityGML, including the Energy Application Domain Extension (ADE) (Agugiaro et al., 2018; Bachert et al., 2024) [2], is leveraged for detailed modeling of urban energy flows.

2. *Data collection and processing based on scalability.* Data acquisition was centered on scalability, allowing the methods and tools used to be applicable to other case studies and larger territorial scales, especially within Italy. Data were sourced from multiple geospatial datasets, including open data by public administrations, certified datasets from regional and national authorities, and specialized partners. Python scripts were developed to automate the data import process into CityGML, ensuring the approach could be replicated in other geographical contexts.

3. *Experimental application of LLMs for semantics-based data matching.* The project involves experimental use of large language models (LLMs) to facilitate semantics-based data matching, particularly in linking data from diverse sources with different structures. This approach was found to be effective in ensuring coherence between the imported datasets and the CityGML semantic framework, improving the quality of urban data integration.

4. *Usage of FOSS software and standards for scalability and interoperability.* We aimed at prioritizing the use of free and open source software (FOSS). The main tools employed included 3DCityDB [3] for CityGML-compliant data storage, Docker [4] for consistent deployment, QGIS [5] for data visualization and analysis, and Blender [6] to validate the readiness for interoperability of the three-dimensional model. Cesium JS [1, 7] (that is, its specific version shipped with 3DCityDB) was also used for web-based 3D visualization. The choice of FOSS fosters robust, scalable, and interoperable solutions while ensuring accessibility for a wide range of stakeholders.

5. *Clarification of roles and integration with other methodological frameworks.* In the context of dissemination and outreach activities, we clarified the role of the components under development within the methodological framework of the Technopole and MakingPEDs research initiatives. Summary diagrams were created or updated to specifically outline the contribution of the database, the input data, and the calculation tools that will interact with it [fig. 4, 5].

Development

Installation, setup, and initial testing

3DCityDB installation and initial tests.

As a first setup step, we installed and tested a local instance of 3DCityDB, an open-source geospatial database for managing CityGML-compliant 3D city models [3]. This setup included the Importer/Exporter plugin and the Cesium-based 3D Web Map Client [7] for web visualization. The first tests confirmed the viability of using the 3DCityDB suite for managing CityGML-compliant 3D models. The Importer/Exporter plugin was used to import and export CityGML files, and the 3D Web Map Client allowed for interactive visualization of the models [fig. 3].

Virtual machine setup and development environment configuration.

A virtual machine was set up to support the project development environment, including the installation of the operating system, necessary tools, and libraries. Docker [4], an open platform for developing, shipping, and running applications, was adopted to ensure consistent deployment of services across different environments, including development and production. This containerized approach simplifies the migration process and ensures compatibility across systems. The virtual machine environment was configured to include all dependencies needed for running, managing, and visualizing the database.

System requirements and infrastructure planning.

The project involved designing a server infrastructure to host the deployment version of the database and related backend tools. Hardware and software requirements were estimated, and the infrastructure will be deployed using physical machines at the Department of Architecture, Roma Tre University. A plan for the server setup was created, including specifications for memory, processing power, and storage to ensure optimal performance for managing large geospatial datasets and 3D models.

Data acquisition and modeling

Data gathering and geometric modeling.

During the project, a data index was drafted, updated, and shared with other project partners, in order to document, for each case study, the data required for data collection and development. This index was formulated to align with the CityGML standard, specifying the information deemed necessary by the research team to conduct assessments and simulations [fig. 6]. As of the current phase, data obtained include not only the geometric data on buildings and energy data already collected, but also the number of levels and typological and functional information [fig. 11, 12].

Data from the geo-topographical database (DBGT) of Regione Lazio [8] were used as a main source for modeling the buildings, as they provided certified and consistent building footprint and height information. The typological and functional information was gathered from values found in these same regional documents [23] ("typology" and "usage" fields) and converted into CityGML using the dictionaries proposed by the standard (code lists for "class" and "function"/"usage") [1]. While CityGML allows for the use of custom dictionaries, this process served as an experiment in applying a mapping approach based on large language models (LLMs) that could also be beneficial for other data linkage and conversion tasks from inconsistent data sources. Specifically, OpenAI's *gpt-4o* model was used, with custom prompts [10].

Other relevant geospatial data sources were identified, including Google Maps mesh data [11] and OpenStreetMap-based products [12]. Even though these sources did not offer information as consistent as the DBGT, they can be useful for integrating metadata (e.g., the number of building levels from OpenStreetMap) or enhancing the modeling level of detail (LoD), as Google meshes enable when imported in Blender [6]. The project explored the feasibility of acquiring higher detail level data, starting with roof surface modeling — up to LoD3, see Biljecki (2017) for insights on the standard specification of levels of detail in 3D city modeling. Blender and its add-ons Blosm [13] and Up3date [14] were tested for accessing mesh data and for exporting data to CityGML. Specifically, the Blosm add-on, capable of importing textured meshes, could potentially be used for defining apertures like windows and doors, as well as roof details, providing a valuable increment in the level of detail for energy modeling.

Energy modeling.

Data from other sources such as the National Institute of Statistics (ISTAT) [15], ENEA (National Energy Agency), and ATER (local housing agency) were utilized to obtain energy-related data such as energy consumption, building year of construction, and the approximate number of occupants. The integration of the CityGML Energy ADE (Application Domain Extension), compatible with the CityGML 2.0 specification, was explored to include detailed energy performance attributes such as energy consumption, different energy carriers, installed energy systems, and thermal properties for buildings (Agugiaro et al., 2018; Bachert et al., 2024). The Energy ADE extension enables detailed representation of energy consumption and production, simulation data, and related infrastructure. This update involved the installation of an open-source extension that integrates the 3DCityDB schema and adds dedicated functions to the Importer/Exporter tool [2]. A first set of energy consumption data, specifically for Roma Tre University, was processed starting from aggregated data by site or address. These were refined to estimate the consumption for individual buildings and subsequently integrated into the CityGML model. This allowed for associating energy consumption with specific building groups within the model, providing a representation of energy consumption that can be accessed through the interactive visualization tools.

Interoperability and visualization

Interoperability analysis.

The interoperability requirements for exchanging geospatial data with energy simulation software were analyzed, starting with IES iCD [16] and focusing on data quality and granularity. CityGML LoD2 was found compatible with the format needed for IES iCD input, which includes building roof characterization and is suitable for urban district representation (Biljecki, 2017). Some elements of LoD3, such as geometric definitions of doors and windows, were considered, but currently represented with aggregated data (i.e., percentage of apertures) rather than fully modeled in three dimensions. The analysis also included evaluating data quality requirements for energy assessments, ensuring that the baseline data would be sufficient for conducting energy simulations.

CityGML import code development.

Python prototype scripts were developed to transform footprint and height data into CityGML format for different building volumes, enabling the automated generation of LoD1 and LoD2 models in 3DCityDB (buildings made of different building parts). In addition to the import of DBGT-based data from Lazio [8], successful tests were conducted using datasets from Emilia-Romagna [17], ensuring the robustness and replicability of the importing method [fig. 1]. The data were imported into 3DCityDB with projected coordinate systems suitable for Italian data (EPSG:25833).

In addition to building data, information on green areas (not yet distinguished between public and private), trees (initial mapping without typological information and not yet imported into CityDB), road areas, and other paved areas was collected [fig. 14]. The represented surfaces (including buildings and open areas) cover approximately two-thirds of the territory, with notable gaps found in bodies of water, sports fields, similar facilities, and other open areas not categorized previously.

The project also integrated typological inferences and dedicated surveys to enrich the data, ensuring that it met the necessary detail and accuracy requirements for urban energy modeling. The code addressed issues related to data integrity and format consistency, ensuring that imported data adhered to the CityGML standard. This phase included correcting malfunctions and generalizing parameter management to make the tools more adaptable to various use cases.

Interoperability tests and visualization.

Interoperability was tested by connecting the CityGML database to QGIS for 3D data visualization [fig. 2]. Plugins such as 3DCityDB Tools [18] and Qgis2threejs [19] were used to validate data translation to CityGML. Data were also exported to KML format for visualization on Cesium Ion [20] and Google Earth [21] [fig. 1]. These tests ensured that the data stored in 3DCityDB could be seamlessly visualized and analyzed using popular geospatial tools, facilitating the integration of CityGML data into other platforms for broader use.

The 3D Web Map Client based on Cesium JS [7] was used to provide interactive visualization of CityGML models, allowing users to explore urban geometries with terrain and satellite imagery overlays [fig. 3]. The developed viewer prototype [fig. 9-14] enables the visualization of specific data sets, or "views," of the complete CityGML model. It allows the combination of three-dimensional data with connected tabular data, which were obtained through exports from 3DCityDB. Specifically, tabular data for each information layer were extracted using specialized SQL queries, combining information from the more complex CityGML schema into a single table related to a specific object type (e.g., buildings). Each of these tables was then imported into Google Drive spreadsheets [22], providing the ability to update data in real time [fig. 7]. For instance, energy simulation results could be automatically written back to these documents using Google's API services [23].

The prototype included the implementation of a conditional coloring exercise, where buildings can be colored based on specific metadata attributes, such as energy consumption levels or building type. Conditional coloring was based on metadata attributes obtained through the linked spreadsheets, and was achieved through custom JavaScript-based dynamic updates of the model [fig. 8]. The viewer was also configured to include additional data layers, such as satellite imagery and digital terrain models (DTMs), enhancing the contextual information available to users exploring the 3D city models.

Results

The research project established a functional geospatial database and management system to support the design and analysis of urban districts. A local instance of 3DCityDB was set up and integrated with CityGML models for urban energy analysis. The development environment was configured using Docker, ensuring a consistent and portable setup.

Spatial data from regional databases were imported into the system, including elements at LoD2. Data integration and modeling efforts successfully generated a semi-automated, highly scalable CityGML database, managed through the 3DCityDB tools. Energy data from Roma Tre University were linked with building geometries, enabling a preliminary overview of energy modeling tools at the urban scale. For this purpose, the Energy Application Domain Extension (ADE) was integrated into the database schema and related 3DCityDB tools.

To ensure interoperability, the CityGML data were successfully integrated with a custom visualizer, QGIS, Cesium Ion, and Google Earth, supporting both data validation and 3D visualization. The custom 3D web-based visualization client, based on Cesium JS, was linked to the database, providing an interactive interface to explore the urban models. This interactive prototype was developed to visualize integrated 3D models and associated data, linking tabular data with geometric representations through Google Sheets.

Future development

Despite the progress, data quality challenges were noted, such as incomplete geometries and semantic attributes. Manual refinement of geometries will be required for certain areas, and missing open-space data categories — e.g. water bodies and some sports facilities — will need to be prioritized for future integration. Additionally, a greater quantity and variety of energy data need to be processed to further enhance modeling and ensure compatibility with energy simulation tools and algorithms. This includes addressing challenges related to compliance with CityGML standards and integrating the Energy ADE, ensuring the standardized representation of energy consumption, generation, and other related metrics.

Interoperability of the CityGML database with other platforms will also be further refined. Specific attention will be given to generalizing and streamlining data conversion and import/export workflows to facilitate the application of the developed methods to other case studies. Finally, the expansion of the interactive capabilities of the custom visualizer will be pursued, providing more insights into metadata and advanced analytics, enabling real-time simulation integration, and expanding user-driven customization options for visualization parameters.

Conclusions

The development of the geospatial database put several foundational components in place. The integration of open-source tools such as 3DCityDB, Blender, QGIS, and Cesium JS has proven effective for managing and visualizing geospatial data and providing scalable and replicable solutions. The flexibility of using CityGML as the underlying data format supports interoperability and future extensions.

The planned enhancements will further integrate energy modeling capabilities, with the aim of developing comprehensive tools for decision-making in urban energy planning.

Publications and dissemination

Workshop lecture. P. Marrone, P. Civiero, V. Palma (2024). Metodologie e strumenti per l'elaborazione del quadro conoscitivo per la digitalizzazione e transizione energetica. Workshop *Digital Twin, integrazione di sistemi Gis e Bim per la transizione digitale. Il paradigma informativo nella rappresentazione e gestione dell'architettura e del territorio*, Università degli Studi Roma Tre, Roma, 6 May, 2024.
http://www.scuolaiad.it/component/zoo/item/digital-twin-integrazione-di-sistemi-gis-e-bim-per-la-transizione-digitale-2

Submitted abstract. Marrone P., Civiero P., Palma V., D'Autilia R. (*to be published*). Urban Digital Twin supporting the implementation of positive energy districts (PED). *Sustainable Built Environment Conference*, Zürich, 25-27 June.

Submitted abstract. Marrone P., Civiero P., D'Autilia R., Palma V. (*to be published*). Un modello per la 'coproduzione' di conoscenze nei processi decisionali in ambito energetico. *TECHNE | Journal of Technology for Architecture and Environment*, 30.

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Research deliverable. Civiero P., Ortiz J., Spohr J. [lead authors] *et al.* (July, 2024). "D2.1 - Full harmonized inputs assessment framework". Internal deliverable for *MakingPEDs - Decision-Making Digital Twins for Climate Neutral PEDs*, WP2.

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[22] https://workspace.google.com/products/sheets/
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Figures

Fig. 1. Results of importing a dataset on Cesena into CityGML, extracted from the Regional Topographic Database of Emilia-Romagna. The images show the 3D component visualized in Google Earth through KML format export.

Fig. 2. Visualization in QGIS of an initial set of buildings in the Valco San Paolo area, as defined in CityGML by converting the available sources.

Fig. 3. 3D visualization in Web Map Client (interface for 3DCityDB based on Cesium JS) of an initial set of buildings in the Valco San Paolo area, obtained from the CityGML database through an export in the specified format.

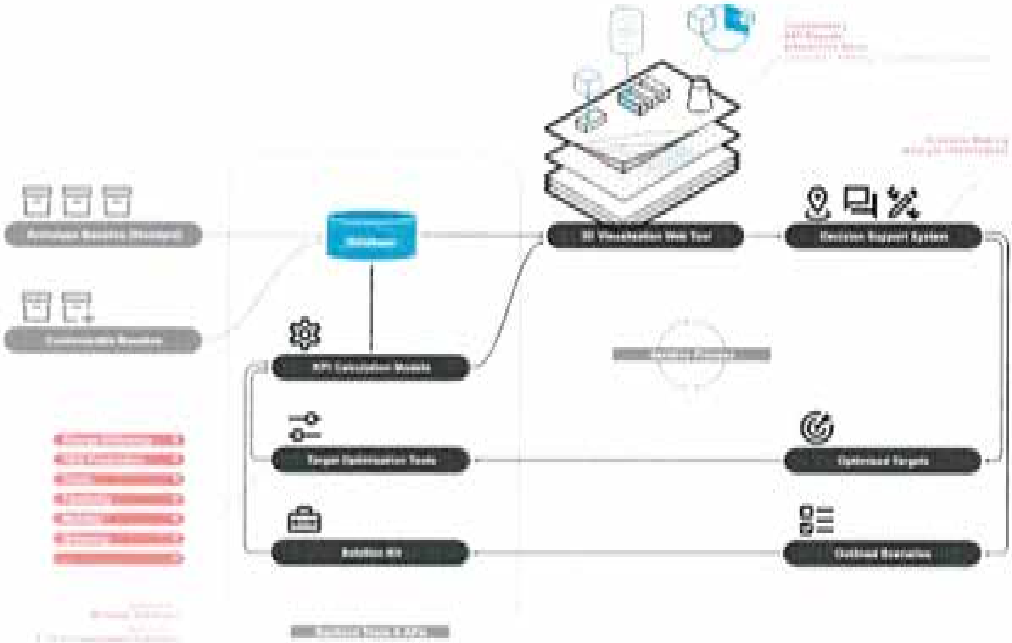

Fig. 4. Methodological framework proposed by the project: an iterative process leverages the geospatial database and the repertoire of solutions for generating transformation scenarios.

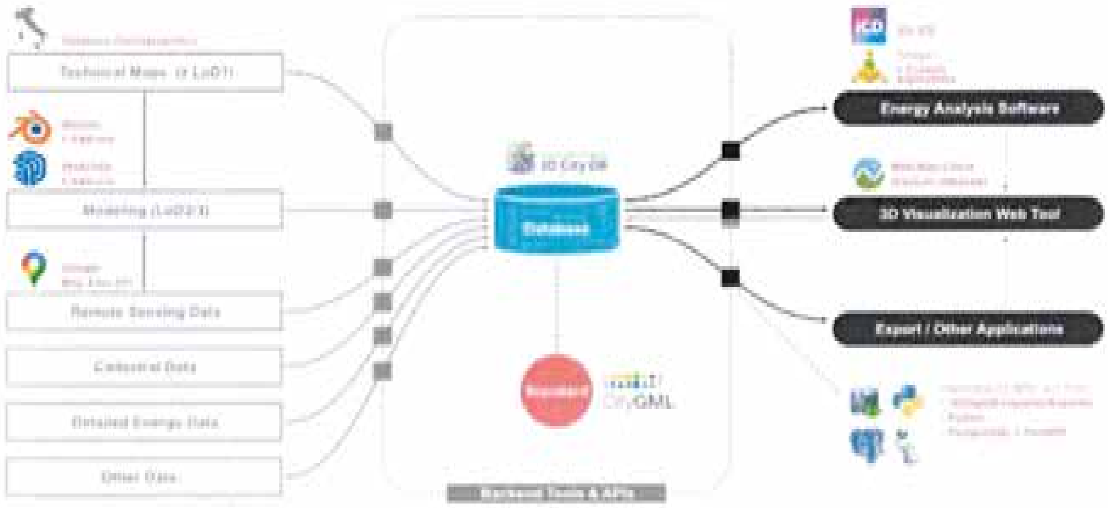

Fig. 5. Diagram of the software components ensuring the study and definition of the data flow through the geospatial database.

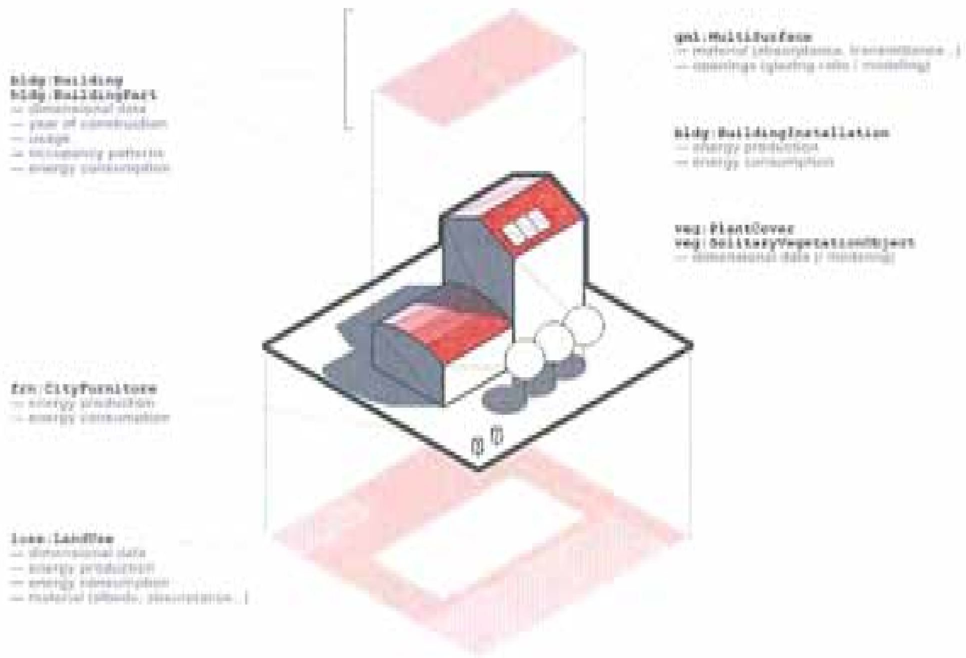

Fig. 6. Schematic notes for assigning energy domain information to the components of the model in CityGML.

Fig. 7. 3D visualization in Web Map Client of metadata read in real-time from a linked document (in this case, a Google Sheets document).

Fig. 8. Execution in 3D Web Map Client of a script for conditional coloring of buildings. A graphical representation of the cooling power demand for summer air conditioning is shown for a selection of buildings at Roma Tre University (colors range from blue to red).

Fig. 9. Overview in the 3DCityDB Web Map Client of the objects (buildings and land use areas) recorded in the CityGML database for the Ostiense area in Rome (Technopole case study).

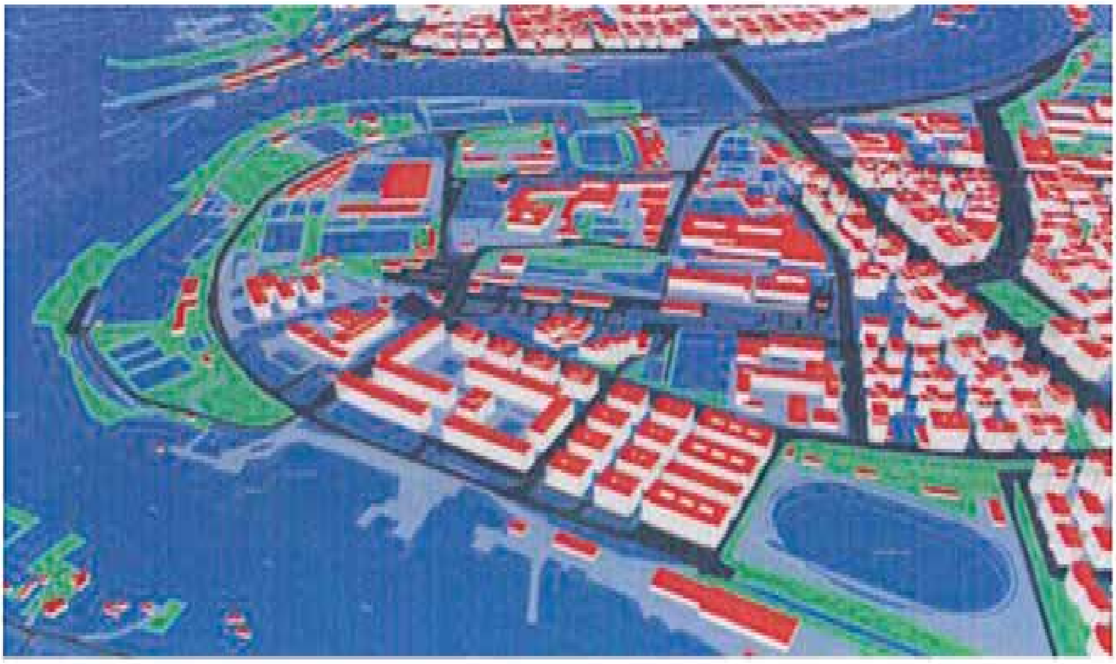

Fig. 10. Bird's-eye view in the 3DCityDB Web Map Client of the objects recorded in the CityGML database (buildings with distinct vertical walls and roof surfaces, and land use areas).

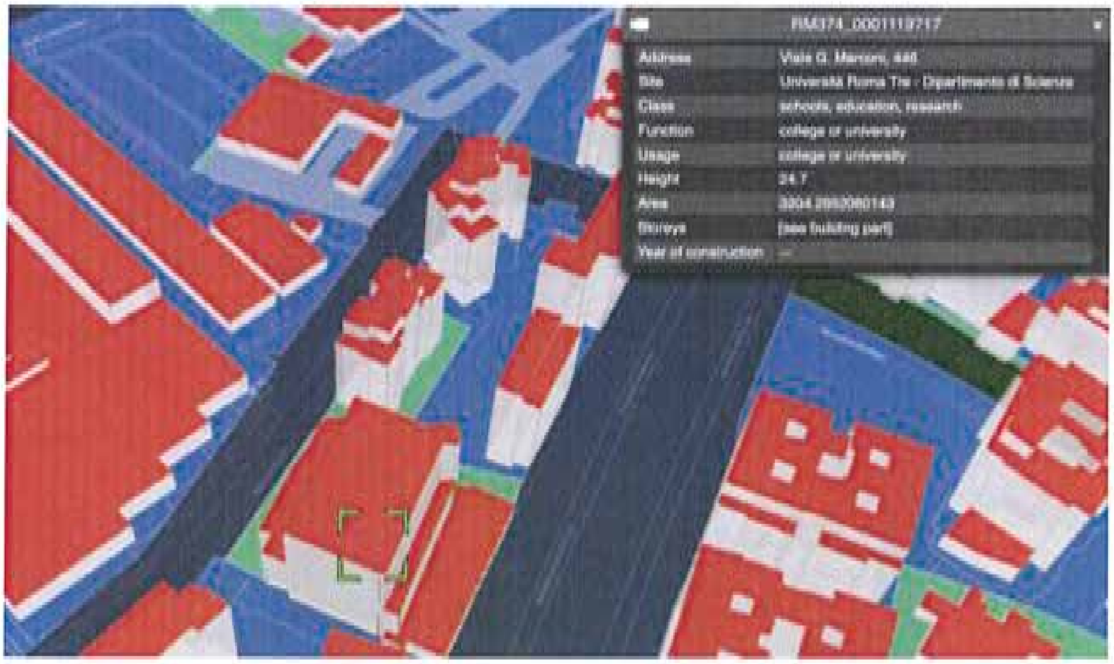

Fig. 11. Detail of the query on the layer exported from the CityGML database to represent buildings and related generic information — saved in a spreadsheet on Google Drive.

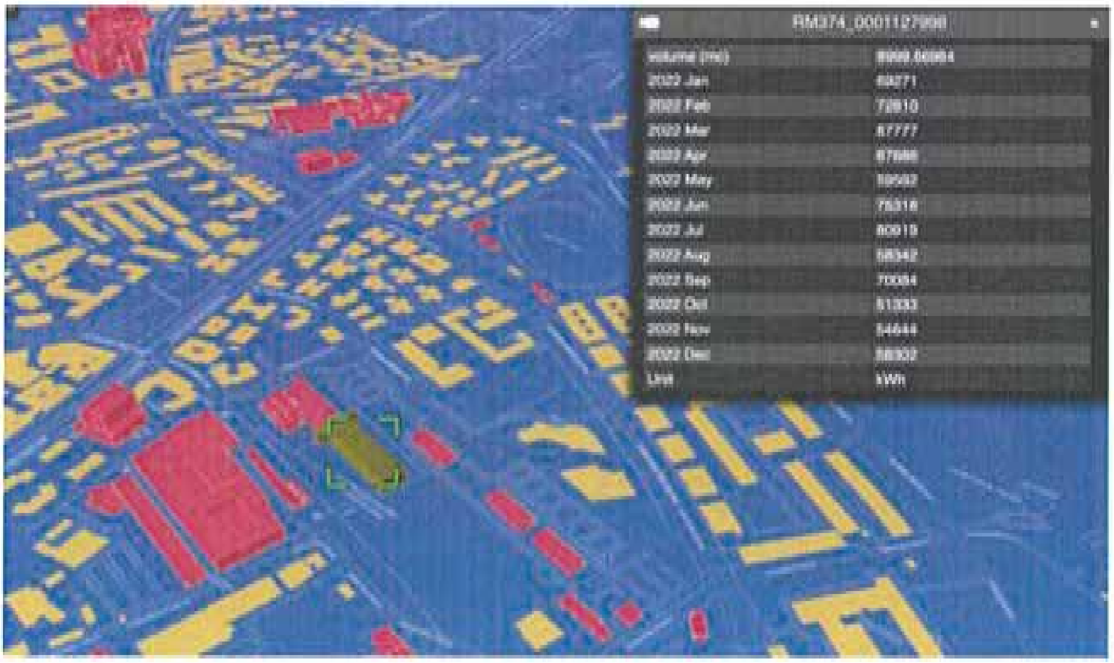

Fig. 12. Detail of the query on the layer exported from the CityGML database to represent the buildings of Roma Tre University and their related energy information.

Fig. 13. Detail of the query on the layer exported from the CityGML database to represent individual building walls and their related information.

Fig. 14. Detail of the query on the layer exported from the CityGML database to represent land use areas and their related information.

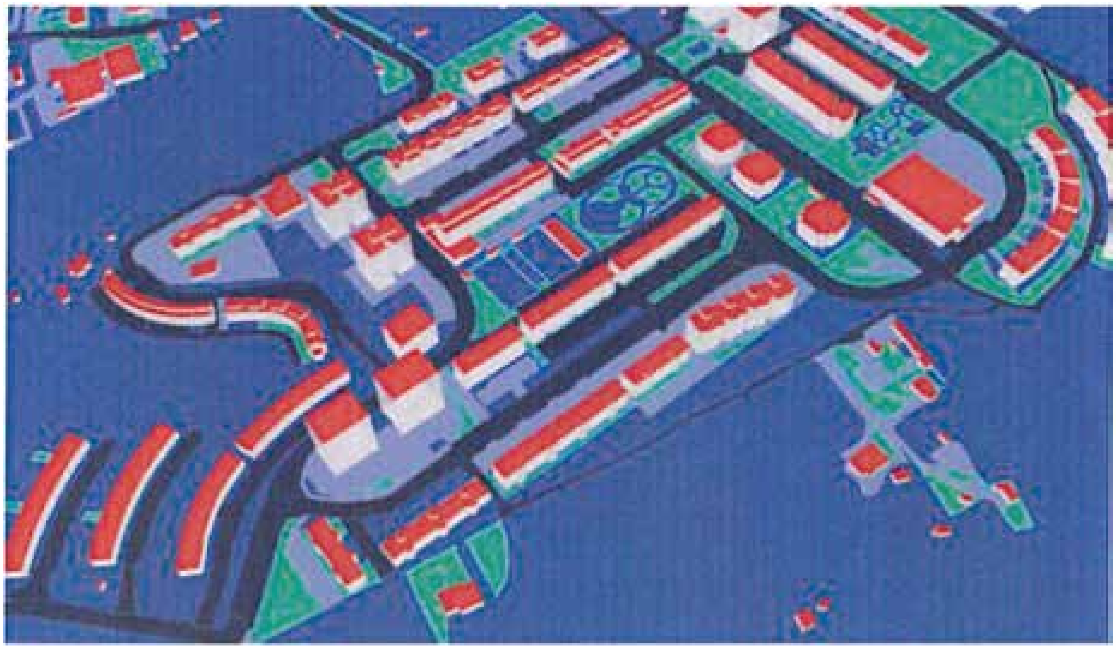

Fig. 15. Bird's-eye view in the 3DCityDB Web Map Client of the objects recorded in the CityGML database. Detail of the data from the Civitavecchia municipality: the MakingPEDs case study area.