

POLITECNICO DI TORINO

Department of Architecture and Design

Master of Sciences in Architecture for sustainability

A GIS–BIM workflow for energy mapping and retrofit prioritization in historic districts: The Digital Twin of Via Roma, Turin

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Abstract

Cities are represented today through a multiplicity of digital models, Geographic Information Systems (GIS) capturing the district and regulatory scale, Building Information Modelling (BIM) capturing the individual building, that are rarely designed to communicate with one another. This fragmentation, compounded by cities' continuous transformation over time, remains a persistent obstacle to coherent, city-scale analysis and decision-making, particularly in historic districts where sustainability demands must be reconciled with heritage preservation constraints. This thesis proposes and tests an integrated GIS-to-BIM mapping methodology designed to represent a historic urban district as a single, coherent, and adaptable digital model, using Via Roma in Turin as a case study. The methodology develops a reproducible workflow linking parcel-level geographic data to building-level parametric BIM models, using Dynamo as a bridge between municipal GIS data, census data, heritage records, satellite data, and the TABULA building archetype database. It is designed to remain robust under real-world conditions of incomplete or heterogeneous source data, drawing on contextual and regulatory knowledge to compensate for such gaps rather than requiring complete datasets as a precondition. The resulting multi-layered model is applied to a sustainability-oriented outcome, assessing retrofit-driven energy performance and renewable energy potential in relation to each building's specific heritage constraints and physical characteristics, and delivered as a decision-support visualization intended to be accessible to specialist and non-specialist stakeholders alike. By testing this workflow against the real, imperfect data conditions of an active historic district rather than idealized or synthetic ones, the thesis addresses four recurring gaps identified in the GIS-BIM integration literature: the absence of a universal integration method, semantic and data loss during translation between paradigms, the difficulty of managing consistent data across district and building scales, and existing workflows' tendency to fall back on coarse simplification when faced with incomplete input data. The findings are intended to demonstrate the extent to which such an integrated methodology improves on treating GIS and BIM as separate mapping layers, and to establish a framework that remains extensible as urban data, regulations, and sustainability demands continue to evolve.

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Chapter 1: Introduction

Cities today are represented through an increasing multiplicity of digital models, each built for a different purpose, at a different scale, and rarely designed to communicate with one another. Geographic Information Systems capture the city at the scale of the district, the parcel, and the regulatory context; Building Information Modelling captures the individual building at the scale of its physical fabric and performance. Both are mature, independently developed paradigms, and both are, on their own, incomplete: a GIS layer cannot represent a building's internal construction logic, and a BIM model, taken in isolation, has no awareness of the urban and regulatory context in which that building actually sits. This fragmentation across independently maintained data sources and modelling paradigms is well documented in the built-environment literature, where the absence of shared semantic or spatial references between systems is repeatedly identified as a barrier to effective city-scale analysis and decision-making (Pasquinelli et al., 2019).

This fragmentation is compounded by a further difficulty: a city is not a fixed object to be mapped once and then considered known. It is a system in continuous transformation, its building stock aging, its regulatory frameworks evolving, its climate and sustainability targets shifting, and its available data sources changing in both quantity and quality over time. Reviews of urban digital twin implementations identify version management as a persistent practical challenge, noting that cities frequently replace an outdated city model outright rather than maintaining a coherent representation of change over time, and that a genuinely useful urban model needs to remain reactive to a continuously evolving physical environment rather than describing a single fixed moment (Lei et al., 2023). Urban energy simulation platforms reflect the same underlying pressure from a different angle: their workflows are increasingly built as modular and extensible by design, specifically so that a growing and diversifying body of city data can continue to be absorbed without the platform itself becoming obsolete (Nouvel et al., 2015). Some applied urban energy models go further still, explicitly projecting a building stock's performance forward in time, accounting for anticipated demolition, new construction, and renovation cycles, rather than describing only its present condition. A mapping methodology built only for the city as it exists today risks becoming outdated as soon as new data becomes available, new regulations are introduced, or new technological capabilities emerge; a genuinely useful approach must therefore be conceived not as a static snapshot, but as a framework capable of being updated, extended, and re-applied as conditions change.

As cities face mounting pressure to become more sustainable, more energy-efficient, and more resilient, while simultaneously preserving the historic and cultural fabric that gives them their identity, this combination of technical fragmentation and temporal rigidity becomes a genuine methodological obstacle, not merely a technical inconvenience. Addressing it requires more

than incremental improvements to either GIS or BIM individually; it requires testing whether the two can be integrated into a single, coherent, and adaptable way of mapping the city, one capable of carrying geographic, regulatory, physical, and performance-related information simultaneously, for every building in a district, while remaining flexible enough to accommodate the incomplete, evolving, and unevenly available data that real urban contexts actually produce.

This thesis proposes and tests such an integrated GIS-to-BIM mapping methodology. The intention is primarily methodological: to develop a workflow that can, in principle, be applied to any urban district, validated not against synthetic or idealized conditions, but against the real, imperfect conditions that any genuine historic district presents, and designed with the explicit expectation that both the underlying data and the questions asked of it will continue to change over time.

1.1 Research Objectives

The overarching objective of this thesis is to introduce a new way of mapping the city, one that responds directly to the technological and sustainability demands of the present era, by developing and validating an integrated GIS-to-BIM methodology capable of representing a historic urban district as a single, coherent digital model, designed not only to describe the city as it exists today, but to remain adaptable to the evolving data, regulations, and sustainability demands cities will continue to face going forward, using Via Roma, in Turin, as a case study. This objective is pursued through the following specific goals:

1. Introduce and demonstrate a new approach to mapping the city, one capable of responding jointly to the technological and sustainability demands facing urban environments today.
2. Develop a reproducible GIS-to-BIM integration workflow, capable of linking parcel-level geographic data to building-level parametric BIM models.
3. Test the methodology's robustness under real-world data conditions, maintaining a coherent, defensible model in the presence of incomplete or heterogeneous source data, using contextual and regulatory knowledge to compensate for such gaps rather than requiring complete data as a precondition.
4. Demonstrate the methodology's capacity to carry multiple, simultaneous layers of information for the same building stock.
5. Apply the resulting model to assess a sustainability-oriented outcome, retrofit-driven energy performance and renewable energy potential, evaluated in relation to each building's specific characteristics and contexts.

6. Deliver the resulting model as an accessible, decision-support visualization, capable of translating the underlying multi-layered dataset into a framework usable by specialist and non-specialist stakeholders.

1.2 Problem Statement and Gaps

Reviewing the literature on GIS-to-BIM integration at building and district scale surfaces four recurring, unresolved problems. These span the technical process of moving data from one system to the other, the practical difficulty of managing that data once multiple scales are involved, and how existing methods respond when the underlying information is incomplete.

1. No Universal Method

When researchers compare the different ways of taking district- or city-level GIS data and turning it into building-level BIM models, no single approach comes out ahead on every measure. A custom-built solution might preserve data well but takes too much time and money to build. A quick, one-off connection might be cheap but can't be reused on the next district. A more flexible, standards-based approach takes years to develop and still isn't finished. In short: connecting district-scale GIS data to building-scale BIM models remains a matter of picking which weakness you're willing to accept, not a solved problem (Liu, Wang, Wright, Cheng, Li, & Liu, 2017).

2. Semantic and Data Loss

A GIS model is built to describe a district as it actually exists on the ground, typically representing each building as a single footprint carrying attributes like land use, construction period, or cadastral ID. A BIM model is built to describe a building in the detailed, construction-oriented way architects and engineers need, broken down into individual elements such as walls, floors, and roofs. Because the two were never designed around the same logic, generating a BIM model from GIS data means BIM has to construct that entire internal element structure from scratch, since GIS never represented it in the first place, and in doing so, some of the original GIS attributes can fail to map cleanly onto the new BIM elements or get attached to the wrong part of the resulting model. This is confirmed in real applied work, not just theory: a real attempt to bring GIS-held building data into a city-scale BIM environment, using rules based on shared IDs, still broke down whenever a building's records didn't follow a consistent naming pattern, leaving that data effectively unusable once converted (Sammartano et al., 2021).

3. Multi-Scale Data Management

Once a model has to represent both an entire district and the individual buildings within it, the harder problem is not building the geometry itself but keeping the underlying data consistent,

complete, and synchronized as it moves between scales, from district-level GIS information down to building-level BIM detail. No single, uniform way of representing a building performs equally well at both scales at once, which means different levels of geometric and semantic detail end up being applied depending on the scale in question, rather than one consistent model serving both cleanly (Lu et al., 2020).

4. Handling Incomplete Data

Existing GIS-to-BIM workflows tend to respond to missing input data by falling back to a uniform simplification, rather than adjusting their treatment based on how much or how little is actually missing. Where survey data for a specific building element is unavailable, the entire model for that building is typically reduced to a coarser, less detailed representation, and a single default assumption is applied in place of the missing value, even for buildings where other partial evidence might have supported a more accurate estimate (Pasquinelli, Agugiaro, Tagliabue, Scaioni, & Guzzetti, 2019).

1.3 Research Questions

These objectives are structured around the following research questions:

1. To what extent does an integrated GIS-to-BIM methodology improve a genuinely new way of mapping the city, compared with using GIS and BIM as separate tools or conventional approaches based on separate mapping layers?
2. Can GIS and BIM be integrated into a single, coherent, and extensible mapping methodology, capable of representing a historic urban district as an evolving model rather than a fixed, single-use snapshot?
3. How far can such a methodology remain robust and defensible when the underlying real-world data is incomplete, heterogeneous, or unevenly available across a district, and what role can contextual or regulatory knowledge play in compensating for such gaps?
4. Can the resulting model be delivered as a tool that end users, not only technical specialists, can directly access, explore, and rely on to inform their own decisions?

Chapter 2: Literature Review

2.1 Turin's Urban history

Turin's identity as a city has always been closely tied to the deliberate reshaping of its own form. What began as a compact Roman military settlement was, over the course of two millennia, expanded, fortified, demolished, and replanned, each phase leaving a legible trace in the streets and blocks that make up the city today. This section briefly describes what has actually happened to Turin's urban form over time.

Turin originated as a Roman castrum: a near-square grid crossed by the Decumanus and Cardo Maximus, meeting at right angles near today's Palazzo Reale and running out to four gates at the perimeter. The city was enclosed by walls roughly 3,000 yards around (about 110 acres), with a population of up to 5,000 at its height. Of the four gates, the Porta Palatina to the north still stands on its old perimeter, its massive brick and stone towers rising above the surrounding buildings. The eastern gate was later absorbed into what is now Palazzo Madama. This four-gated grid remained the template for every later expansion of the city (Cardoza & Symcox, 2006).

Once Turin became the Savoy capital, the city grew southward into a new district known as the "Città Nova". A straight axis, today's Via Roma, was cut in 1587, running from the old ducal palace and Piazza Castello out to a new gate, Porta Nuova, which was built well beyond the old walls and joined to the city by a bastioned loop. Piazza San Carlo was laid out at its midpoint and the old Palazzo Ducale was given a unified porticoed front, with Piazza Castello itself widened to match. A dedicated ducal body, the Council of Buildings and Fortifications, was established to oversee this new district's planning, regulating street layout, façade height and decoration, and building materials. Two further extensions followed on the same model: one to the east, reaching almost to the Po, and one to the west. Together they roughly doubled the size of the fortified city over the course of a century (Coppo & Moglia, 1995; Cardoza & Symcox, 2006).

One of Napoleon's first acts after Turin's absorption into the French Empire was to order the demolition of the city's walls and most of its urban fortifications, opening the city outward on every side. The city was, however, given a more rational administrative order: the old system of blocks named after saints was replaced with four districts reflecting the main directions of traffic, and a sequential system of street numbering, modelled on Paris, was introduced in 1808 (Cardoza & Symcox, 2006).



Figure 2.1 Plan of Turin drawn by Captain Carlo Morello in 1656, from Avvertimenti sopra le fortezze (Biblioteca Reale di Torino, Manoscritti militari, 178, cc. 15b–16a). Reproduced from Coppo & Moglia (1995), Tav. 1.

After the monarchy's restoration, the city resumed its outward growth, and by the late 1840s had filled out the area bounded by the boulevard ring still recognizable today. Turin briefly became the capital of the newly unified Kingdom of Italy in 1861, only lose that status just three years later, when the capital was transferred to Florence. The loss plunged the city into an extended period of economic and demographic uncertainty, and it was in response to this crisis that Turin's leadership began, from the 1880s, to reshape the city as a modern industrial and commercial center, a starting stage for the large-scale urban (Cardoza & Symcox, 2006).



Figure 2.2 Excerpt of Andrea Gatti's Carta geometrica della Real Città di Torino e sue adiacenze, lithographed in Turin in 1823. Reproduced from Coppo & Moglia (1995), Tav. 5.

The old city grid, still largely unchanged since its Baroque-era layout, began to strain against the demands of a modernizing city by the late nineteenth century. In 1877, a proposal emerged for a new diagonal street cutting through the historic center to link Piazza Castello and Piazza Solferino, easing traffic through streets that had never been designed for it. A cholera scare in the mid-1880s, along with elevated mortality reported in the Dora district, added urgency to the case for opening up the old fabric to more light and air. A definitive renewal plan was approved in March 1885, authorized by royal decree, and carried out over the following half-century in four separate phases, between 1886 and 1935. The result was two new diagonal cuts through the old grid, Via Pietro Micca and Via/Piazza IV Marzo, which broke the historic city's rigid orthogonal pattern for the first time and introduced wider, straighter streets (Coppo & Moglia, 1995).

The same logic that drove the 1885 risanamento, clearing away old, irregular fabric in favor of wide, regular, modern streets, reached its fullest expression half a century later in the reconstruction of Via Roma itself. A 1931 pamphlet made the case for rebuilding the street entirely in a modern idiom, presenting the proposal as a natural continuation of Turin's own long-standing habit of renewing its urban core rather than a break from it (M.I.A.R. Group, 1931). The reconstruction that followed replaced the historic San Pietro block with a new, unified composition of continuous porticoed frontages, a project examined in detail as the Via Roma case study in Chapter 3 (Bonicelli & Ratti, 1934).

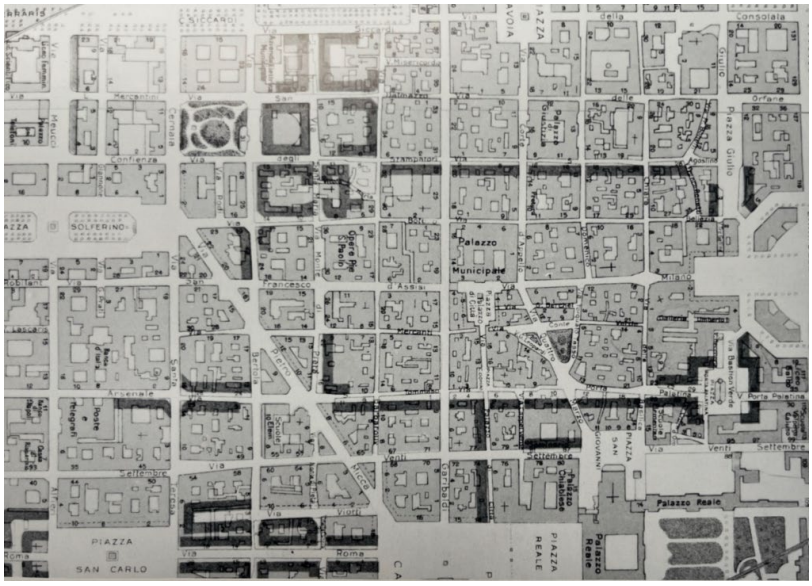


Figure 2.3 Excerpt of the Pianta di Torino coll'indicazione dei due piani regolatori e di ampliamento, printed in 1925 (Archivio Storico della Città di Torino, Tipi e disegni, 64-8-22). Reproduced from Coppo & Moglia (1995), Tav. 8.

The reconstruction of Via Roma in the early 1930s did not mark the end of large-scale change in Turin's built environment; it was, only a pause before the most disruptive period in the city's modern history. Within a decade the Second World War brought destruction on a scale the city

had never experienced. Bombing raids began in June 1940 and intensified through the winter of 1942 and the summer of 1943, and by the time the war ended roughly forty percent of Turin's building fabric had been destroyed or seriously damaged (De Magistris, 1999).

The years that followed were not governed by any adopted plan. For more than a decade after Liberation, rebuilding proceeded under a provisional 1945 measure that did little more than fix new street alignments ahead of informal reconstruction, while the city's actual general regulatory plan (Piano Regolatore Generale) took until 1959 to reach approval. In the intervening years, the single most common building operation was not new construction but the addition of extra storeys onto existing buildings, and public investment went toward infrastructure and industrial capacity rather than housing quality (De Magistris, 1999).

A wave of migration from southern Italy happened in the metropolitan area through the 1960s and 70s. But by Turin's industrial base contracted from the 1980s, the city's focus shifted from outward growth to reusing land it already held, chiefly its old railway corridor. This culminated in a new master plan (approved 1995) by Gregotti Associati, centered on the Spina Centrale: roughly four kilometers of railway land where the tracks were buried and quadrupled for an integrated transport system (Comune di Torino, Ufficio del Piano Regolatore, 1995).

The final chapter of this trajectory, was written in the run-up to the 2006 Winter Olympic Games, which Turin hosted as the culmination of its post-industrial reinvention. In 2006 the City Council approved a variant to the master plan removing the height limit that had constrained new construction, specifically so that the Mole Antonelliana would remain the tallest structure in the city by symbolic status even as literal building heights moved elsewhere in the years that followed (Cardoza & Symcox, 2006).



Figure 2.4 Comune di Torino. (2025). Dati di base – Carta di sintesi – Aree [dataset]. Geoportale Piemonte.

2.2 Evolution of Urban Representation of the City

Representing a city is never a neutral act of copying what exists; it is always a selection. Every survey defines its own parameters, and defining parameters means choosing which elements of a constantly changing reality are worth capturing while leaving others out. This section traces how that selection problem has been addressed for Turin specifically, from the earliest known view of the city, through an early-twentieth-century survey tradition built on paper and measured drawing, through the plan as an instrument of governance rather than record, to the digital, georeferenced representations in use today (Moglia & Boido, 2008).

The foundation of this tradition is a study coordinated at the Politecnico di Torino in the 1960s, which set out to read Turin's historic core, the area within its Baroque walls, before their Napoleonic demolition and the nineteenth-century expansions, as the outcome of a long process of urban, architectural, political, and social transformation, rather than as a static plan. The method this study developed was later partly codified into a technical standard for surveying historic urban fabric and gave a shared, repeatable language to city's survey tradition (Moglia & Boido, 2008).

That same research group went on to test whether their method held beyond Turin, applying it to other Piedmontese cities to see whether it could generalize, before shifting its focus once again, this time from the static form of the city to its function. A repeated case was Turin's network of covered porticoed streets, several kilometers of continuous covered routes from over four centuries, studied not as architecture in isolation but as infrastructure vitalized by the commerce that took place under it. Reading the city this way required tracking transformations over months and years, and organizing the resulting observations into a structured, queryable record rather than a single finished drawing (Moglia & Boido, 2008).

Turin's own cartographic record makes this same image visible, since each successive survey re-measured and re-drew the city according to the techniques and purposes of its own moment, rather than simply adding detail to a single continuous record.

The oldest known printed view of Turin as a whole is a 1577 woodcut, “Augusta Taurinorum”, engraved by Giovanni Criegher after a design by Giovanni Caracha, published in Filiberto Pingone's work of the same title. It reuses the same woodblock as an earlier 1572 version, a reminder that this earliest representation was already an instrument of dynastic image-making as much as a record of the city's streets. The print is a perspective view rather than a measured plan: it shows the Cittadella, the Porta Palatina, the Porta Marmorea, and the city's two main axes and four quarters, but its purpose is closer to a portrait of Savoy power than to a technical survey.

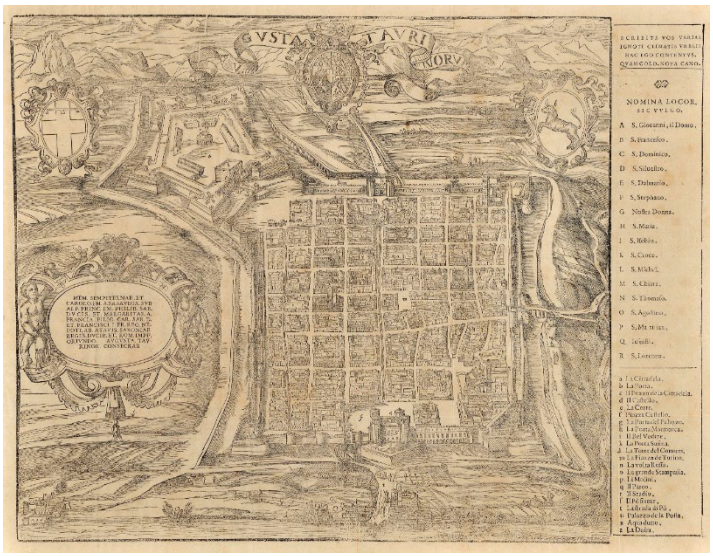


Figure 2.6 "Augusta Taurinorum," 1577, engraved by Giovanni Criegher: the earliest known printed view of Turin.

A 1656 military survey (Fig. 2.1), drawn to assess the city's fortifications, represents the city purely as a strategic object: walls, gates, and the block pattern relevant to defense, with little concern for property boundaries or individual buildings. A century and a half later, Ignazio Amedeo Galletti's 1790 geometric plan of the royal city and citadel (Fig. 2.6) reflects a different purpose entirely. It is an administrative, geometrically precise survey of the whole urban and fortified territory, produced for the state rather than for a military commander.

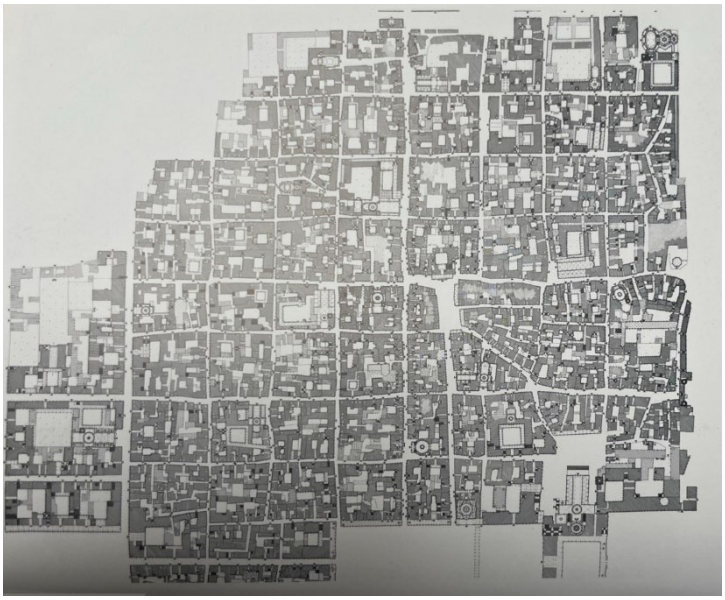


Figure 2.5 A conjectural philological reconstruction of Turin's mid-eighteenth-century urban fabric, from Cavallari Murat's 1968 study Forma urbana e architettura nella Torino barocca, vol. II. Reproduced from Coppo & Moglia (1995), Tav. 3.

By 1866, representation had shifted purpose again. The Catasto Rabbini (Fig. 2.7), a cadastral mosaic approved that year, records the city not for strategic or administrative geometry but for taxation and property law: every individual parcel is defined, because the map's entire function

is to establish who owns what. The same city is being measured again, and a set of questions determines what the map chooses to show.



Figure 2.7 Excerpt of the "mosaicatura" of the Catasto Rabbini cadastral maps, approved 17 May 1866 (Archivio di Stato di Torino, Ministero delle Finanze, Catasto Rabbini). Reproduced from Coppo & Moglia (1995), Tav. 6.

Where the 1656, 1790, and 1866 surveys each recorded the city as it already existed, a Piano Regolatore Generale represents the city twice over: what is there now, and what is permitted to be built in its place. A 1925 municipal plan (Fig. 2.8) shows this dual character clearly, combining a record of the existing street pattern with the two regulatory schemes then governing future construction, including the diagonal cuts discussed in Section 2.1. Representation, at this point, stops being purely descriptive and becomes prescriptive: the map is no longer only an image of the city, but an instrument for deciding what the city is allowed to become.

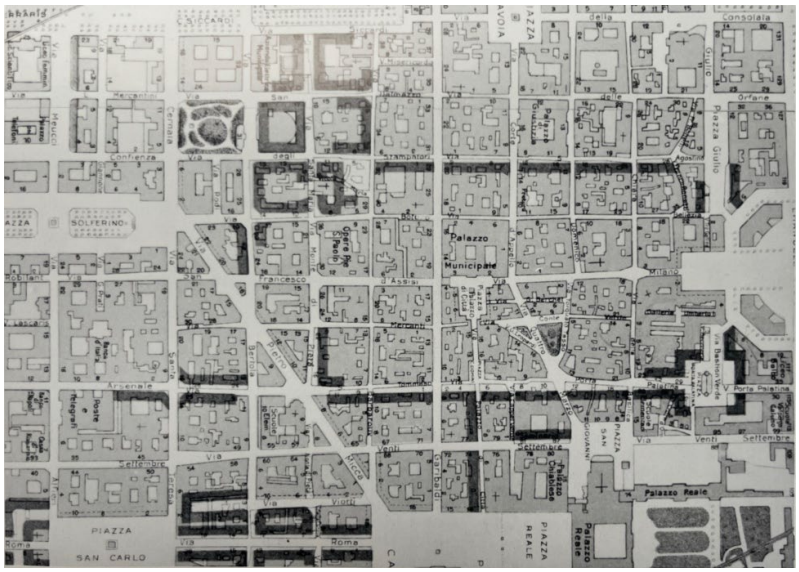


Figure 2.8 Excerpt of the Pianta di Torino coll'indicazione dei due piani regolatori e di ampliamento, printed in 1925 (Archivio Storico della Città di Torino, Tipi e disegni, 64-8-22). Reproduced from Coppo & Moglia (1995), Tav. 8..

This same logic reached its fullest, in Turin's first postwar general regulatory plan, approved by presidential decree on 6 October 1959, fourteen years after Liberation, following a 1947-48 design competition and a long period of largely unplanned reconstruction (Section 2.1). The 1959 Prg is not merely another historical document; it remains, in amended form, the representational instrument that still governs what can legally be built in Turin today, making it the clearest possible bridge between the plan-as-representation described here and the plan-as-lived-regulation.

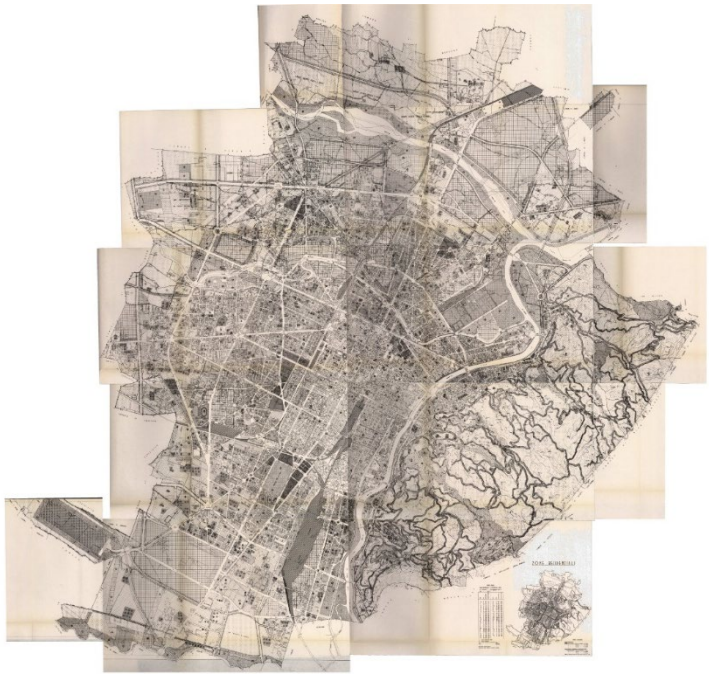


Figure 2.7 Turin's 1959 Piano Regolatore Generale, approved by presidential decree, 6 October 1959.

The same instrument continues to represent and govern the city today, in a substantially revised form. Turin's currently general regulatory plan was adopted by the City Council in 1993 and approved by the Piedmont Region in 1995, and it is still amended by variants rather than replaced outright, the zoning map (Fig. 2.10 bis) is published and maintained by the City of Turin's own Geoportale, alongside companion tables covering historic buildings, geomorphological hazard, and other regulatory layers.

Reflecting on this whole trajectory, the same research tradition eventually confronted a problem specific to the digital era: georeferenced data does not resolve the difficulty of selection, it intensifies it. As the volume of spatially referenced information available for any given area grows, deciding what to select and how to synthesize it into a meaningful representation becomes harder rather than easier, and documenting why certain information was chosen becomes as important as the representation itself (Moglia & Boido, 2008).

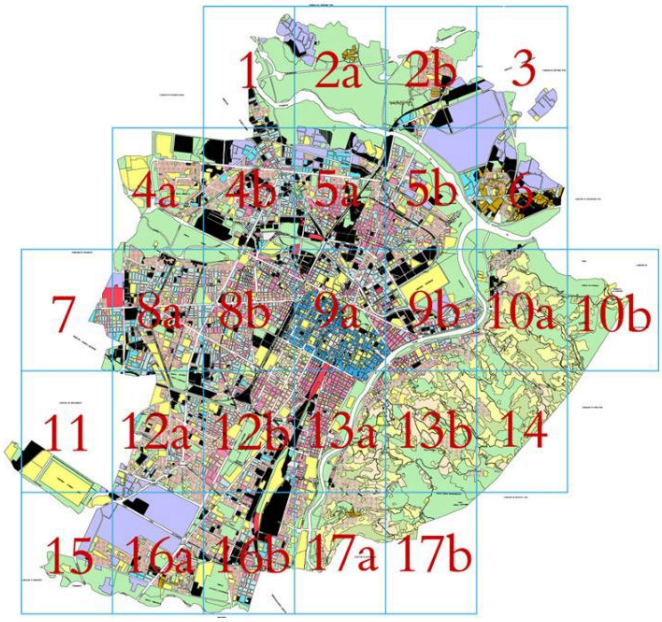


Figure 2.8 bis – Turin's currently-in-force zoning plan ("Tavola n. 1 – Azzonamento"), Comune di Torino Geoportale.

Turin's present-day representation carries this same trajectory into a fully digital, queryable register. The city, in this form, is no longer a single drawn sheet answering one question; it is a layered, continuously updatable structure that can be queried and re-rendered for whatever question is being asked (Sammartano et al., 2021).

These successive representations are not simply a chronology of maps. Each one answers a different question about what Turin is and what it is for, and each selection made along the way is the same problem this thesis inherits at building scale: not how to capture everything about a historic street, but how to select, structure, and represent what actually matters for the questions being asked of it.

2.3 Geographic Information Systems (GIS)

Geographic Information Systems are frameworks for storing, processing, analyzing, and displaying data based on their geographic location. They are relevant to this research because they allow geographic representations of space to be linked to descriptive information about the objects or phenomena contained within them. In simple terms, a map can show where a building is located but only through GIS can information about that building's identification number, address, cadastral reference, year of construction, land-use type, number of occupants, planning status or other attributes be added to its geographic footprint. Such models couple spatial with nonspatial attributes and allow urban information to be queried, compared and analyzed at multiple scales (Longley et al., 2015).

GIS therefore progressed from computers processing map data to geographic information systems. While initial efforts were focused on digital mapping, these technologies have since expanded to encompass spatial databases, remotely sensed information, statistical datasets, 3D city models and web-based data. Within the built environment, GIS evolved from primarily depicting parcels and infrastructure to increasingly support the analysis of buildings as components of urban systems. This evolution of GIS is especially important because information about buildings resides across multiple datasets (territorial, cadastral, demographic, regulatory, environmental, building) rather than being encompassed in a single model.

1. Spatial Data Structure and Information Management

GIS usually depict geographic information using vector and raster data formats. Vector data describe points, lines, and polygons to represent discrete spatial objects such as parcels, roads, administrative boundaries and building footprints. Raster data store space as grids and are therefore applied to satellite imagery, elevation models or land-cover datasets.

Vector and raster layers are commonly combined in urban analysis. Building footprints can for instance be intersected with Digital Terrain Models or Digital Surface Models in order to derive height information and approximate building volumes. Sammartano et al. (2021) describe this type of modelling operation for the development of Torino's 3D city model.

Because they relate to space, geographic information technology depends on georeferencing and coordinate reference systems. Datasets produced by disparate organizations can only be reliably combined when their spatial extent is explicitly defined using common coordinates. GIS also enables spatial queries of intersection, containment, proximity, adjacency and others. With these tools, a building can be related to its enclosing cadastral parcel, census area, planning zone or environmental restriction based on its geographic location alone.

Spatial databases enable those relationships by allowing geometry and attributes to be stored together in databases. This allows multiple information sources to be joined, queried repeatedly and updated without treating each map as a standalone file. However, those datasets must include consistent identifiers, terminology, spatial reference, and validity period to work together successfully. Multiple files do not inherently improve their interoperability.

2. GIS and Municipal Building Information

Municipalities commonly store vast quantities of data related to buildings, parcels, population and regulations. They are often managed by separate departments with distinct information needs. Cadastral systems record parcel geometry and identifiers, topographic maps contain geometric information, census databases store demographic information, and separate planning and heritage systems manage regulatory information.

GIS serves as a common spatial framework where heterogeneous datasets can be associated with one another. Analyzing public building data in Northern Italy, Pasquinelli et al. (2019) combined topographic, cadastral, census and civil registry information to operationalise an integrated Building Information System (BIMS). Similar challenges affected their work including missing or outdated records, differing attribute terminology across datasets, and different update schedules between systems.

Turin exhibits many of the same challenges. Sammartano et al. (2021) describe how building-related information is distributed among technical, administrative, cadastral and real estate databases developed using independent data models, software and guidelines. Some datasets are primarily tables of information that are not consistently linked to geographic data. Though their primary research concerns establishing an operational 3D city model, they show that georeferencing those tables allows individual records to be compared and interpreted at urban scales.

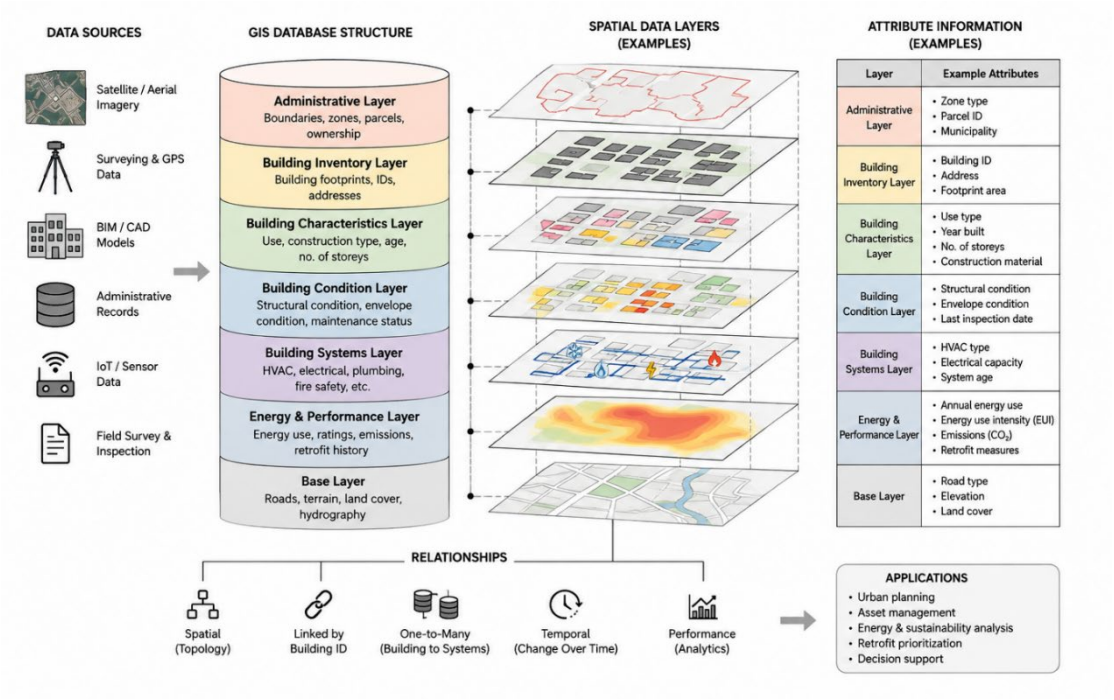


Figure 2.9 GIS database structure for integrated building information.

Yet aggregating information at building scale is complicated by the fact that census and demographic records are often only available at larger spatial units. Their association with buildings might therefore require aggregating, disaggregating or assuming how many people occupy each structure. Information may even refer to different years, requiring temporal harmonisation in addition to spatial integration. GIS can connect those datasets through space, but careful consideration is needed to account for differences in data resolution, accuracy, or timeframe.

3. Heritage and Historic Building Information

GIS can also play an important role in heritage management as heritage designations and regulatory restrictions are inherently geographic. By mapping heritage areas, individual buildings or regulatory conditions, these attributes can be connected to footprints or spatial objects. Doing so allows heritage information to be considered along with physical or environmental attributes of buildings.

Dang et al. (2024) leverage municipal heritage classifications, cadastral information on buildings, year of construction and provided typological information to analyze retrofit measures in Amsterdam's historic inner-city districts. This analysis illustrates how spatially-enabled heritage information can be integrated into building-stock level assessments to interpret technical measures within the legal and cultural context of individual buildings.

Heritage considerations can critically change the feasibility of energy retrofit measures. While two buildings might have identical energy performance, retrofit options on protected buildings or within conservation areas may be limited by regulatory restrictions. Semantic information within GIS can help establish these differences at district scale.

Historic districts can also highlight limitations in municipal datasets. Detailed information on building typologies, prior alterations, and heritage significance is frequently incomplete or unavailable. Large-scale studies often need to leverage building archetypes or generalized classifications to compensate for gaps in information. GIS assists in organizing and relating the available information, but cannot substitute for missing historic records.

4. From Two-Dimensional GIS to Semantic 3D City Models

Traditional urban GIS stores buildings primarily as two-dimensional footprints. These may support many planning, cadastral and statistical applications but do not allow for storing information about height, gross floor area, roof geometry or façade orientation. Heightened interest in environmental and energy simulations has therefore motivated the development of urban 3D city models.

Simple extrusions can be derived by vertically extending building footprints using attribute information about building heights. The geometric resolution of these models is then directly related to the available input datasets. For instance, Pasquinelli et al. (2019) introduced simplified geometries for buildings where roof data was incomplete, even if footprints were available at high positional accuracy.

3D city models can also be semantic in nature. They go beyond graphical representation of cities by describing the meaning or purpose of different objects. CityGML has become a popular standard for these models as it provides both geometric and semantic structures for

urban objects. Semantic 3D city models can therefore link attributes to buildings and their components. In that way, they can serve as information environments suited for urban analyzes.

Nouvel et al. (2015) use CityGML to create the underlying framework of the SimStadt urban energy simulation tool, where city geometry is combined with attributes required for heating demand calculation, solar irradiation assessment, and retrofit measures. Rossknecht and Airaksinen (20 20) perform a similar study by integrating 3D energy information into Helsinki's cityGML, allowing simulation results to be georeferenced back to building objects.

Both examples demonstrate that GIS purposes have expanded beyond visualization. Despite their similarities, Semantic 3D city models are distinct from BIM models. BIM contains highly-detailed information about the components and materials found in construction but is usually developed around the needs of a single building. Meanwhile, city models aim to consistently represent large quantities of urban objects across an entire city.

5. GIS for Urban Energy and Retrofit Decision Support

GIS are especially useful for urban energy analysis as demographic and building characteristics can be linked geographically and assessed at different spatial scales. They can then be exported as thematic maps that visualize energy demand or retrofit potential across cities and neighborhoods.

Mastrucci et al. (2016) generated GIS-based statistical model to estimate energy use for nearly 300.000 dwellings in Rotterdam. Building characteristics, information about households, and census-block level energy consumption was used to derive dwelling-level energy use and retrofit potential. The authors used maps of energy use intensity to inform which buildings should be targeted first according to their energy saving potential and retrofit costs.

SimStadt allows for similar analyzes at urban scale where heating demand, photovoltaic systems, and refurbishment scenarios can be calculated for entire cities (Nouvel et al., 2015). Energy characteristics are often statistically estimated from the building age, typology, or assumptions where individual building information is missing.

These compromises should be noted. Defining building attributes from archetypes and assumptions allows urban-scale analysis. Yet they come at the cost of individual-building certainty. Assessments of individual buildings in historic districts should take this into consideration, as geometric or energy performance similarities can mask fundamental differences in construction, prior alterations, or heritage restrictions. GIS allows for effective contextualization and urban-scale analysis but whether individual buildings can be accurately represented depends on available data.

6. Strengths and Limitations of GIS for Building-Level Studies

GIS allows buildings to be contextualized within a broader geographic framework. Cadastral, demographic, regulatory, heritage, environmental, and energy attributes can be linked to spatial objects. They can then be evaluated and analyzed at multiple scales ranging from individual buildings to entire cities. This has proven especially useful for municipal information management, urban planning and building-stock assessments.

GIS datasets commonly lack information needed for building-specific modelling or energy simulations however. Most GIS store buildings either as footprints, extruded volumes or as semantic city objects with limited attributes. Where walls and roof surfaces can be represented, they rarely contain detailed information about material layers, construction assemblies, parametric relationships or dependencies between building components.

This gap is partly due to the intended purpose and scale of GIS. Rather than representing buildings in meticulous detail, municipal systems must efficiently manage geographic information at the scale of entire cities. Detailed information is better served by building-oriented BIM models focused on the components of single constructions. Moreover, adding walls and roof surfaces does not resolve underlying issues with incomplete or conflicting attributes. Pasquinelli et al. (2019) and Sammartano et al. (2021) highlight that harmonizing multiple datasets remains essential even when detailed spatial models are available.

GIS will therefore form the foundational information domain for this thesis. It will allow territorial, demographic, cadastral, heritage, regulatory, geometric and environmental information to be collected and related to buildings. Detailed, semantically-structured, and parametric building models cannot be retrieved from those GIS databases on their own accord. This establishes the need to transition from GIS toward Building Information Models, which will be discussed in the following chapter.

Table 2-1 Comparison of 2D municipal GIS, semantic 3D GIS/CityGML, and BIM in terms of information content, urban scalability, and building-component detail

Representation	Typical information	Urban scalability	Building-component detail
2D municipal GIS	footprint, parcel, address, attributes	High	Low
Semantic 3D GIS / CityGML	volume, surfaces, roof, thematic attributes	High–medium	Medium
BIM	walls, floors, roofs, openings, assemblies, parameters	Lower when individually modelled	High

2.4 Building Information Modelling (BIM)

Building Information Modelling (BIM) can be considered an evolution from drawing-based building documentation towards the digitally based organization, representation, and management of building information. While BIM is commonly associated with three-dimensional modelling approaches, this is not strictly true of all BIM environments. A regular 3D model might simply represent the visible building geometry, whereas BIM environments link geometric objects to semantic information about what the objects represent and how they relate to other building components. Eastman et al. (2011) describe BIM as "an information-based approach that enables building objects to have geometric representation along with embedded non-graphical data that can be created, exchanged, and used by disparate software applications throughout the life cycle of a building." Similarly, Gerrish et al. (2017) characterise BIM as process for organizing and sharing information rather than producing a geometric representation alone.

1. Object-Oriented and Parametric Building Representation

One of the core principles of BIM is that building information is organized using object-oriented logic. Buildings are divided into walls, floors, roofs, windows, doors, spaces and building systems rather than represented as unconnected lines and surfaces. Semantic information regarding dimensions, materials, thermal properties, function, classification, cost or required maintenance could be included within these objects as well. Relationships between elements can also be represented; a window could be said to be hosted by a wall while a wall could be bounded by floors.

Fundamentally, BIM allows buildings to be digitally represented according to how they are understood in reality. The parametric nature of BIM further distinguishes it from conventional geometric modelling approaches. If object geometry and properties are controlled by parameters and rules, changes to one element can propagate associated changes through other parts of the model or associated information. This ability is particularly useful where multiple models of a building must be created or modified systematically. Parameters allow commonly-used rules to be defined, while allowing the values to differ between individual objects. This makes it possible for both standardization and differentiation to coexist within a BIM model.

Semantic information remains key. It would be of little value to analyze the area of every wall within a building without understanding that these objects are indeed walls. BIM enables information about buildings to be structured according to the functional and construction logic of buildings. This use of semantically-rich objects makes BIM uniquely suited to building-stock

studies where attribute data originating from outside databases can be linked to building objects through their parameters.

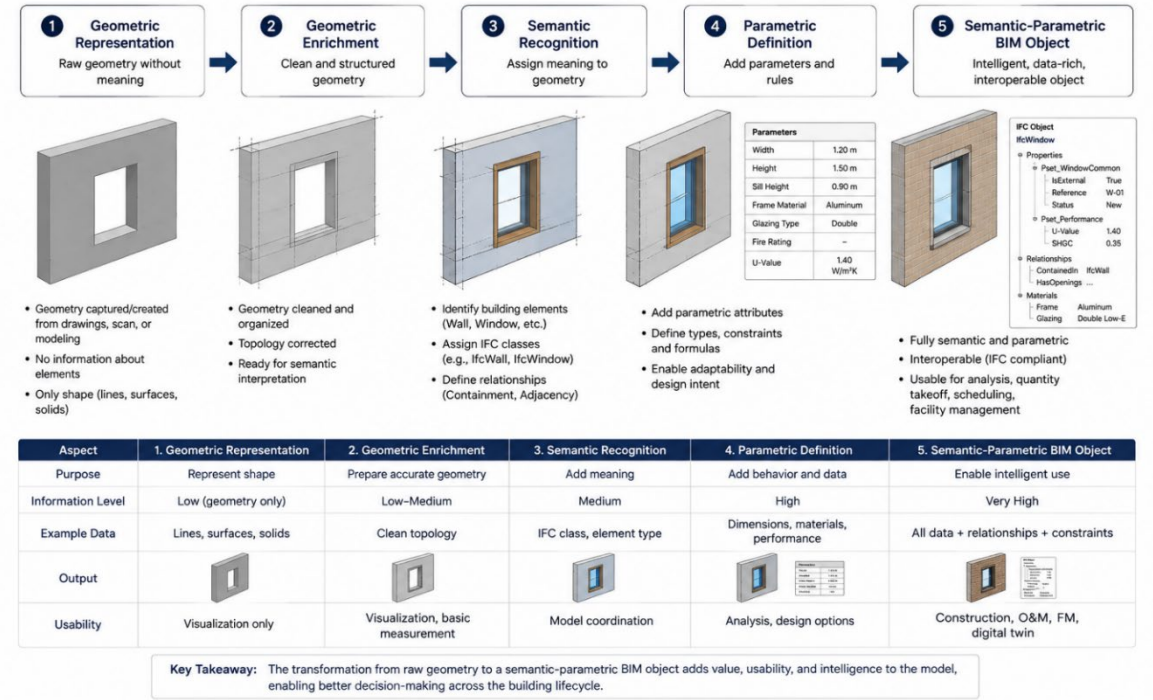


Figure 2.10 From Geometric Representation to Semantic-Parametric BIM Object

2. BIM for Existing and Historic Buildings

Although originally developed for design and construction, application of BIM to existing buildings is conceptually straightforward: as-built models can be created to document the current building state. In practice however, existing-building BIM is complicated by incomplete documentation, uncertain building conditions, or significant modelling effort. Volk et al. (2014) surveyed researchers and professionals regarding existing building application of BIM, finding that incomplete or uncertain information, often combined with significant effort building information models created manually, consistently appeared as barriers to BIM implementation. More recent research has identified similar issues; Desogus et al. (2021) explain that existing-building BIM models for renovation interventions are often created from scratch in an as-built condition where incomplete, outdated or incompatible documentation may be available.

Methods for creating existing-building BIM tend to combine archival drawings, surveys and manual inspections with newer technologies like laser scanning or photogrammetry. Scan-to-BIM techniques provide reliable geometric information, but pure geometry does not automatically translate to a semantic building model. Altohami et al. (2021) note that although laser scanning of existing buildings can produce detailed records of as-built conditions,

material schedules, construction characteristics or the purpose of components may still require additional research or manual interpretation. This translation from survey data to semantically structured objects thus remains reliant on expert decisions.

Difficulties are further compounded for heritage buildings. Historic Building Information Modelling, or HBIM, has been described as an extension of BIM for managing historic built environments. Murphy et al. (2009) describe HBIM as a method of surveying historic buildings and combining that information with parametric models of architectural elements. Historic buildings often include irregular non-parametric forms or complex components with unknown modification histories. Standard BIM objects or families may therefore lack the flexibility to represent this information accurately.

HBIM therefore becomes less about replicating every detail of a building within a BIM platform and more about representing geometry, historical context and conservation details in a structured form amenable to management within BIM. This consideration is important on an urban scale: historic buildings within a district may range from well-documented monuments to undocumented vernacular buildings which have never before been surveyed. Creating a consistent level of model detail across the district may involve disproportionate survey efforts for some buildings or obscure important differences. Ultimately, building information demands for heritage building stocks must be weighed against the data that is realistically available.

3. BIM for Energy Assessment, Retrofit and Building Management

If building attributes can be semantically linked to objects, then BIM may support uses that go beyond the digital representation of architecture. Many buildings components have roles in both energy simulation and retrofit assessment: geometry, thermal properties of materials and construction systems can serve as input for simulation while model parameters can be used to track performance indicators or retrofit decisions. Yildirim and Polat (2023) connect BIM to building-energy simulation tools to evaluate retrofit scenarios according to energy consumption, emissions reductions and economic performance.

In the context of existing buildings, this functionality can be extremely valuable. Unlike new-build designs where retrofit decisions are hypothetical, actual buildings have pre-existing characteristics that influence retrofit outcomes. Desogus et al. (2021) summaries BIM's advantages for existing buildings as a common information environment where component sizes, properties, functions and maintenance schedules can be organized and associated with monitored data for use in energy simulation or evaluation. Their study connects BIM models to external data sources using visual programming and application programming interfaces; rather than duplicating information in separate databases it can be associated with BIM objects directly.

Gerrish et al. (2017) describe similar uses of BIM for facility and performance management. BIM's structure allows seemingly distinct types of information (design conditions, operational measurements, building management data) to potentially be linked through the model itself. However, they also caution that the presence of certain information in proximity to a BIM model does not guarantee that it will be stored in a manner useful for downstream tasks. Different teams using differing software with inconsistent data exchange may produce information silos despite the large quantity of information within any given model. Effectively linking data to BIM not only requires access to that data, but consensus on how to describe, access and maintain it.

4. Open BIM and Interoperability

Most BIM workflows are implemented in proprietary software environments. This has both advantages (building-specific authoring tools, application-specific features) and disadvantages (files can only be accessed by one software platform). Solutions for these problems have led to the concept of Open BIM. Open BIM is concerned with structuring BIM information so that it can be exchanged or accessed by disparate software applications.

Industry Foundation Classes (IFC) are a major enabler of this goal. Developed by buildingSMART, ifc provides a common schema for describing building objects and their properties as well as relationships between objects. Dave et al. (2018) present an open-standard based approach which linked BIM objects to external sensor and information systems using IFC. Their workflow combined IFC with globally unique identifiers, allowing objects within the BIM model to maintain links to information sources outside the model itself.

It should be noted that open file formats do not ensure interoperability automatically. Different software applications may interpret the same schema in inconsistent ways, especially when dealing with complex geometry or bespoke properties. Additionally, information may be lost during translation or require custom conversions. Interoperability must address both geometric similarity and semantic meaning. Both of these considerations apply when attempting to integrate BIM models with GIS databases developed with substantially different objectives in mind.

Ultimately, the quantity of information included in a BIM model should reflect its intended purpose. The amount of information included in, or reliably deduced about a BIM object is called its Level of Development (LOD). Concepts like LOD or Level of Information Need attempt to balance modelling efforts with how much information would actually be required to use the model for a specific purpose, rather than implying that more detailed geometric information is always better. This becomes important when applied to existing buildings that have varying levels of documentation available. These concepts will be discussed further in Section 2.9.

5. *Building-Level Strengths and Urban-Scale Limitations*

BIM tends to be very effective at the scale of the individual building. BIM's semantic hierarchy mimics how buildings are understood in reality: a building is composed of floors which contain spaces and spaces are composed of elements. Both general information about the building and detailed information about its components can be attached to appropriately granular objects within the model. Sammartano et al. (2021) study municipal buildings in the city of Turin, associating each room in their BIM models with attribute information through unique identifiers and shared parameters. This structure allows for a far greater level of semantic granularity at the building-level than is available from footprint-based urban datasets.

Extending that same detail to multiple buildings in a district or across an entire city creates problems. Large amounts of detailed data require more computing power and are usually created one building at a time. Georeferencing and integration with other municipal datasets are usually added after the model has been created, and are not part of the primary data organization logic. Sammartano et al. (2021) also list difficulties with georeferencing, internal data hierarchies, file formats, and model maintenance as challenges in bringing detailed BIM models into an urban geospatial context.

BIM should not be viewed as an alternative to GIS, but rather as complementing GIS where it is lacking. BIM can provide a parametric, semantically-rich model of building components that conventional urban GIS does not. By that same token, an individual BIM file does not inherently contain cadastral context, demographic information, regulatory constraints, heritage designations or spatial relationships with the rest of the city. Bridging this gap while retaining the strengths of each model type is the methodological challenge of GIS–BIM integration.

2.5 GIS–BIM Integration and Interoperability

Given GIS's and BIM's respective strengths, researchers have begun to explore how they may be integrated. While GIS organizes geographic objects primarily at the territorial and urban scale along with relationships between them, BIM describes singular buildings through semantically defined objects related parametrically. Linking them could therefore associate parcels, infrastructure, regulations and demographics at the urban scale with individual building geometry, construction and performance data. Successful interoperability depends not only on passing files between environments but also on whether geometry, semantics, spatial reference and object identities can still be understood after translations between GIS and BIM (Noardo et al., 2020). GIS and BIM first require compatible representations at each level.

1. Conceptual and Semantic Differences between GIS and BIM

The immediate obstacle to GIS–BIM integration stems from how information is structured within each domain. A GIS may represent a building as a footprint, a volume or feature with attributes,

while BIM separately identifies its constituent walls, floors, roof, openings and spaces, along with related properties. EachGIS building element may therefore link to multiple objects within a BIM, while a single BIM object like a wall may lack equivalent semantics in GIS.A "wall" feature in GIS could contain material information about every surface in a building, but it might also apply only to the exterior shells. Identifying the corresponding object in BIM requires additional interpretation. Reciprocally, detailed attributes in BIM such as profiles or custom parameter values may not have corresponding classes in GIS.

Scale compounds these semantic inconsistencies. GIS aggregates broader quantities of information distributed across cities, whereas BIM emphasizes individual assets' characteristics (Pasquinelli et al., 2019). The authors note that while CityGML better accommodates top-down representations of cities, IFC-centric models usually demand significantly more geometry and semantics about buildings than most legacy datasets of existing cities can provide. As a result, integration necessitates choosing what information should or should not exist at each spatial or semantic layer, rather than only converting file formats.

Fundamental differences also appear in geometry representation. GIS tends to use boundary representations, polygons or surfaces and occasionally simplified solids, while BIM uses full parametric solids, constructive geometry and object-level coordinate systems. Furthermore, topology is treated differently by each discipline; many relationships may be implicit or optional in one domain but need explicit reconstruction in another. BIM origin also usually uses local project coordinates which must then be georeferenced, but mismatches can occur at this stage as well. When authors of the GeoBIM Benchmark exchanged files between software using identical open standards, they found significant variation in how geometry, semantics and coordinate reference systems were handled (Noardo et al., 2020).

2. IFC, CityGML and Data Conversion

IFC and CityGML are, respectively, the primary open standards for BIM and semantic 3D geoinformation. Despite their complementary nature, several ontological and structural inconsistencies can arise during their conversion. As BIM features objects and relationships used in construction, IFC defines a schema according to this vocabulary. Meanwhile, CityGML structures cities according to geospatial and thematic concepts. For information to meaningfully transfer between them, translations must occur at geometric and semantic levels.

Data conversion is often accomplished unidirectionally, turning information from one domain into something the other can process. Common workflows thus include both IFC-to-CityGML conversion and IFC-to-GIS. Zhu et al. (2019) develop such a workflow by introducing an open-source method for traversing IFC's spatial hierarchy to extract geometry and convert it into shapefiles. These methods can open detailed BIM geometry to GIS analyzes, but they are limited by the destination schema's ability to represent information. Successfully mapping

geometric surfaces does not ensure that semantic relationships between objects or object behaviors will carry over. Data conversion is therefore only one portion of GIS–BIM interoperability.

That multiple software may interpret the same standard differently further complicates conversion. The GeoBIM Benchmark found that software packages did not always agree on geometry, semantics or coordinate reference systems when authors submitted the same IFC files as input (Noardo et al., 2020). The problem was present despite both groups using open standards. Compatibility is therefore dependent both on the specification of the data itself and how it is interpreted by software later. Open standards help decrease reliance on closed, proprietary file formats but cannot fully enforce how their guidelines should be interpreted. Semantic discrepancies and information loss may persist, so relationships still need to be mapped where the formats' underlying concepts differ.

3. Integration Strategies

The literature describes several general methodological approaches that address these challenges. One is conversion-based integration. Data is transformed to fit the receiving environment's schema, producing a model usable by target applications. Its primary advantage is that little-to-no changes need to be made in software to read the resulting dataset. Conversion is easiest when only a subset of the information is needed, such as when including BIM geometry in a GIS workflow. On the other hand, meaning may be lost when information lacks an analogous concept in the target schema.

A variation on conversion is Extract–Transform–Load (ETL) integration. Information is extracted from a source environment, transformed into target schema-friendly versions and loaded as data or a new model. Kang and Hong (2015) describe a proposed BIM/ GIS–based ETL architecture which disentangles BIM geometric processing from other information types. By transforming each element independently before recombining them, ETL methods provide explicit control over translation mappings. They are also well-suited for repetitive tasks but are typically designed around a specific source and target pair. Once software or datasets are updated, rules may need to be rewritten to accommodate changes.

Federated and database-centric methods make up another category. These methods maintain BIM and GIS in at least partial compliance with their native schemas and link information through common database references, identifiers or queries. While the onus shifts from semantic conversion to maintaining references between datasets, a primary challenge is keeping linked objects synchronised. Updates to one must be applied to the other, and rows referring to the same physical object need consistent identifiers across files.

Middleware, application programming interfaces (APIs) and semantic-web tools further decentralise data interactions. Middleware can connect services, requests or databases by

translating or routing information between them, while semantic-web tools like ontologies and linked-data represent relationships between different terms. Such techniques afford greater flexibility when several applications need to interact but suffer from higher initial complexity and dependency on precise semantic mappings. As such, Lei et al. (2023) cite interoperability, including semantic standard inconsistency and data conversion, as major technological hurdles to developing urban digital twins.

Finally, workflows specific to particular software and visual programming represent a fourth integration strategy. These techniques eschew general interoperability standards in favor of scripts or APIs which can read values from one environment and express them as objects or parameters in another. Sammartano et al. (2021) provide one example by demonstrating a workflow in Turin using Revit and Dynamo software to create unique identifiers and associate shared parameters including address, construction information, building stories, room sizes and uses. This information was then integrated into GIS using ArcGIS software. As this approach relies on scripts rather than fixed translators, it can adapt to different datasets as long as users define conversion parameters. However, they are generally less portable than open formats and tailored to function within specific software ecosystems.

Table 2-2 Principal Methodological Approaches to GIS–BIM Integration

Approach	Principle	Main advantage	Main limitation
Direct conversion	Translate one format/schema to another	Relatively simple deployment	Semantic/data loss
ETL	Explicit extract–map–transform–load rules	Controlled and repeatable	Schema-specific development
Federated/database	Maintain separate models linked by IDs	Preserves native information	Synchronisation complexity
Ontology/middleware	Intermediate semantic/service layer	Flexible multi-system integration	High development complexity
API/visual scripting	Custom transfer between software environments	High workflow automation	Software dependency

4. Information Preservation, Identity and Synchronization

Preserving semantics across translations is critical to appraising integration success. Geometry can be perfectly aligned, but attributes may be lost, linked to incorrect objects or misinterpreted by another application. Lei et al. (2023) summaries recurrent challenges as including semantic loss, differing coordinate references, geometry validation and topological correctness. Such inconsistencies have greater consequences if integrated datasets support simulations or analytics because small errors in translation can invalidate entire calculations.

Consistent identifiers between objects are one strategy for preserving meaning when changing schemas. Lu et al. (2020) discuss difficulty discerning if two records in disparate databases refer to the same building without common identifiers. While their approach in West Cambridge linked GIS and BIM datasets successfully, integration is not synonymous with synchronization. Related records will drift apart if a change is made to one database and not the other. Persisting connections between datasets is thus as important as conversion and requires consistency strategies like entity matching, data versioning or scheduled update frequencies.

This issue is especially relevant for cities' master datasets or records of historic buildings. Sammartano et al. (2021) found that even determining which administrative data fields referred to the same real-world attribute could require reconciling records across Turin's databases, created by different offices and at different times using heterogeneous data models. In short, semantic interoperability must occur before BIM conversion. Data originally recorded in those systems must be harmonized enough to know which buildings are the same and which fields can be trusted. Interoperability cannot retroactively resolve ambiguity within source datasets.

Ambiguity also introduces difficulty when automating model generation. A GIS dataset may include footprint and height data for one building, period of construction and usage type for another, and detailed architectural heritage data for a third. A script branching from a standardized BIM template would then have to omit, infer or artificially input those parameters. These methods may be reasonable for investigating homogeneous building stocks or applying metrics at an aggregate level. But many districts involve tighter construction tolerances between legal height limits, allowable retrofits and physically adjacent buildings. GIS–BIM integration should therefore record information confidence where possible, including metadata about record origin. Tables understanding what may and may not be compatible across datasets begins with GIS and BIM integration but does not end there.

5. Towards Multi-Scale Interoperability

Currently, no single strategy dominates interoperability in all situations. Conversion is easy but can cause semantic loss; ETL processes facilitate explicit mappings but require rule definition; linked or federated systems avoid semantic overhead but depend on persistent synchronization; ontology- and middleware-based tools can transcend semantic discrepancies at the expense of technical complexity; and visual-scripting environments are highly automatable within defined parameters but often lack transferability. It is therefore perhaps unsurprising that interoperability has not yet been solved despite substantial progress towards better standards and supporting software (Lei et al., 2023; Noardo et al., 2020).

In urban building-stock work, fully resolving interoperability may be neither possible nor desirable. The goal rather is linking GIS and BIM models so that information at multiple scales can reference each other while preserving enough identity and meaning for future applications.

This is especially challenging when datasets about the same district may be heterogeneous, or when varying levels of detailed information exist from building-to-building. These considerations of working between cities and buildings impart an intermediate scale of information modelling. The next section introduces the concept of DIM and its potential role in addressing this gap.

2.6 District Information Modelling (DIM)

District Information Modelling (DIM) attempts to bridge the gap between information represented at scales between buildings and cities. Building Information Modelling (BIM) represents individual buildings or assets, whereas Geographic Information Systems (GIS) organize spatial information at larger scales across cities or territories. However, many urban applications span multiple buildings at once and involve infrastructure networks, environmental conditions and human activities. DIM may be understood as relating information concerning buildings and urban systems in an environmentally bounded district area. Unlike BIM however, DIM does not yet correspond to a single modelling standard and has been used predominantly in specific research applications rather than as a clearly defined information paradigm.

One of the most explicit formulations of DIM was developed within the European District Information Modelling and Management for Energy Reduction (DIMMER) project. Patti et al. (2015) describe the District Information Model as an environment in which information from BIM, GIS, energy distribution systems, monitoring devices and users can be correlated to support district-level energy management. Rather than constructing one exceptionally detailed model of every building, the approach connects several information domains so that building characteristics can be interpreted together with energy networks and geographically referenced data.

1. From Building Information to District Information

District scale has been considered particularly relevant as an intermediate step because many urban challenges involve relationships between multiple buildings. District energy supply systems, heating networks, electrical grids, solar exposure, public infrastructure and environmental conditions cannot be understood on a building-by-building basis. However city-wide datasets lack information about individual buildings, floors or spaces.

In this sense, DIM augments building information rather than replicating BIM at larger scales. The DIMMER project uses GIS to provide geographical context to BIM models, with additional information models describing energy systems such as heating and electricity networks. Rather than combine these datasets into a single model, however, Patti et al. (2015) argue that they can be operationally linked within a distributed digital environment. In this sense, the district model represents relationships between specialized models rather than a single unitary dataset.

This distinction addresses an important aspect of multi-scale modelling. Whereas BIM represents relatively detailed information about buildings, district applications may require information at different levels of detail. Energy analysis may require knowledge of building use, shape and volume, whereas facility management may require access to information about individual rooms. Sammartano et al. (2021) presents research linking municipal asset databases, cadastral information and BIM models within a digital Turin 3D geodatabase. These authors progressively aggregate information from municipal-scale datasets including building footprints and volumes, towards cadastre-based information at the level of floors and rooms. This illustrates how district- scale information requires relationships to be maintained between datasets at different levels of granularity, rather than simply adding more building data to citywide models.

2. Information Integration and Interoperability

Crucially, the usefulness of DIM relies on interoperability between these information sources. Whereas BIM models represent individual buildings, GIS organizes spatial relationships between them and tabular databases might represent system networks or building attributes. Semantic inconsistencies will arise if these datasets are exported between one another without consideration for their original formats or purposes. The DIMMER project addresses this problem by adopting a distributed information architecture, in which separate datasets can communicate with one another through middleware and web services. Whereas BIM, GIS and system information might remain separate, their selected attributes could be accessed through district-based applications (Patti et al., 2015).

To a certain extent, this reflects the distinction between data integration and data centralization. Creating a district model does not necessarily require consolidating all datasets into one master file. Connections can be made between datasets which retain their individual structures. Maintaining this kind of federated architecture has particular benefits when datasets belong to multiple administrative authorities, as often occurs between building owners and municipalities. Of course, this requires careful management of identifiers, semantic mappings and updating protocols.

The complexity increases further when real-time data are included. Within the DIMMER project, information concerning sensor measurements from buildings were related to building and district energy network models so that monitored energy consumption could be compared with physical building attributes. The middleware included a semantic layer defining district entities and relationships to allow cross-domain queries involving buildings, energy networks, sensors and monitored energy quantities. Bottaccioli et al. (2017) present a related system integrating GIS, BIM, IoT sensor information and real-time weather information for contextualized building energy monitoring and simulation. These examples show how DIM is primarily concerned with

structuring relationships between datasets across a district, rather than providing three-dimensional visualizations.

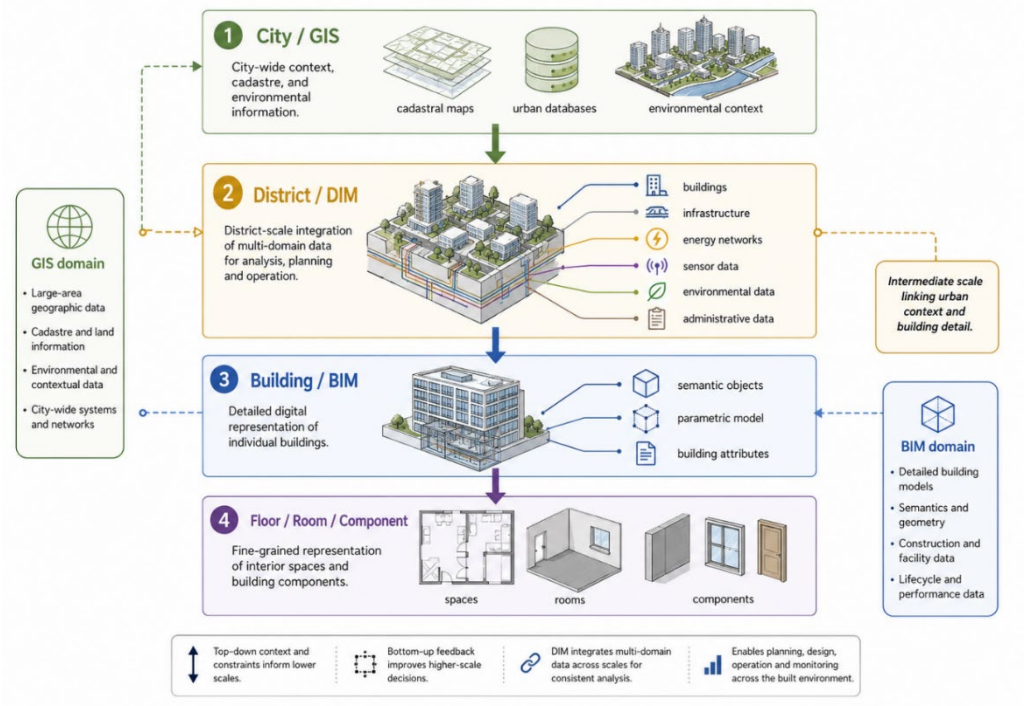


Figure 2.11 Information Scales in District Information Modelling (DIM)

3. DIM for Energy Management and Decision Support

DIM has been principally developed for applications in energy management. Individual buildings consume energy, yet energy infrastructure is frequently shared between buildings through district networks. By bridging these levels of information, districts can be analyzed at scales that retain relationships with individual buildings.

Patti et al. (2015) present an approach for relating building information models with measured energy consumption, district heating networks and user profiles to support decision-making around energy efficiency strategies, demand response and maintenance practices. Instead of being the analysis itself, the district model served as informational basis for analyzing energy consumption across buildings.

Del Giudice et al. (2017) expanded on this methodology, integrating GIS, BIM and System Information Models using a shared ontological framework for urban energy optimization. These authors present urban energy comparison tools that enabled public administrators, building managers and energy practitioners to compare energy information across buildings in order to evaluate energy saving and CO2 reduction interventions. This approach shows how DIM supports information comparison between buildings while retaining identification of individual assets.

District information can also enable spatial decision support. Geographical relationships between buildings enable patterns of consumption, demand or retrofit potential to be compared visually or analytically across districts. This type of decision-support extends beyond consideration of an individual building, instead focusing on where particular actions should be prioritized based on built environment context.

4. DIM, CIM, 3D City Models and Digital Twins

District Information Modelling should not be confused with several related terms that have been used interchangeably by different authors. District Information Modelling has sometimes been compared to City Information Modelling (CIM), semantic 3D city models and Urban Digital Twins. These terms share certain characteristics, but are distinct.

City Information Modelling generally refers to broader notions of digitally representing and analyzing urban systems to support planning or decision-making. Gil (2020) refers to CIM as an organizing framework for multiple related urban digital fields such GIS, urban science, 3D city modelling, urban analytics and planning-support applications. DIM is largely situated within this realm but focuses specifically on an intermediate district scale. Where DIM has been used as a principle for integrating urban information, it has often been applied to energy systems.

Semantic 3D city models primarily provide geometrically and semantically structured representations of objects within three-dimensional space. A 3D city model may be one part of DIM, but a 3D geometric building model alone does not provide a full District Information Model. Conversely, DIM includes information about energy systems, sensor networks, building use profiles and administrative databases that may lie outside traditional 3D city models.

District Information Modelling is also distinct from the notion of Digital Twins. Where DIM may be static or updated at scheduled intervals, Urban Digital Twins strongly implies continuous or frequently updated information synced with physical conditions. Real-time implementations of DIM fulfil some of these criteria but they are not conceptually synonymous. Digital Twin urban developments are discussed further in Section 2.7.

5. Limitations and Role within Multi- Scale Urban Modelling

DIM also faces limitations associated with data heterogeneity. A district dataset may include buildings represented with varying geometric and semantic detail, as well as infrastructure or monitoring datasets that follow different schemas. Sammartano et al. (20 21) demonstrate that information concerning the same buildings in a single Italian municipality was disaggregated across several offices, databases and update cycles. Establishing district-wide relationships between datasets will require harmonization when datasets were created independently from one another.

Existing and historical building districts present particular challenges for DIM. Creating BIM models for every building would require enormous surveying and modelling effort that has rarely been carried out uniformly at city scales. Simpler models that treat all buildings as identical rectangular prisms lose much of the geometric detail necessary for analysis or energy simulations. An effective district information environment will therefore need to balance heterogeneous levels of information availability between buildings.

District Information Modelling is therefore only tangentially related to this thesis. Rather than focusing on its technology or applications, district-scale modelling is recognized as an intermediate step between building and city-wide information. Instead of existing separately as city-wide GIS datasets or individual BIM models, district information modelling represents a method for relating individual buildings to one another through infrastructure networks and geographically referenced datasets. Urban building energy simulation is one example of an analytical methodology that depends on these kinds of multi-building relationships, and is discussed in the following section.

2.7 Urban Building Energy Modelling (UBEM)

Urban Building Energy Modelling takes the principles of building-energy modelling up to district-, neighborhood- or city-scale. It aims not just to run energy simulations for multiple individual buildings, but to estimate and spatially analyze energy demand, consumption, emissions and retrofit potential across entire building stocks. According to Pan et al. (2023), UBEM applies building-energy modelling to district and city scales, requiring generation of energy models which account for building geometry, physical properties and operation, while simultaneously considering weather conditions across multiple buildings and meeting simulation computation limits created by big building numbers.

UBEM workflows therefore commonly involve data collection and preprocessing, model generation, simulation or prediction runs, calibration or validation with measured results, and application of results to support planning scenarios or retrofit prioritization (Pan et al., 2023). Uncertainty is introduced at each stage. Geometry may be incomplete or inaccurate, construction information may be estimated from age profiles, occupancy may be simplified into standard schedules, and refurbishment histories may be unavailable or inconsistent. Model precision at the scale of individual buildings therefore does not necessarily imply precision in knowledge at city scales. UBEM approaches can be divided into different modelling methodologies.

1. Modelling Approaches

UBEM methods are commonly classified according to how energy performance information is calculated. For example, they may be classified by whether they employ bottom-up or top-down

approaches. Top-down approaches use aggregate energy observations, then statistically relate them to features or characteristics of the building stock. Such methods require less detailed technical data and can therefore be applied where such information is unavailable. However, they produce aggregate indicators that are less capable of isolating the physical basis of poor energy performance or predicting the effects of specific retrofit strategies. Francisco et al. (2020) provide a similar distinction between city-scale benchmarking and bottom-up energy diagnosis. Benchmarking methods can calculate relative performance metrics with limited information about individual buildings, but they often provide little direct guidance on potential physical improvement measures.

Bottom-up approaches estimate building performance from information describing each individual building or small number of representative building types before aggregating predictions to larger spatial scales. They may be physics-based, statistical or hybrid. Physics-based models use parameters such as construction properties, building geometry, HVAC system characteristics, ventilation and occupancy routines, weather conditions and internal loads to represent actual thermal processes. This provides a basis for predicting conditions not already observed in historical data, such as proposed retrofit measures, but physics-based models require detailed input data and significant computational resources to produce results. Data-driven approaches attempt to derive relationships between variables from measured energy consumption and other observed features. Their predictive power can allow them to operate with a reduced physical description, although these methods rely heavily on the availability of historical data for training. Hybrid models combine statistical and physics-based techniques where possible to reduce each modelling approach's limitations (Pan et al., 2023).

Typically these categories are not mutually exclusive. Mastrucci et al. (2016) describes its Rotterdam bottom-up method as a statistical approach. Gas consumption measured at the national level was disaggregated to individual dwellings using GIS data relating floor area, dwelling type and construction period, household occupancy and other factors. This case highlights that top-down vs. bottom-up approaches indicate the scale at which energy use is allocated to buildings, while physics-based vs. data-driven distinguishes whether models use fundamental thermal calculations or derived statistical relationships.

2. Input Data, Geometry and Building Archetypes

UBEM relies on both geometric and non-geometric datasets. Geometric information can be derived from GIS building footprints and heights, but can also use semantic 3D city models to represent geometry explicitly. Cadastral, census and municipal datasets can describe building usage, construction ages, floor areas, renovation histories and occupancy where available. Energy simulations also demand input assumptions concerning envelope U-values, ventilation rates and air change schedules, types of heating system installed and weather conditions.

Explicit geometry impacts energy use in UBEM models through multiple pathways. Total building volume affects potential internal air volume heated or cooled, while surface area impacts losses through transmission and solar radiation gains. Surface orientation can affect solar gain through windows or walls. Mastrucci et al. (2016) found that less compact building types had higher heating demand because their envelope areas increased relative to heated volume. Building age was also strongly correlated with estimated retrofit potential because older buildings were likely to have lower thermal performance.

Since many of these characteristics are unknown for whole city districts, UBEM usually relies on building archetypes. Archetypes group buildings by user-defined criteria such as construction type or age, geometry, spatial typology or usage, and associate typical values for physical or operational properties with each group. SimStadt, for instance, organizes built-libraries according to building-physics archetypes defined by age and type categories; occupancy and usage schedules; and technology archetypes describing energy systems characteristics (Nouvel et al., 2015). If individual parameters are missing, some information can be estimated geometrically where possible or inferred based on aggregate data probabilities.

Broad archetypes reduce the data required for large-scale modelling, but introduce uncertainty through generalization. Two buildings of same age and use type may have different levels of thermal insulation, have received different refurbishment interventions in the past, contain different systems or be occupied by households with different routines. Pan et al. (2023) therefore highlights archetype generalization as a major source of error, noting dependencies between simulated results and how arbitrary choices such as assumed floor area, temperature setpoints or HVAC type can strongly affect predicted urban energy use.

Table 2-3 Principal UBEM Approaches and Their Data Requirements

Approach	Main inputs	Strength	Main limitation
Physics-based	Geometry, envelope, systems, occupancy, weather	Can test retrofit and future scenarios	High input and computation requirements
Data-driven	Measured energy, weather, building attributes	Suitable where physical data are limited	Depends on representative historical data
Hybrid	Simplified physical + measured data	Balances physical interpretation and calibration	Greater methodological complexity

3. GIS, CityGML and Energy Information

GIS based analyzes provide a foundation for UBEM by ensuring energy estimations can be aggregated and mapped back to geolocated buildings. Individual calculations at building-level can then be related to their spatial environment and neighborhood context. Visualizations

produced by Mastrucci et al. (2016) mapped estimated energy consumption, energy saving potential and retrofit cost-effectiveness at neighbourhood scales across the city of Rotterdam. The visualizations demonstrated that areas with theoretical highest retrofit cost effectiveness did not yield greatest absolute savings; urban density and district level stock characteristics were also influential.

Semantic 3D city models allow this process to consider explicit volumes and surface differentiation. Nouvel et al. (2015) combined CityGML with SimStadt to provide an energy-analysis platform applying to city objects represented at levels from district down to building, then interior zones and differentiated thermal surfaces. The platform bundles heating-demand and cooling-load calculation engines, solar irradiance and photovoltaic simulation, CO_2 emissions estimation, and refurbishment retrofit-measure scenarios while allowing level of model detail to vary depending on data availability.

The CityGML Energy Application Domain Extension (Energy ADE) adds representations for numerous energy-specific properties not held adequately by the base city model, including detailed boundary surfaces, construction layers and material properties, occupancy schedules, equipment behavior and heating or cooling systems. Rossknecht and Airaksinen (2020) visualize how building-specific information was combined with a CityGML model of Helsinki in similar fashion. An enriched city model was exported as a 3DCityDB before relating individual building objects to geometry in SimStadt. Where information such as flat floor area or precise occupancy was available from other sources, it could substitute assumptions otherwise generated from archetypes or statistical estimates. Methodologically, this improves on rigid archetypes by allowing discrete levels of knowledge to co-exist throughout a single urban model.

4. Calibration, Validation and Uncertainty

Validation against measured energy consumption where available can provide one method of quantifying modelling uncertainty. Rotterdam's statistical model was validated against several postcode areas with measured gas consumption data, ultimately achieving predicted heating demand within ±20% for most districts. Analysis of spatial prediction errors identified districts where other building or social features may have caused the models to diverge from measured data. (Mastrucci et al., 2016). The Helsinki study also compared simulated heating demand against measured energy consumption before applying retrofit and climate change scenarios.

Calibration can be used to reduce disagreement between model predictions and measured results, but it will not address uncertain inputs. Pan et al. (2023) suggests that explicit uncertainty and sensitivity analysis can help identify which parameters most affect UBEM results. Their review further suggests that UBEM may benefit from probabilistic treatments of uncertain parameters rather than relying on a single deterministic value for each building.

Occupant behavior represents a particularly challenging input. Simplified occupancy schedules allow large scale models to represent some effects of different heating habits or ventilation routines, but cannot capture variation at level of individual thermostat settings or detailed time-variant activity patterns. As such, gaps between theoretical energy demand and measured energy consumption remain difficult to narrow where detailed data are unavailable.

5. Retrofit Assessment and Historic Building Stocks

UBEM is frequently used to compare retrofit scenarios across building stocks. Physics-based models calculate savings from altered U-values or heating systems while statistical methods rescale reference benchmarks to match historic consumption. Such studies can priorities investments by identifying which buildings or areas could benefit most from energy or carbon reductions.

UBEM assumptions may require adaptation when applied to historic city districts. Dang et al. (2024) used bottom-up parametric energy modelling on Amsterdam's protected city center and highlighted failures of traditional archetype assumptions. "One size fits all" archetypes allowed large numbers of residential buildings to be analyzed quickly, but the methodology struggled to capture unique partial renovations, monumental building elements, or qualitative information about condition of individual building fabric elements.

Where energy assessments need to consider heritage value or protection rules, UBEM faces related challenges. Buildings of similar age and appearance may have very different renovation histories or allowable interventions. Prescriptive retrofit strategies based on construction period could therefore appear energy-efficient while being unsuitable for certain building facades or roof constructions. For energy analysis of historic districts it may therefore benefit UBEM to retain as much building-specific data as possible. The capability for merging detailed heritage information with simulated building performance creates an important argument for semantic 3D city models discussed in section 2.6.3.

UBEM creates a vital link between contextual district data and decision support at the scale of individual buildings. Research in this area has repeatedly shown energy performance and retrofit measures can be simulated across entire building stocks based on GIS data, but that physics-based, statistical or hybrid results are sensitive to how input data is interpreted. Increased efforts to integrate built models with measured information, automatically updated as it becomes available, may help address uncertainty. The concept of Digital Twins is introduced next.

2.8 Digital Twins in the Built Environment

Definitions of Digital Twin (DT) have emerged primarily from sectors outside built environment disciplines before being gradually applied to buildings, infrastructure and cities. In their

comprehensive review, Lu et al. (2020) cite aerospace modelling as the earliest origin of the concept. A Digital Twin is defined as "a digital replica of physical assets, processes, and systems that can be used to monitor its changing conditions" (Lu et al., 2020). Applied to the built environment, Digital Twins can be seen as an extension of conventional digital models which associate building or city assets with information reflecting their current conditions over time.

Variations between definitions notwithstanding, temporality and data connectivity appear to be defining concepts behind most Digital Twin frameworks. While a BIM model or 3D city model could represent the physical characteristics of assets in considerable detail, the mere presence of geometric data does not convert the model into a Digital Twin. Lu et al. (2020) place particular emphasis on heterogeneous information integration while stating that Digital Twins may draw information from multiple sources to be updated with regard to their current conditions and simulated predictions. Harode et al. (2023) similarly summaries recent developments as an evolution from static building models towards linked information systems with integrated operational and sensor information, as well as analytical functions. Thus, the difference appears more functional than visual.

1. Digital Models, Digital Shadows and Digital Twins

Terminology requires some clarification as DT is often used to describe systems with varying degrees of connectivity. In summary, Harode et al. (2023) describe three categories depending on the directionality and automation of information exchange processes. A digital model can be understood as any digital representation of physical entities without automatic information exchange between physical and digital entities. For example, changes made to the physical building would have to be manually updated by a designer. Digital shadows extend this concept by automatically linking physical assets to their digital representations. Changes in physical conditions may be measured and associated with a virtual model, but any form of analysis or control related to the digital representation remains manual. Bidirectional or Automated information exchange is therefore required for a Digital Twin under this stricter definition.

The distinction helps define Digital Twins against web-based visualizations of cities or static/building-wide databases that may be updated on a periodic basis. Sensor deployment alone does not automatically convert static models into Digital Twins either. Measurements taken from sensors may be displayed adjacent to a model, but without semantic connections to corresponding physical objects, information often fails to integrate with models in ways that could influence analysis. For example, measurements would need to be persistently associated with the exact wall, room or HVAC component they describe. Continuing on this stricter definition of Digital Twins therefore requires automated connectivity at both directions and some form of persistent linking between changing information and the physical objects it describes.

Bidirectional control does not mean that each individual DT needs to function autonomously. Harode et al. (2023) further divide each direction into several levels of maturity ranging from passive monitoring and visualization all the way to analysis, prediction, simulation and autonomous control. Each higher level incorporates more technological complexity and data interactions. Practically speaking, it may be useful to distinguish foundational requirements of DTs—dynamic representation of assets and systematic connectivity between physical and digital information—from advanced features such as machine learning, simulation or autonomous control.

2. BIM, IoT and Building Digital Twins

BIM provides a logical starting point because building components have unique semantic identities, geometry and attributes that can be enriched with operational information. However, traditional BIM models do not continuously connect to physical measurements. Without integration of real-time measurements, many attributes of BIM models effectively remain static or administrative. To address this shortcoming, sensors that measure variables such as temperature, humidity, energy consumption, occupancy or equipment conditions can be incorporated with building models (Desogus et al., 2021). These sensor readings are often collected in databases or cloud services and connected to corresponding elements in BIM models (Pan et al., 2023).

Such automated integration enables operational information extracted from sensor readings to be combined with existing building data. A range of applications related to facility management and operation become possible. For example, geometry, material properties and asset identities tend to remain static while aspects related to system operation or environmental conditions change over time. Harode et al. (2023) demonstrate how sensor data reporting air quality measurements and environmental conditions could be combined with 3D building information in a Digital Twin prototype of a hospital operating room. Similarly, Desogus et al. (2021) combined low-cost IoT sensors and real-time as well as historical visualizations of indoor environmental quality with a Revit model through Dynamo and an API.

Simulation adds yet another dimension by using measured data to adjust or calibrate analytic models, or by testing alternative conditions through simulations before implementing them on physical buildings. Energy consumption could therefore be predicted based on changes to lighting, HVAC schedules or weather conditions. Benefits of connectivity therefore include supporting predictive maintenance, fault detection, energy optimization or testing future scenarios through simulation. A critical consideration in each application is how accurately the digital information represents its physical counterpart. Building semantics, construction details, and material properties influence analytical models. In addition, measured data may be incorrect or imprecise if sensor calibration is lacking or Wi-Fi networks are unstable.

3. From Building to Urban Digital Twins

Conceptualizing DTs at the city scale presents unique challenges. Cities have no single digital model that can encapsulate all required information. An Urban DT may encompass multiple disparate systems including building stock, infrastructure, transportation networks, energy systems, weather conditions, citizens and administrative information. Each information system may be maintained by separate stakeholders who manage their data at varying spatial extents and temporal resolutions.

Under these conditions, Lu et al. (2020) argue that Urban DTs should instead be understood as federated collections of connected representations. Their proof-of-concept in West Cambridge utilized a multilayer architecture intended to link information models of buildings with asset-management systems, building-management systems, indoor-outdoor space management and real-time sensors. Information could therefore traverse scales from systems, to single buildings, groups of buildings and up to the entire campus.

GIS and semantic 3D city models form a logical basis for urban integration. Ruohomäki et al. (2018) document how Helsinki transitioned from primarily visualization-focused 3D city models towards semantic web platforms in which city objects may relate to metadata, events and real-time information. Two points are particularly noteworthy in the cited study. First, urban information must have clear spatial references if sensor observations or social events are to be related to specific buildings, blocks or streets. Second, live information feeds originating from sensors or building automation introduce aspects of DTs into these evolving urban platforms. Maintaining this added complexity requires attention to semantic interoperability and data quality.

Urban DTs should not be conflated with 3D city models. While city models may serve as their geometric or semantic backbone, Urban DTs additionally require time-varying information architecture that can represent change over time and possibly allow for interaction with real-world processes at higher levels of maturity.

Table 2-4 Evolution from Digital Model to Digital Twin

Type	Physical → Digital	Digital → Physical	Typical characteristic
Digital Model	Manual	Manual	Static or manually updated
Digital Shadow	Automatic	Manual	Automated monitoring
Digital Twin	Automatic	Automatic / systematic feedback	Dynamic two-way connection

4. Energy Management and Decision Support

One instructive example of temporal information is energy consumption. Standard urban energy models may represent annual or typical conditions while sensor measurements enable continuous or hourly resolution. Francisco et al. (2020) found that annual energy benchmarks obscured variation in energy consumption across occupied versus unoccupied buildings and times of peak energy demand. Their case study demonstrates how temporally segmented energy use benchmarks could help building owners or managers pinpoint when and which buildings were particularly inefficient. The authors discuss benchmarking as an enabler of DT-enabled energy management in cities because continuously updated or near-real-time energy performance indicators could support operational decision-making as well as identification of retrofit opportunities with the greatest impact.

DTs could therefore complement UBEM. Whole-building energy models provide procedures for quantifying building-stock performance and benchmarks, but DTs could continuously associate simulation models or benchmarks with physical measurements. For example, monitored operational data can help calibrate urban energy models or detect differences between predicted and actual energy use. Furthermore, as buildings are retrofitted or operational conditions change over time, model parameters could theoretically be adjusted if data allows.

Existing building stock arguably benefits most from this connection to measured operational data. Without exterior scans or regular BIM updates, static building databases risk quickly becoming outdated. Digit twin frameworks could allow documented material changes, system replacements or monitored energy consumption to continuously update corresponding components in a building model throughout its lifecycle. There is of course a risk of losing valuable information if these procedures are not implemented correctly, nor do they occur frequently enough.

5. Challenges and Relevance to Urban Building Information

Scaling DT beyond single buildings to cities obviously introduces technical challenges on a larger scale. Lei et al. (2023) conducted a systematic literature review of urban DTs and further distilled the main challenges through a Delphi survey of experts. The study identified interoperability as one of the most significant technical barriers across urban DT studies including issues related to data conversion between formats and software interoperability. Other frequently cited challenges included data quality, inconsistent standards, information integration, information complexity, connectivity, version management, latency and implementation costs.

It should be noted that several of these challenges relate to the continuity of DTs. While a static building or urban model may stay usable even when parts of its information become outdated,

DT frameworks are expected to continuously synchronize with real-world measurements. Procedures for database updates, sensor calibration, revision management and even building object identification therefore become maintenance issues for Urban DTs instead of one-time modelling challenges.

Additional issues become relevant when multiple organizations are involved in urban-scale deployments. Data could be fragmented between municipalities, building owners, utility providers or private companies supplying sensors and hardware. Some data may even be privacy-sensitive or confidential if it concerns building occupants or particular operations. Because of these considerations, Lei et al. (2023) state that successful implementation of Urban DTs requires cooperation beyond software and data interfaces. Finances, stakeholder responsibilities and value propositions also become relevant topics.

From the perspective of urban building information, these concerns take on additional significance with existing building stocks. Real-time sensor data cannot be meaningfully linked to physical buildings if their digital representations lack a persistent identity or geometric and semantic description. Fragmented cadastral, GIS, heritage and BIM databases would need to harmonies their concept of what constitutes a building or point of interest before sensor data can resolve contradictions between datasets. Uncertain construction data or missing heritage attributions cannot be substituted by precise sensor measurements or rich analytic models. Similarly, if geometry and semantics are poor, automated technologies like energy simulation will have limited impact.

Therefore, creating linked GIS-to-BIM information systems should not inherently qualify as creating a DT. Like Urban DTs generally, it could however establish key prerequisites such as building identities aligned between datasets, georeferenced BIM models, structured semantic parameters and links between urban-scale and building-scale information without implementing real-time connectivity. Distinguishing between the two allows us to avoid describing every web-enabled 3D city visualization as a DT while acknowledging how interoperable urban and building data can act as a foundational layer for future development.

Before leaving the subject of Digital Twins, it is useful to consider how they could be viewed by different stakeholders. Urban DTs in particular face the challenge of communicating increasing volumes of information to users across different roles. One potential approach is to make information accessible via web-based geospatial environments. It is in this context that we will next introduce the concept of Virtual Globes.

2.9 Virtual Globes in the Built Environment

Virtual Globes are interactive digital environments where information referenced to geographic space can be explored on a three-dimensional representation of the Earth. They extend

conventional web maps by allowing terrain, imagery, buildings and other spatial objects to be viewed simultaneously from alternate scales and perspectives. They are of relevance to the built environment primarily because they offer a single platform to access complex geospatial information rather than act as substitutes for databases, simulations or modelling environments themselves.

Technological advancements in browser-compatible graphics and web mapping have gradually made it possible for large three-dimensional urban datasets to be viewed without relying on specialized desktop GIS software. CesiumJS is one example of this progression. CesiumJS is an open-source JavaScript library for interactive three-dimensional geospatial visualization on a georeferenced WGS84 globe which supports formats such as 3D Tiles, glTF, GeoJSON and imagery layers (Cesium GS, 2026). This functionality has become increasingly leveraged for 3D city models, urban energy information and spatial decision-support interfaces.

1. Georeferenced 3D Urban Visualization

One key advantage of Virtual Globes is their ability to situate three-dimensional building information in geographic context. This allows individual buildings to be interpreted in relation to streets, surrounding buildings, terrain and other visible spatial layers. They are therefore particularly useful for district- and city-scale information where interpretation requires knowledge of both individual buildings and the wider urban condition.

This concept is illustrated by Pasquinelli et al. (2019), who built a web-accessible Building Information System for the municipality of Gavardo, northern Italy. Diverse municipal datasets were first consolidated into a CityGML-based 3D city model which was stored in 3DCityDB. This model could then be exported from 3DCityDB and published using Cesium so that users can navigate and interrogate their urban representation in a web browser. Critically, the Virtual Globe acts only as the visual and interactive component in this process. The integration of cadastral information with demographic statistics and building models occurred prior to publication within the spatial database and associated CityGML dataset.

This detail is important: Virtual Globes can display information from GIS software, BIM software, databases, energy sensors or building simulations, but creating a Virtual Globe does not itself ensure that those sources can be integrated together. Incorrect attributes or inconsistent identifiers will produce the same errors in three-dimensional visualizations as they would in a GIS. Visualization can help integrate building information across scales and applications, but it will not automatically integrate that information for users. Virtual Globes should be treated as interfaces to integrated information rather than a method of integration itself.

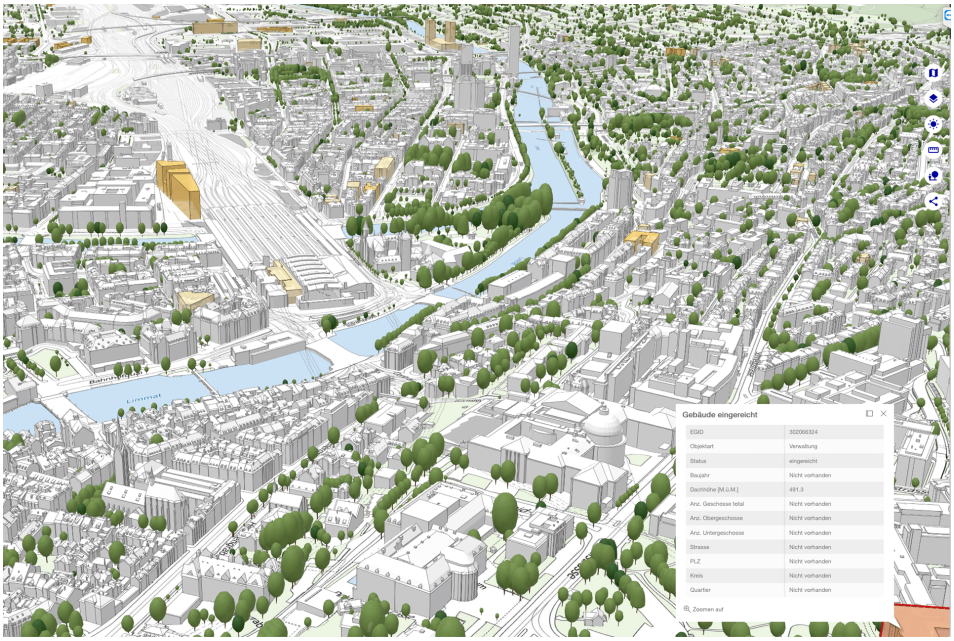


Figure 2.12 Position of the Virtual Globe Within an Urban Information Workflow of Zurich

2. CesiumJS and 3D Tiles

The problem of rendering large urban datasets is partly computational. Serving every polygon of geometry for every building in a city at the highest available resolution would be unnecessarily slow and cumbersome. Tile-based data structures provide a solution by dynamically requesting relevant portions of data at appropriate resolutions based on the user viewpoint.

The OGC standard for 3D Tiles was developed to efficiently stream large heterogeneous three-dimensional geospatial datasets. 3D Tiles are especially relevant for cities because they allow clients to request visible tiles from extensive pyramids of data rather than attempting to load everything simultaneously (Open Geospatial Consortium [OGC], 2023). Large building datasets can quickly become computationally intensive as model resolution increases.

A 3D citymodel stored as 3D Tiles should not be confused with an urban information model. Although 3D Tiles can be used to store geometric approximations of building information, the OGC specification only describes how this information can be effectively streamed and displayed in a browser environment. This includes no provisions for how information is semantically structured or what kind of urban analyzes should be performed. Thus, 3D Tiles and CityGML are largely complementary: a semantically-enriched city model can be used to store, analyze and simulate information about the built environment which can then be transformed into 3D Tiles for publication and visualization.

Rossknecht and Airaksinen (2020) describe this process with regard to their Helsinki project. Energy data was first added to a semantic CityGML citymodel using the Energy ADE and stored in 3DCityDB before energy simulations were written back to the database. The enriched city

model was then transformed to 3D Tiles and visualized through a custom-built CesiumJS web application. Modelling decisions, simulation analyzes and communication through web visualization remain clearly delineated from one another, but this publication pipeline also creates connections between them.

3. Attribute Visualization and Building-Level Querying

Publishing 3D city models in Virtual Globes offers particular benefits when buildings can be related to thematic attributes. Semantic properties can be visualized to classify buildings according to energy demand, emissions, retrofit potential or other criteria of interest. With thematic representations applied, city models become interfaces for spatial analysis rather than just visualizations of reality.

Pasquinelli et al. (2019) display building energy indicators alongside their 3D city model of Gavardo in Cesium. Individual buildings are colored according to gas consumption, making it possible to analyze energy performance spatially instead of through numeric tables alone.

Rossknecht and Airaksinen (2020) developed these interactions to allow for building-level querying in their Helsinki implementation. Simulation outputs were expressed as attributes which could be applied to visually style buildings based on heating demand, CO_2 emissions or anticipated savings from retrofitting. Additional information could then be displayed when users selected individual buildings. The Virtual Globe therefore supports navigation between two types of information: an overview of the whole district that highlights spatial patterns and detailed information about individual buildings.

Urban retrofit decision support requires both of these perspectives. Information about energy performance, heritage values and retrofit feasibility are all clearly distributed across space. Representing that spatial variability facilitates the discovery of opportunities and informs general retrofit strategy. Individual building selection can then be used to explore patterns within the context of specific assets.

Visualization can also highlight underlying uncertainties or errors in building datasets. Rossknecht and Airaksinen (2020) note that missing values and anomalously high energy demands were quickly identifiable when results were visualized for each building in Helsinki. Spatial inconsistencies do not cause themselves to be corrected through visualization, but a Virtual Globe can help users identify where energy datasets require additional treatment.

4. Decision Support and Accessibility

Urban decision-support results can reach wider audiences when placed in Web-based Virtual Globes. Browser-compatible applications allow users to view and query three-dimensional datasets without needing access to the specialist software where simulations and analyzes were previously completed. Coupled with mobile-accessibility, CesiumJS provides the ability to

communicate complex building information to municipal workers, planners, developers or building owners who may not directly interact with GIS, BIM or energy simulation software.

How information is communicated will strongly influence its usefulness. Decision support may technically involve thousands of attributes for each building, but creating thousands of simultaneous data visualizations would be unreadable. Lei et al. (2023) list information complexity as one of several key challenges that should be considered when designing urban digital environments. The ability to filter data, classify buildings through color codes or interactively select buildings can be more beneficial than attempting to expose the raw underlying database.

Virtual Globes are therefore well suited to sharing results of urban decision-support analyzes. In many cases, the logic used to calculate those results will come from elsewhere. Simulations determine energy demand; heritage databases define categories of protection; cost models estimate retrofit feasibility. The Virtual Globe communicates spatial relationships between those outputs. Disconnecting the visualization from analytical or administrative datasets can help avoid attributing capabilities to Cesium that are instead applied externally.

5. Limitations of Virtual Globe Environments

Virtual Globes also have several disadvantages. Detailed geometry can limit rendering speeds which makes data tiling, generalization and level-of-detail (LoD) increasingly necessary at larger scales. Web Visualization likewise introduces additional limitations. Conversion between CityGML and web-compatible formats should not dissociate semantic attributes from their associated building objects. Truncating geometries can also improve performance, though deciding what information to exclude will be highly dependent on the application.

Photo-realistic three-dimensional models may also give a false impression of precision or certainty. Thermal bridging was approximated and assigned to buildings in the Helsinki model; heritage information for Gavardo required additional research to associate with individual buildings. Decision-support information is only as reliable as its source material, but that fact can become obfuscated by visually detailed building models. Virtual Globes should not be mistaken for primary data sources or computational tools.

Decision support applications may ultimately be limited by users' ability to understand complex information. Visual interactions are one tool for making that information understandable, but photographs of buildings and color-coded districts are only proxies for comprehensive energy data. Additional supports such as charts and explanations will still be necessary to share information with end users.

Virtual Globes act as the presentation/view layer for multi-source, geospatially referenced information about the built environment. Effective visualization connects semantic attributes with

geographically referenced three-dimensional objects, transforming numerical results into spatially-explicit relationships. This does not reduce the necessity for integrated GIS databases, BIM models, semantic interoperability or analytic tools discussed in previous chapters. Virtual Globes do not constitute a DT on their own, but software applications like Cesium can offer a consistent platform to explore and share their outputs.

Because virtual globes must make efficient use of geometric and semantic information at varying scales, LoD becomes a significant consideration. Selecting how much building detail to depict, and at what distances that detail should change, is the principle subject of the following section.

2.10 Level of Detail (LOD)

The expression *Level of Detail* (LOD) is widely used in digital representations of the built environment, but its meaning differs substantially between GIS, three-dimensional city modelling and BIM. In geographic modelling, Level of Detail generally concerns how an urban object is geometrically represented at different scales. In BIM, the similar acronym LOD commonly denotes *Level of Development*, which concerns the reliability and maturity of model elements rather than simply their geometric complexity. A further concept, *Level of Information Need*, addresses how much geometric, alphanumeric and documentary information is actually required for a particular purpose. Distinguishing these concepts is essential because greater geometric complexity does not necessarily imply greater information reliability or greater usefulness.

1. Level of Detail in GIS and 3D City Models

In 3D city modelling, LOD emerged as a means of representing the same urban object with different degrees of geometric abstraction. The principle responds to a fundamental problem of urban modelling: a building representation appropriate for regional visualization or statistical analysis may be inadequate for façade analysis, while modelling every building at architectural detail would impose unnecessary acquisition, modelling and computational costs.

CityGML provides one of the most established implementations of this concept. Earlier CityGML 2.0 literature commonly describes five levels, from LoD0 to LoD4. CityGML 3.0 revised this structure and now supports four predefined Levels of Detail, LoD0–LoD3, while allowing both outdoor and indoor objects to be represented within these levels. The former LoD4, which was specifically associated with interior representations, was therefore removed as a separate category.

For buildings, the levels can broadly be understood as a progression from coarse spatial representation towards increasingly explicit architectural geometry. LoD0 represents buildings through two-dimensional or 2.5-dimensional footprint- or roof-related geometries. LoD1

commonly represents buildings as simplified volumetric blocks. LoD2 introduces more differentiated building envelopes, particularly roof geometry and semantically distinguishable boundary surfaces. LoD3 supports considerably more detailed architectural representations, potentially including openings such as windows and doors. CityGML 3.0 nevertheless allows greater flexibility than this simple progression suggests, including different representations for indoor and outdoor parts of the same object.

The distinction between these representations is relevant to analytical applications. Pasquinelli et al. (2019), for example, found that the positional quality of their municipal building footprints was adequate for a LoD2 model, but roof information was unavailable. Buildings were therefore generated primarily as LoD1 extrusions, although external surfaces were semantically classified to support energy calculations. Their case illustrates that achievable LOD depends not only on geometric accuracy but on the information available for each building component.

Similarly, SimStadt was developed around CityGML partly because its multi-LOD structure allows city models to adapt to available building parameters and specific analytical requirements. Nouvel et al. (2015) emphasise this flexibility as an advantage for urban-energy applications, where complete architectural geometry is rarely available for entire building stocks.

LOD should therefore not be interpreted simply as a scale from "poor" to "good" models. A lower-detail representation may be entirely appropriate for an application that requires only building volume, exposed area or general roof form. Biljecki et al. (2016) further argue that the conventional CityGML LOD categories can conceal considerable geometric variation within the same nominal level, demonstrating that LOD classifications are useful abstractions but do not describe every aspect of model quality or complexity.

2. BIM Level of Development

Within BIM practice, Level of Development addresses a different problem. It describes the extent to which a model element has been developed and the degree to which users can rely on its geometric representation. BIMForum explicitly distinguishes Level of Development from Level of Detail: an object can appear visually detailed while still being unreliable in dimensions, position or design intent.

The BIMForum framework, based on definitions developed through AIA practice, commonly distinguishes LOD 100, 200, 300, 350, 400 and 500. At LOD 100, an element may exist only conceptually or symbolically. LOD 200 introduces an approximate but recognizable representation. At LOD 300, quantity, size, shape, location and orientation are sufficiently developed to be measured according to the design intent. LOD 350 additionally represents interfaces with adjacent or dependent elements and is particularly relevant to coordination. LOD 400 contains detail sufficient for fabrication, assembly or installation. LOD 500 differs

conceptually from this progression: rather than representing a higher design-detail stage, it indicates an existing or as-constructed condition established through observation, verification or interpolation, with its accuracy identified.

This final distinction is particularly relevant to existing-building modelling. A highly detailed reconstruction of a historic wall does not automatically constitute reliable as-built information if its internal construction has not been surveyed. BIM development therefore concerns the certainty and intended use of the information; not merely how realistic the geometry appears.

Nor should BIM LOD be treated as equivalent to project phase. BIMForum notes that a model at any given stage usually contains elements at different Levels of Development, depending on the knowledge available and the purposes for which those elements are required. This is particularly important for existing buildings, where different components may be documented to very different degrees.

3. Level of Information Need

The limitations of fixed LOD scales have encouraged a shift towards specifying information according to its intended purpose. The Level of Information Need formalizes this principle. ISO 7817-1:2024 establishes concepts and principles for determining the detail and extent of information required for particular information exchanges throughout the lifecycle of built assets. In the Italian context, the standard has been adopted as UNI EN ISO 7817-1:2024, following the earlier UNI EN 17412-1:2021 framework.

The important change is conceptual: the objective is no longer to request the highest possible "LOD", but to determine what information is necessary for a defined purpose. Information need may concern geometry, alphanumeric properties and documentation, and these requirements need not increase uniformly. A maintenance application, for example, may require moderate geometric detail but extensive information concerning condition and performance.

Table 2-5 Distinction between CityGML LoD, BIM LOD and Level of Information Need

Concept	Domain	Principal meaning	Typical purpose
CityGML LoD	GIS / 3D city modelling	Geometric/spatial representation at different scales	City modelling, urban analysis, visualization
BIM LOD	BIM	Development and reliability of individual model elements	Design, coordination, fabrication, as-built representation
Level of Information Need	BIM / information management	Required extent and granularity of information for a specific purpose	Avoiding insufficient or excessive information

Desogus et al. (2021) provide a useful existing-building example. Their BIM model intentionally adopted an intermediate level of graphic representation while associating richer information concerning material characteristics, deterioration, residual performance and maintenance. The authors argue that greater geometric complexity would have been unnecessary for the intended management application. This demonstrates why geometric and semantic information requirements should be considered separately.

Level of Information Need therefore provides a more application-oriented perspective than if every model should progress towards maximum detail. It also reduces the risk of over-modelling, where resources are invested in geometry or attributes that do not contribute to the intended analysis.

4. Application Requirements, Cost and Model Generalization

Increasing modelling detail has consequences for data acquisition, production time, storage, processing and visualization. At city scale, these costs multiply across thousands of objects. The appropriate representation must therefore be determined by the intended application rather than by geometric realism alone.

Urban energy modelling illustrates this relationship. A simplified building volume may be sufficient to estimate heated volume or exposed envelope area, while roof morphology becomes important for solar and photovoltaic analysis. Façade openings may be necessary when window-to-wall ratios are required explicitly, and interior zones become relevant for more detailed thermal or operational analysis. Rossknecht and Airaksinen (2020) identify model LOD among the factors affecting the accuracy of energy calculations, alongside missing information concerning refurbishment, heated floor area, window ratios and occupant behavior.

Historic-building applications can require different priorities. Detailed façade or roof geometry may be necessary to assess heritage-sensitive interventions even where internal construction remains uncertain. Dang et al. (2024) emphasize that maintaining greater customization is particularly important for heritage buildings because retrofit feasibility depends on individual architectural characteristics and protection conditions.

The relationship between detail and application is therefore non-linear. Greater detail can improve analyzes, but it can also increase modelling effort without improving the reliability of the required result. Model generalization remains necessary when data, computational resources or intended applications do not justify finer representation.

5. Adaptive Detail for Heterogeneous Existing Building Stocks

The greatest difficulty arises when a district contains buildings for which different quantities and qualities of information are available. Urban modelling workflows frequently respond by assigning the entire stock a common lower LOD or by replacing unavailable characteristics

with archetypal assumptions. These strategies produce consistent models and simplify automation, but they can discard valid information from better-documented buildings or create artificial uniformity.

An alternative is an adaptive representation, in which geometric and semantic information are developed according to available evidence and analytical need. Sammartano et al. (2021) discuss multi-scale urban information in Turin in precisely this context, moving from city-scale geometries towards floors and indoor information where richer datasets exist. Their work also highlights the possibility of combining GIS-scale representations with more detailed BIM information rather than demanding the same representation for every asset.

This approach is especially relevant to historic districts. One building may have accurate footprint, elevation and archival information, another may have detailed survey data, while a third may be known only through cadastral geometry and general construction-period information. Modelling all three at the same apparent detail could obscure these differences in evidence. Conversely, reducing all three to the least detailed representation would unnecessarily discard available knowledge.

For this reason, LOD in multi-scale existing-building modelling should be accompanied by explicit consideration of information reliability, provenance and application requirements. The objective is not to maximize geometric detail but to provide the amount of trustworthy information necessary for the intended analysis. For GIS-to-BIM workflows, this means that individual building models may legitimately contain different degrees of geometric and semantic development, provided these differences are controlled and transparent. Such flexibility is particularly important when heterogeneous urban information is transformed into building-level parametric models, because the digital representation should reflect what is known rather than imply a uniform precision that the source data cannot support.

2.11 Related Works

No methodology is developed in a vacuum, and the challenge this thesis addresses, translating city-scale spatial data into detailed, building-level models for energy and heritage assessment, has already been tackled, in different ways, by other cities and research projects across Europe. This section reviews three such efforts: Rotterdam's early attempt at a citywide digital platform, Helsinki's building-energy modelling using the CityGML Energy ADE standard, and the TABULA project's pan-European approach to classifying residential building stock into representative archetypes for energy assessment.

These three were chosen because each tackles a different piece of the same underlying problem, at a different scale and with a different technical approach. Rotterdam's case shows what happens when a city tries to build a single, unified digital representation of itself, and the governance and data-silo problems that effort ran into. Helsinki's case shows a more technically

mature, standards-based approach to modelling energy performance across many buildings at once, but at the cost of the fine-grained, building-specific detail a historic district like Via Roma demands. TABULA's case shows a third approach entirely: rather than model every building individually, it classifies buildings into a manageable number of representative types, trading precision for scalability. Read together, these three examples mark out the space this thesis's own methodology has to work within, precise enough to respect a historic building's individual character, but structured enough to scale across an entire street.

2.11.1. Rotterdam

Rotterdam's digital twin developed out of the city's Digital City programme, launched in 2017 as part of the EU Horizon 2020 RUGGEDISED project. This brought together three "lighthouse" cities (Rotterdam, Glasgow, Umeå) and three "fellow" cities (Brno, Gdańsk, Parma) to test smart-city solutions. The programme's starting point was a familiar one: a range of smart-city applications for energy, mobility, and waste management had already been built in Rotterdam, but each had been developed as a stand-alone, siloed solution with its own data formats, so almost nothing could be shared or reused between them. The city's response was to develop an Open Urban Platform intended to interconnect these applications around a single, three-dimensional digital twin of the city (Barcik et al., 2023).

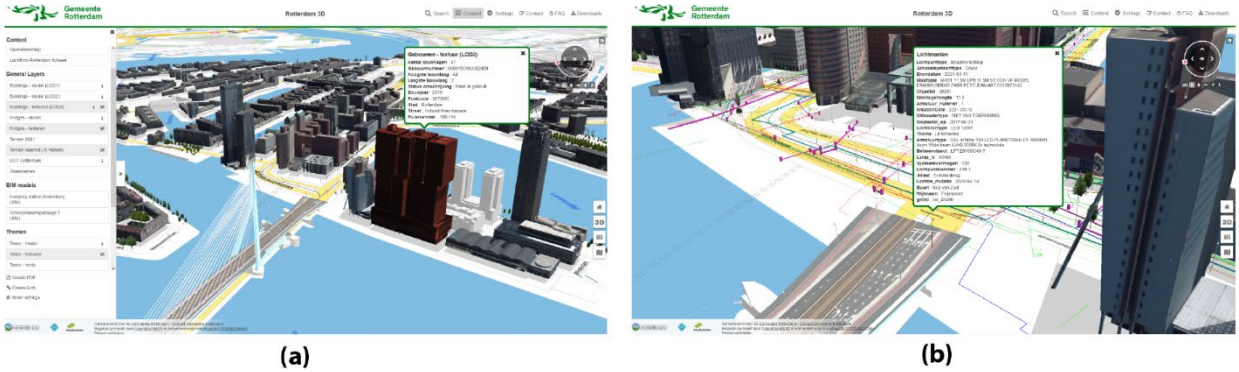


Figure 2.13 The Rotterdam 3D city model: (a) building-level detail (construction year, floors, underground levels); (b) the city infrastructure layer (roads, electricity, water and sewage pipes). Reproduced from Barcik et al. (2023), Figure 6.

As of the most recent implementation report reviewed, Rotterdam's 3D city model remained at the proof-of-concept stage rather than a finished production system. What had been built, however, was substantial: a layered model in which roads, water canals, public lighting, and underground infrastructure (electricity, telecommunications, water and sewage pipes, and metro lines) could each be switched on or off as separate data layers, alongside a building layer carrying attributes such as construction year, number of floors, and number of underground levels for individual structures. A tree-mapping layer and real-time feeds for traffic, public transport, and bridge openings were also integrated. For public engagement, the platform supported an augmented-reality feature letting residents view a planned building or park in situ by scanning a QR code at the construction site (Barcik et al., 2023).

Several smart-city applications were already feeding real operational data into this model rather than remaining theoretical. Electric buses charged from rooftop photovoltaic panels, with charging schedules optimized against route timetables, measurably reduced nitrogen-oxide emissions. A smart waste-management system using fill-level sensors cut collection-truck mileage by roughly 20 percent, with corresponding reductions in fuel use, emissions, and noise. An intelligent street-lighting network allowed remote dimming and automatic fault reporting from individual lamp posts. Each of these was already operational in Rotterdam and already reporting telemetry back into the digital twin (Barcik et al., 2023).

The same study compared Rotterdam's platform directly against Brno's own city data portal, data.Brno, and the comparison is instructive for what it shows about trade-offs rather than a simple ranking. Rotterdam's platform offered 3D visualization, augmented reality, underground infrastructure layers, and a citizen-participation feature that Brno's did not; Brno's platform, in exchange, offered open API access for downloading raw data and direct publication of city-council information, neither of which Rotterdam's did. The authors' broader conclusion is directly relevant to any methodology, like this thesis's, that aims to work across multiple cities or districts: every city's digitalization approach turns out to be shaped by its own local priorities and legacy systems, and a single unified model cannot simply be copied from one city to another without adaptation (Barcik et al., 2023).

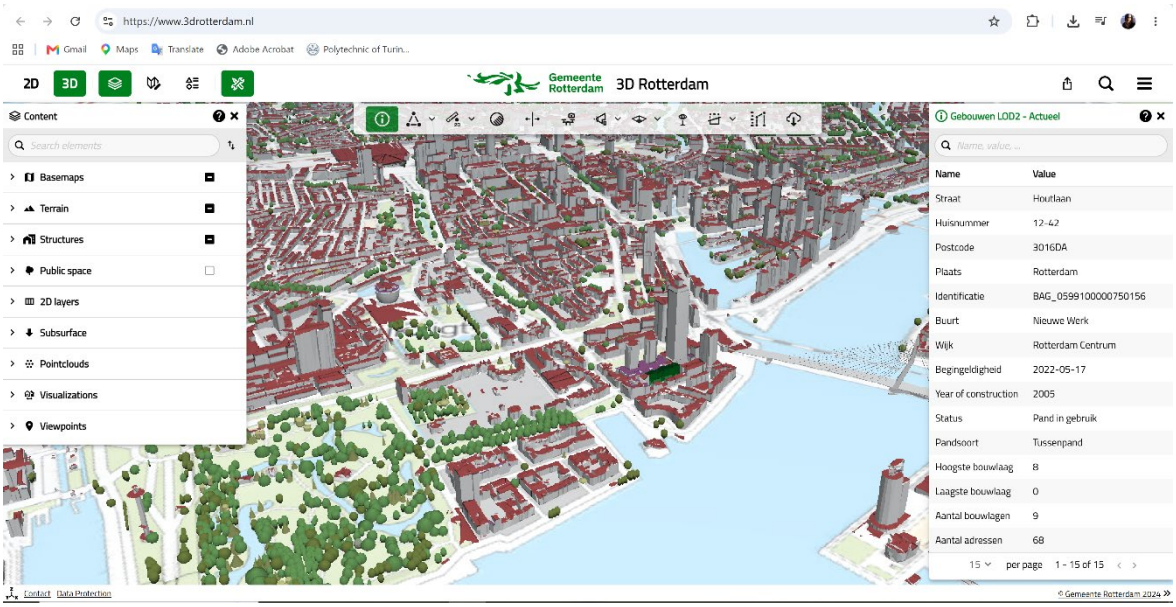


Figure 2.14 The official 3D Rotterdam platform (3drotterdam.nl), showing LOD2 building geometry and per-building attribute data. Source: Gemeente Rotterdam, 2024.

What Rotterdam's case demonstrates most clearly for this thesis is the gap between an ambitious, unifying data platform and the harder problem of populating it with genuinely detailed, building-specific information. The 3D model's building layer, as described, carries only a handful of coarse attributes per building (construction year, floor count, underground

levels) - useful for city-wide visualization, but far short of the geometric and energy-performance detail a single historic building on Via Roma requires. Rotterdam's platform solves the problem of connecting many data sources into one interface; it does not, on its own, solve the problem this thesis addresses, of generating rich, individual building models automatically from that same underlying city-scale data.

2.11.2. Helsinki

Where Rotterdam's case shows a city trying to unify many data sources into one platform, Helsinki's case shows a narrower but more technically mature problem: predicting the heating demand and resulting CO2 emissions of an entire building stock, building by building, directly from a 3D city model. The work was carried out in direct support of a real policy target, the City of Helsinki's own strategy to become carbon-neutral by 2035, with an 80 percent cut in emissions relative to 1990, and heating is identified as the single largest contributor to the city's emissions. The value of this case for the present thesis lies less in any single result than in its workflow: how raw municipal data was gathered, how it was processed into something a simulation engine could actually use, and what came out the other end (Rossknecht & Airaksinen, 2020).

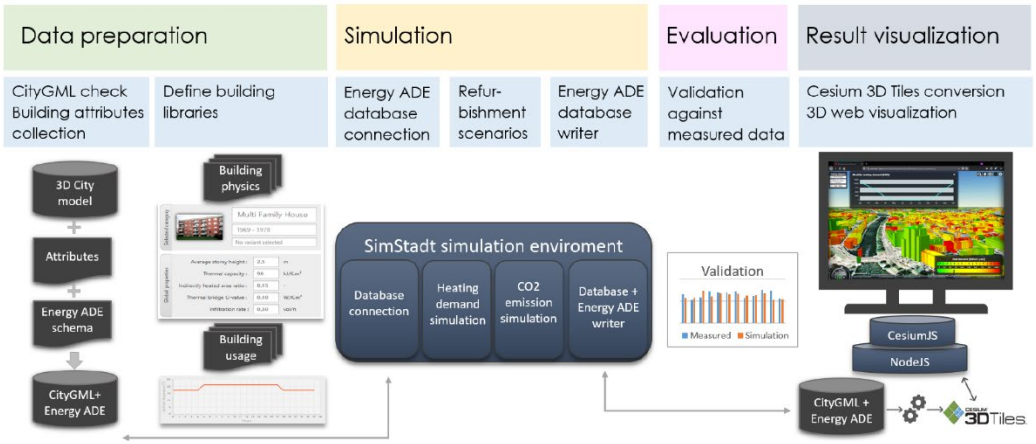


Figure 2.15 Overview of the Helsinki heating-demand prediction concept: from CityGML/Energy ADE data preparation, through SimStadt simulation, to validation and 3D web visualization. Reproduced from Rossknecht & Airaksinen (2020), Figure 2.

The workflow begins with data collection, and Helsinki already had more of the necessary raw material assembled than most cities would. The city maintains its own 3D city model in CityGML format, and alongside it, a separate dataset called the Helsinki Energy and Climate Atlas, which holds building-level information such as construction year, floor area, and heating consumption for much of the city's stock. Neither of these, on its own, was built with energy simulation in mind, so the first task was simply gathering them together in one place. A third strand of input came from outside the city entirely: the Finnish Meteorological Institute supplied both historical observed weather and long-term predicted test-reference-year data built specifically for building

energy simulation, including projections out to 2050. Because the simulation software the team intended to use, SimStadt, had never been configured for Finnish buildings before — only for German and New York building stock — a further round of data collection was needed just to describe what a typical Helsinki building actually is: its construction, its usage patterns, and the heating system likely to serve it (Rossknecht & Airaksinen, 2020).

Processing this raw material into something usable meant translating it into a shared, machine-readable structure rather than leaving it as separate spreadsheets and city registers. The team adopted the CityGML Energy Application Domain Extension (Energy ADE), a schema designed specifically to attach energy-relevant attributes to individual buildings within a CityGML model, and stored the enriched model in a 3DCityDB, a database built purposely for this kind of 3D city data. Populating that schema required defining three distinct building-type libraries from scratch for the Finnish context: a building physics library, classifying buildings by construction-year range and refurbishment status, with thermal capacity, storey height, infiltration rate, and the thermal transmittance of each construction element; a building usage library, describing occupancy, ventilation, and heating patterns by building function; and an energy systems and fuel library, calibrated specifically to Helsinki's own Helen district heating network, whose CO2 emission factor was itself forecast to fall sharply as the city decarbonises, from 400 g CO2/kWh in 1990 toward a targeted 30 g CO2/kWh by 2035 (Rossknecht & Airaksinen, 2020).

With the data structured and the libraries in place, the analysis itself proceeded as a series of simulation runs rather than a single calculation. SimStadt was extended to query the 3DCityDB directly, pulling each building's Energy ADE attributes automatically rather than requiring them to be entered by hand, and two future scenarios were run against the interpolated 2012–2050 climate data: a "business as usual" scenario, in which refurbishments were assigned to individual buildings by chance but weighted toward the least efficient ones first, and a more ambitious "rapid development" scenario assuming a higher refurbishment rate throughout the city. Crucially, the simulation results were not exported to a separate report but written back into the same Energy ADE schema inside the 3DCityDB, so the model of the city and the results of analyzing it remained one and the same object rather than two disconnected files (Rossknecht & Airaksinen, 2020).

The results that came out of this process worked at two different scales at once. At the scale of the whole city, climate change alone was predicted to reduce heating demand by roughly 4 percent per decade; layered with refurbishment, the reduction reached 0.7 TWh by 2035 under the cautious scenario and 1.5 TWh under the ambitious one, translating into a CO2 cut of up to 82 percent relative to 1990 once the declining district-heating emission factor was factored in, though the authors note this still fell short of the city's own stated ambition of a 2.0 TWh/year reduction through modernization, at the refurbishment rate actually observed in the data. At the scale of the individual building, the same results were published as an interactive 3D web

application, built by converting the CityGML model into 3D Tiles format and serving it through CesiumJS on a Node.js server, letting a user color the whole city by heating. demand, CO2 emissions, or projected savings, then click any single building to see its construction year, floor area, and volume alongside interactive charts of its heating demand under each future scenario (Rossknecht & Airaksinen, 2020).



Figure 2.16 Screenshot of the resulting 3D web visualization, coloring buildings by simulated space-heating demand and giving per-building attributes on selection. Reproduced from Rossknecht & Airaksinen (2020), Figure 7.

The final stage of the workflow, validation, is what makes this case genuinely useful as a comparison rather than just a technical showcase. The results were checked against measured consumption data for 1,915 real buildings, and the simulation's mean absolute percentage error came out at 19.6 to 25.6 percent depending on which floor-area figure was used, with 96 buildings deviating by more than 100 percent — traced back to faulty or missing usage-zone data in the source atlas rather than to the simulation method itself. Rather than patch over this, the authors simply dropped the unreliable usage-zone data from later runs and relied on net floor area instead, a decision that says as much about the workflow as any of its technical steps: the accuracy of a city-scale energy model turns out to depend at least as much on the quality of the municipal data feeding it as on the sophistication of the simulation engine processing it (Rossknecht & Airaksinen, 2020).

For this thesis, tracing Helsinki's workflow end to end is more instructive than any single number in it. It shows a coherent path from raw, disconnected municipal datasets, through a shared open schema and a purpose-built simulation environment, to results that are validated, visualized, and fed back into the same city model they came from, a sequence this thesis's own GIS-to-BIM methodology follows in its own way. Where Helsinki's workflow reaches its limit is

in the middle step: the building libraries that make the whole pipeline possible are generic, imported approximations of a typical building's construction and use, not detail actually surveyed from the buildings in question. That is precisely the gap a historic, individually heritage-classified street like Via Roma cannot tolerate, and Helsinki's own validation numbers show, in concrete terms, what that gap costs even in an otherwise well-built workflow.

2.11.3. TABULA Project

Where Rotterdam's case shows an attempt to unify city-wide data into one platform, and Helsinki's shows a standards-based simulation pipeline built directly on a 3D city model, TABULA takes a third, deliberately different approach to the same underlying problem: rather than model every building in a stock individually, it classifies the entire residential building stock of a country into a manageable number of representative archetypes, and calculates energy performance for those archetypes rather than for each real building. The trade-off this makes explicit, scale against precision, is exactly the trade-off this thesis's own building-by-building methodology is designed to avoid, which makes TABULA a useful counterpoint rather than merely a predecessor.

TABULA ("Typology Approach for Building stock energy Assessment") was an Intelligent Energy Europe project running from 2009 to 2012, coordinated by the Institute Wohnen und Umwelt (Darmstadt, Germany), with thirteen national partners developing a residential building typology for their own country under a shared methodology. The Italian typology was developed by the Politecnico di Torino's own Department of Energy, Vincenzo Corrado, Stefano Corgnati, and Ilaria Ballarini, which makes TABULA a direct methodological predecessor rather than a distant international comparison (Loga, Diefenbach, & Stein, 2012).

The classification workflow begins with what TABULA calls the "Building Type Matrix": each country's residential stock is divided into a grid, with building size class (single-family house, terraced house, multi-family house, apartment block) along one axis and construction-year band along the other. Every cell of this grid defines a generic "building type," and each type is then represented by a single exemplary building, a real or synthetic reference building with a photograph, a defined envelope construction, and a defined heating system, chosen to be broadly typical of its cell rather than a survey of any specific real address. The Italian typology, focused on the country's middle climate zone where most of the residential stock sits, defined eight construction-period bands and 32 building types in total (Loga, Diefenbach, & Stein, 2012).

For each exemplary building, three states are then defined and calculated: the existing, that is non-refurbished state; a "standard" refurbishment package that reflect measures commonly carried out in practice; and an "advanced" package reflecting a more ambitious, near-passive-house level of intervention. These three states, calculated using a common reference procedure

based on EN ISO 13790, are published together as a "Building Display Sheet", a double-page graphic showing the building's existing envelope and systems on one side and the energy savings achievable under each refurbishment package on the other. Every national partner published a full set of these sheets in a "Building Typology Brochure," written in the country's own language and aimed directly at building professionals and energy advisors rather than only at researchers (Loga, Diefenbach, & Stein, 2012).

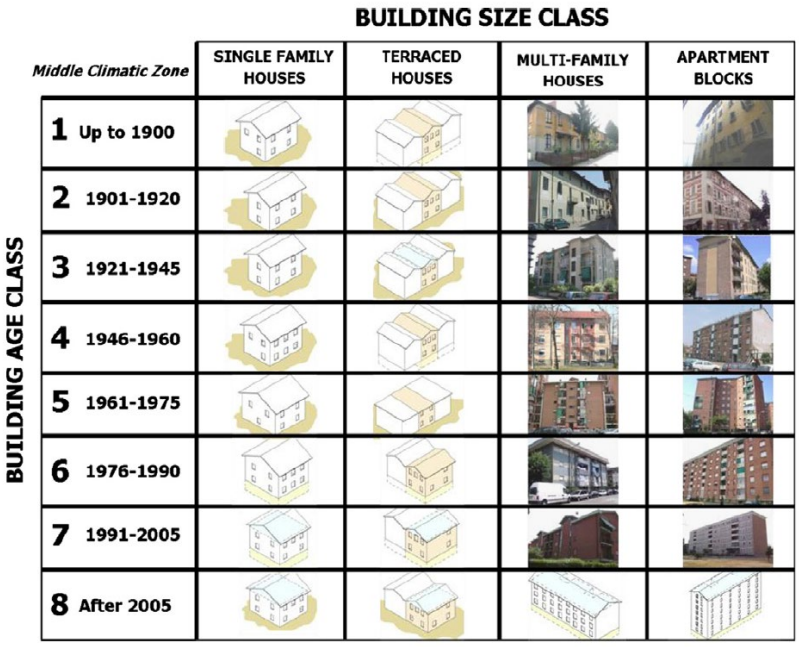


Figure 2.17The TABULA "Building Type Matrix" for Italy, classifying the national residential building stock by size class (columns) and construction-year band (rows), with a photographed exemplary building for each cell. Source: Corrado, Ballarini, & Corgnati (2014/ TABULA project.

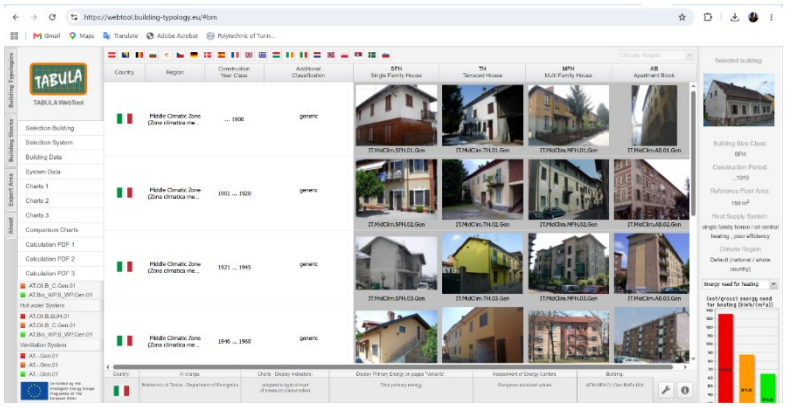


Figure 2.18 Screenshot of the TABULA Building Typology WebTool, showing Italy and building-type selection.

The results of this classification were published twofold: in the printed national brochures, and in an interactive "TABULA WebTool" allowing a user to select a country and a building type and see its energy balance calculated live, with the option to compare the existing state against the standard and advanced refurbishment packages. An "expert version" of the tool additionally

exposes the underlying construction and system datasets directly, rather than only the summary results (Loga, Diefenbach, & Stein, 2012).

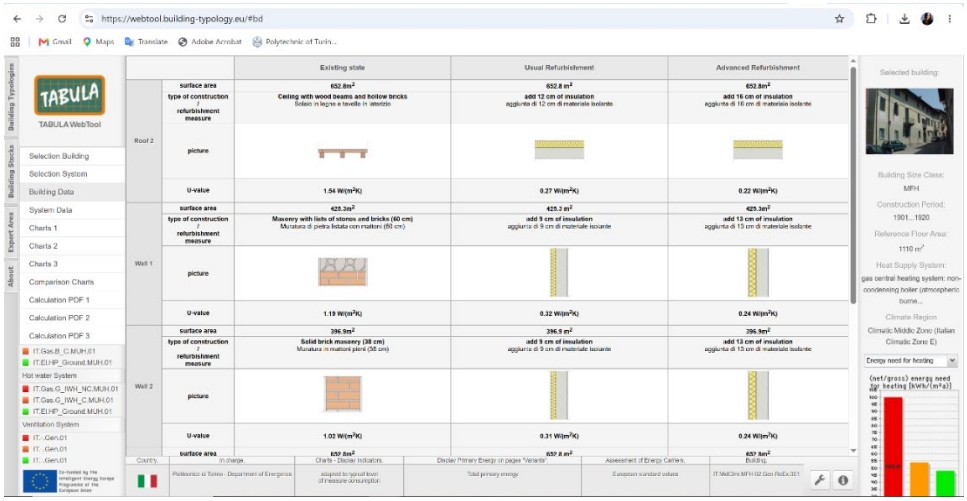


Figure 2.19 Screenshot of the TABULA Building Typology WebTool, showing Proposals for building envelope refurbishment on the two levels "Standard and "Advanced"

TABULA's own final report is candid that this approach has a real cost, and the honesty of that admission is exactly what makes it useful here. The exemplary buildings are, by design, illustrative rather than statistically representative: their envelope areas and construction details "are not necessarily representative in a statistical sense," and validation studies comparing calculated to measured consumption, carried out by several national partners, showed considerable deviations between the two. The project's own recommendation for the future was the development of "adaptable model buildings" that could be flexed to match a real building's actual number of storeys, neighbors, and construction period more closely, in effect, an acknowledgement that the archetype approach was a starting point rather than a finished answer to individual-building accuracy (Loga, Diefenbach, & Stein, 2012).

For this thesis, TABULA marks the opposite end of the scale-versus-precision spectrum from Helsinki's building-specific simulation, and it does so with an admirable degree of honesty about the trade-off. Classifying an entire national stock into a few dozen archetypes makes city- or country-scale energy assessment tractable, and the shared, published typology has clearly proven useful as a reference dataset for later, more detailed studies, including several already discussed in this thesis. But an archetype approach cannot, by construction, capture the individual variation of a real historic street: a single generic "pre-1946 apartment block" type cannot distinguish a heritage-protected building on Via Roma from an ordinary building of the same age elsewhere in the city, still less account for the specific retrofit constraints heritage protection actually imposes. That distinction between a representative archetype and an individually surveyed, heritage-classified building, is precisely the gap this thesis's own GIS-to-BIM methodology is built to close.

Chapter 3: Methodology

3.1 Case Study: Via Roma

Via Roma is Turin's principal commercial street, running in a straight line from Piazza Castello, past Piazza San Carlo at its midpoint, to Porta Nuova station. As established in Chapter 2, its earliest tract dates to the 1587 cutting of Via Nuova, the founding axis of the Baroque "Città Nova" expansion; over the following three and a half centuries it remained the city's most prestigious address, until the entire street was demolished and rebuilt in the early 1930s. a single street whose present-day fabric is almost entirely the product of one deliberate, well-documented, architecturally coherent intervention, built under heritage constraints that remain legally active today.

The street was cut in 1587 as Via Nuova, later called the Contrada Nuova. It was the first axis of Turin's expansion south of its old Roman walls under Savoy rule. The new street followed a line where narrow lanes already existed, so the builders did not need to demolish much to create it (Coppo & Moglia, 1995; Re & Sessa, ca. 1983). Every building along the street had to follow the same design: shops and a mezzanine at street level, a grand floor above with windows topped by triangular or arched pediments, and a plainer top floor. The roofline and window spacing were kept uniform across all the buildings, no matter what stood behind each façade (Re & Sessa, ca. 1983).

In 1620, the street was also laid out on a strict geometric grid. The blocks nearest the street were about 94 meters deep, and the street itself ran roughly 134 meters between cross streets. This proportion was less exact at the two ends, where the parade ground near the Cittadella and the old city walls got in the way (Re & Sessa, ca. 1983). Turin's street was rigid and military in feeling, built as a uniform ceremonial route for the Duke rather than a competition between rich families. In fact, it had no special buildings at all when it was first built, aside from two matching churches at its northern end (Re & Sessa, ca. 1983).

The street's midpoint, Piazza Reale (now Piazza San Carlo), was laid out from 1638 with a uniform arcaded frontage and its own twin churches, Santa Cristina and San Carlo, set at its southern mouth; the whole arrangement was consolidated and recorded in the 1672 Theatrum Sabaudiae view of the city, which shows the Contrada Nuova already functioning as the deliberate ceremonial approach from the new gate to the ducal palace at Piazza Castello (Re & Sessa, ca. 1983). The eighteenth century brought two further changes of detail rather than of plan: Juvarra's 1730s reworking of the Santa Cristina façade adapted the seventeenth-century double order to a more flexibale, updated design, and in 1773 the porticoes themselves were structurally reinforced, their arches and columns consolidated into the sturdier order still visible today (Re & Sessa, ca. 1983)

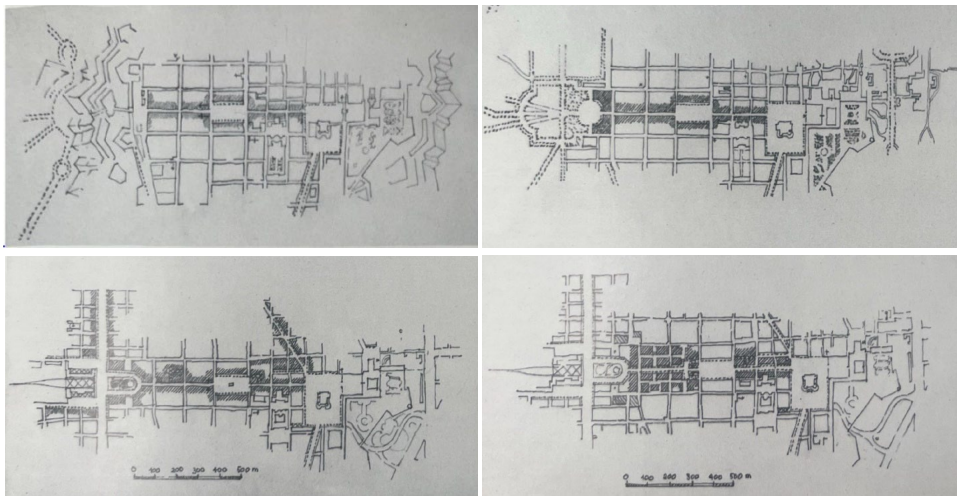


Figure 3.1 Sequential diagrams showing the cutting of the Contrada Nuova (later Via Roma) through Turin's pre-existing urban fabric, and its extension in successive building campaigns. Re & Sessa (ca. 1983), after the Istituto di Architettura Tecnica del Politecnico di Torino (1968)

The demolition of the Porta Nuova gate and the opening of a tree-lined piazzale in its place, which was a part of the wider Napoleonic and Restoration-era reworking of the city's edges, extended the axis south with two further blocks (designed by Gaetano Lombardi, 1818–26). This framed a new octagonal piazza, later Piazza Carlo Felice (Re & Sessa, ca. 1983). It was at this point, with the completion of the railway terminus at the new piazza (1865–1867) and in step with the political optimism of Unification, that the street took the name Via Roma. Its character also began to shift toward commerce: the Galleria Natta, a glazed shopping passage modelled on the passages of Paris and London, opened through the block on the piazza's east side in 1858, and the larger Galleria Nazionale followed on the west side in 1888–89 (Re & Sessa, ca. 1983). By the early twentieth century, complaints about poor hygiene and cramped conditions in the blocks behind the street's narrow historic lots were already being raised, well before the political change that eventually triggered a full reconstruction (Coppo & Moglia, 1995; Politecnico di Torino, 1984).

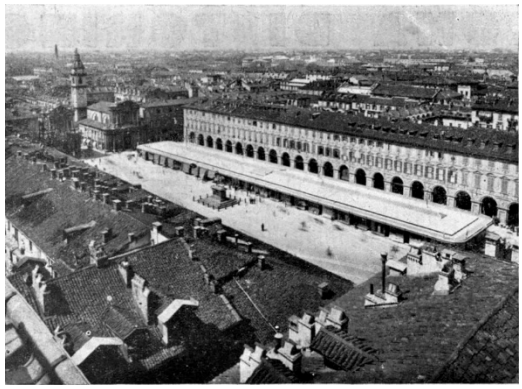


Figure 3.2 Piazza San Carlo and the surrounding roofscape shortly before Via Roma's total reconstruction. M.I.A.R. Group (1931)

Long before the reconstruction actually happened, Via Roma had already been argued over for decades. In 1861, Giovan Battista Martin Franklin made the first real proposal: either give the whole street the same arcaded look, or cut a covered shopping gallery through the middle of the blocks. Nothing came of it, other projects took priority at the time (Re & Sessa, ca. 1983). The debate picked up again in the early 1900s, after the nearby Via Pietro Micca had shown that this kind of large-scale street-cutting could actually be done. Architects argued over details: should the porticoes be arched or trabeated (flat-beamed)? Should the arcades run along one side of the street or both? And what to do with the two old churches sitting in the middle of the street? No plan solved all of this cleanly.

In 1914, architect Pietro Betta and painter Felice Carpanetto put forward one of the better proposals, wrapping an arcade around Piazza San Carlo. But a large cinema building, nicknamed the "Ghersi", was being built on the piazza at the same time, which made any clean, comprehensive plan harder to pull off (Re & Sessa, ca. 1983). A city plan was finally approved in 1922. But it didn't offer property owners any compensation for widening the street, so nobody wanted to build under those terms, especially in the tough postwar economy. The plan had to be completely redone in 1925–26, this time with tax breaks and longer deadlines to make it worth builders' while (Re & Sessa, ca. 1983). By 1928 the ideas being floated had gotten bolder. Architect Umberto Cuzzi proposed widening the street to 75 metres and lining it with fifteen-storey towers, a plan even he didn't expect to get built. It was more of a provocation, meant to push the conversation forward (Re & Sessa, ca. 1983).

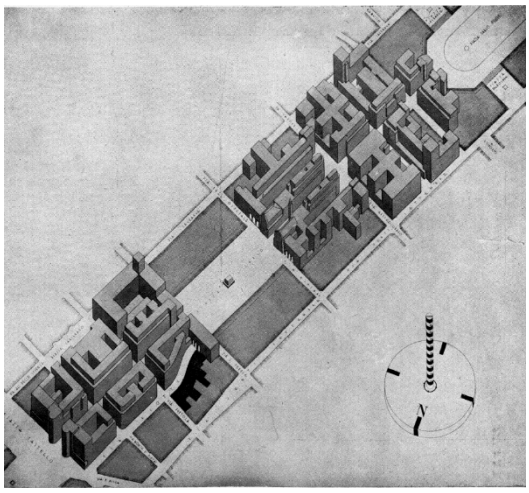


Figure 3.3 The M.I.A.R. group's own axonometric masterplan for Via Roma, proposing freestanding sculptural blocks in place of the traditional continuous street wall — the scheme was not the one ultimately built. M.I.A.R. Group (1931).

In 1931, a group of modernist architects publishing as M.I.A.R., Giuseppe Pagano Pogatschnig, Gino Levi-Montalcini, Umberto Cuzzi, Ottorino Aloisio, and Ettore Sottsass, argued publicly for a more radical design than what was eventually approved, proposing to break the street's continuous frontage into freestanding sculptural blocks arranged along sinuous, Mendelsohn-influenced volumes, entirely without porticoes (M.I.A.R. Group, 1931; Re

& Sessa, ca. 1983). The city instead chose to keep the traditional continuous street wall and portico, and building proceeded lot by lot in that more conservative form; the M.I.A.R. proposal nonetheless had a lasting influence on the culture of Turinese architecture and was shown with approval at the 1931 Mostra dell'Architettura Razionale in Rome (Re & Sessa, ca. 1983).

Demolition of the first stretch of Via Roma, from Piazza Castello to Piazza San Carlo, began in May 1931. Work moved fast: the whole stretch was torn down and rebuilt in just over two years, reopening on 28 October 1933 (Re & Sessa, ca. 1983).

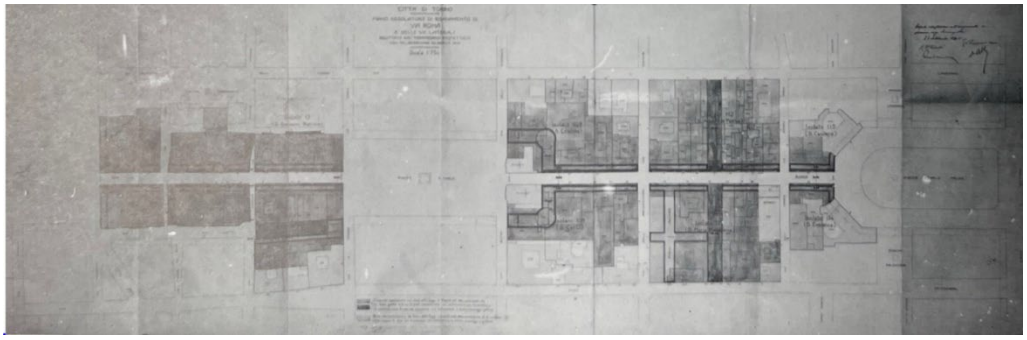


Figure 3.4 The 1926 "Piano Scanagatta," the executive plan for the reconstruction of Via Roma's first tract, showing the street's block subdivisions and the portico line set for the whole stretch between Piazza Castello and Piazza San Carlo. Comune di Torino, Ufficio Tecnico Comunale (1926), reproduced in Re & Sessa (ca. 1983).

What changed most was the street itself, not just the buildings on it. The roadway was widened from its old 10.5–11.3 meters to 14.8 meters, with a new portico 5.8 meters deep added on each side, so the whole cross-section of the street grew substantially even though it kept the same line it always had (Re & Sessa, ca. 1983). This widening had already been fixed two years earlier, in the 1926 executive plan for the reconstruction, known as the "Piano Scanagatta" after the city's chief engineer, Giorgio Scanagatta, which set the exact width of the street and its porticoes, and applied the rule only to this first stretch, between Piazza Castello and Piazza San Carlo.

Along this new, wider street, a handful of large buildings replaced what had been many small, older properties, helped along by the 1929 financial crisis. This pushed landowners to sell and let the city consolidate scattered plots into a few large holdings. This made it possible to rebuild in bigger, more coordinated pieces rather than lot by lot. The best-documented of these, the San Pietro building, shows how a single new building could now absorb what used to be several separate plots, including the old Teatro Carignano, folded whole into the new structure rather than demolished (Bonicelli & Ratti, 1934).

For the second tract, from Piazza San Carlo to Porta Nuova, the city tried a different approach. Instead of assigning the design directly, it held a national competition in 1933. Architects submitted very different visions: some kept the classical look of the first tract, others proposed towers, courtyard housing blocks, or bold modern monuments (Re & Sessa, ca. 1983). In the

end, no single competition entry was built as submitted. Marcello Piacentini was brought in to coordinate the whole tract instead, he decided where the two old churches would sit, and set the height, spacing, and style every building on the street had to follow. Five different architects then designed the five blocks within those shared rules, so the street reads as one design even though many hands built it (Re & Sessa, ca. 1983).

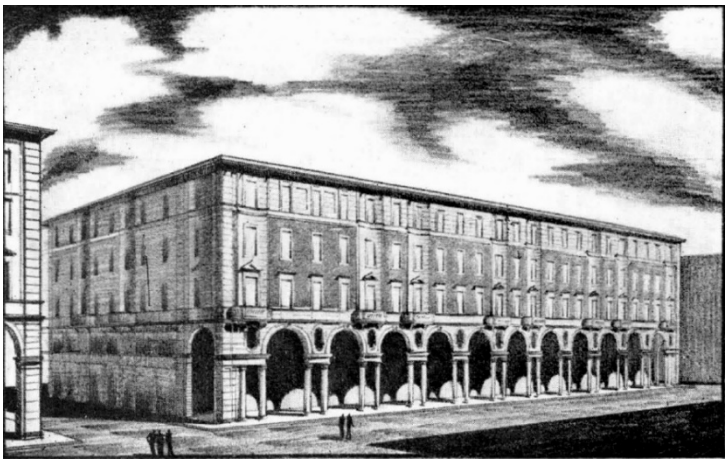


Figure 3.5 The rebuilt northern stretch of Via Roma, San Pietro block, completed 1934. Bonicelli & Ratti (1934).

The result looked different from the first tract: more severe, more geometric, faced in travertine instead of stone. Construction ran through the mid-1930s, and the second tract opened on 30 October 1937 (Re & Sessa, ca. 1983; Melis, 1938).

Despite the split authorship and the seven-year gap between the two tracts, Via Roma reads as a single composition because both stretches share the same basic elements: a continuous ground-floor portico carried the full length of the street, a stone or travertine-faced base, plain upper floors set behind a regular window grid, and a uniform cornice height, with no direct residential entrances onto the street itself so that the whole frontage under the porticoes could be given over to shops. The two halves remain distinguishable mainly through smaller details, the more classicist detailing of the first tract as against the starker Rationalism of the second, and differences in the style of the original street lighting installed in each stretch (Politecnico di Torino, 1984; Re & Sessa, ca. 1983).

A separate, independent confirmation of how thoroughly the 1930s reconstruction reshaped this stretch of the city comes from a Politecnico di Torino research project mapping the historic urban fabric of central Turin, coordinated by Paolo Scarzella and building on two earlier city-wide surveys (1968 and 1984). Its overview map classifies the whole central area by the period in which each block's built fabric was laid down, and marks the two Via Roma tracts as their own distinct category - "9.1", the reconstruction of the first tract toward Piazza Castello, and "9.2", the reconstruction of the second tract toward Porta Nuova - set apart from every

surrounding fabric of earlier date (Politecnico di Torino, Dipartimento di Ingegneria dei Sistemi Edilizi e Territoriali, ca. 1990s).

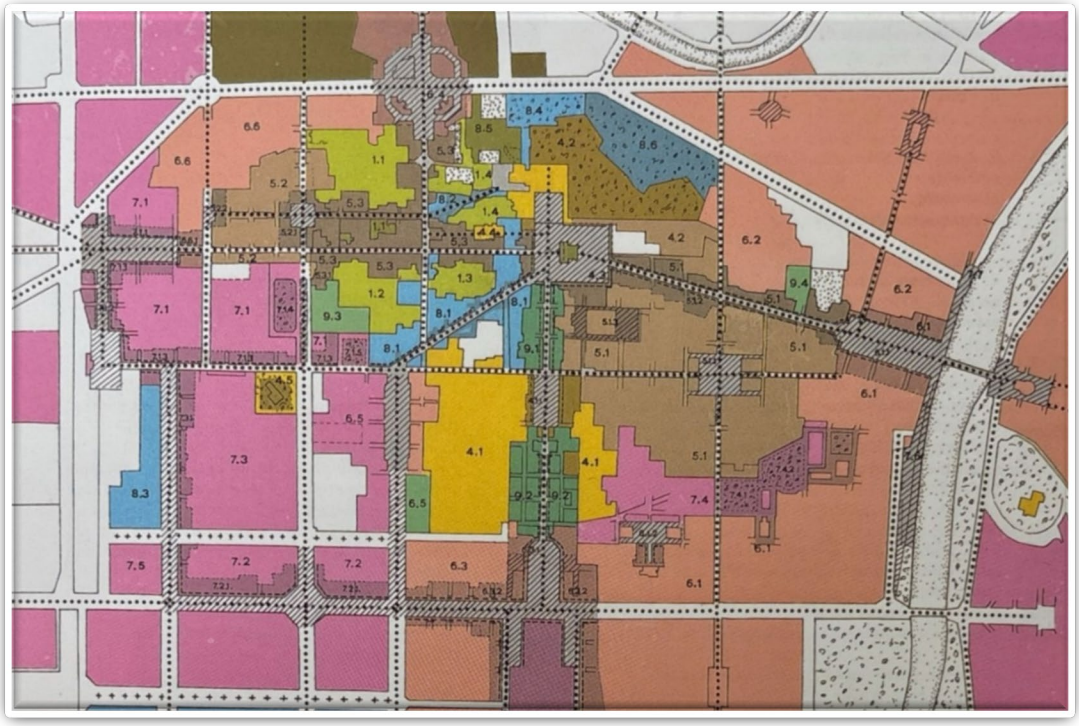


Figure 3.6 Overview map of historic urban fabric in central Turin, classified by period of construction. Politecnico di Torino, Dipartimento di Ingegneria dei Sistemi Edilizi e Territoriali (ca. 1990s).

This 1930s fabric is, with only minor changes since, what stands on Via Roma today. The street is still Turin's main shopping street, and its double row of arcades still shelters the same continuous line of shops it was built for. Retrospective accounts written around the reconstruction's fiftieth anniversary noted that while the street's architecture aged well as a coherent whole, the same rebuilding also pushed out much of the residential population that had lived there before, leaving a street that is busier with shoppers today than it ever was with residents (Re & Sessa, ca. 1983).

Because of its age and unified design, Via Roma today is protected as a single historic composition, not as separate individually listed buildings. It also shows up in the city's own historic-fabric maps, which mark it out, building by building, as its own construction-period zone, separate from the older streets around it.

But these records don't talk to each other. The heritage listing, the historic-fabric maps, and the ordinary property records each hold a different piece of information about the same buildings, kept in separate files and formats. Via Roma is a good case for this thesis precisely because that gap exists, a combined GIS-to-BIM record can bring these scattered layers of information together into one place.

3.2 Rationale for Case Study Selection

The selection of Via Roma in Turin as the case study was guided by the need to test the proposed GIS–BIM methodology within a real and sufficiently complex urban environment. Rather than selecting an isolated building or a homogeneous residential district, Via Roma provides a dense central area in which urban morphology, historical value, heterogeneous building characteristics, energy performance, and planning constraints coexist. This makes it particularly suitable for investigating how geographically distributed urban information can be integrated with building-scale information to support energy assessment and retrofit decision-making.

A first reason for its selection is its historical and architectural significance. Via Roma forms one of the principal axes of Turin's historic center, connecting Porta Nuova and Piazza Carlo Felice with Piazza San Carlo and Piazza Castello. However, as discussed in the previous section, its current architectural coherence is the result of several historical transformations, particularly the extensive twentieth-century reconstruction of the street. Historical documentation shows that this process involved demolition, reconstruction, alternative urban-design proposals, coordinated façade design and the establishment of the continuous portico system that characterizes the street today. Consequently, the area represents a useful example of an urban fabric in which modernization requirements and heritage values are closely interconnected.

A second consideration concerns the morphological characteristics of the study area. The broader studies of Turin's central urban fabric demonstrate that the city center cannot be understood simply as a collection of individual buildings. Its identity is produced through the relationship between blocks, streets, courtyards, building fronts, porticoes, public spaces and successive periods of transformation. Via Roma therefore provides an appropriate context for a methodology in which building performance is examined together with urban-scale characteristics. Parameters such as building height, footprint, number of floors, volume, exposed façade area, surface-to-volume ratio and the presence of porticoes can be considered alongside building-specific information rather than treating each building independently from its surroundings.

The area is also particularly relevant from an energy-retrofit perspective. The historic and architectural character of Via Roma means that technically effective interventions cannot necessarily be implemented without considering their impact on the existing urban image. Street-facing façades, porticoes and other historically significant elements may impose different levels of intervention constraint. As a result, two buildings with similar calculated energy performance may not have the same retrofit possibilities. This condition supports one of the main principles of the research: energy demand alone is insufficient for defining retrofit priorities in a historic urban environment. Energy indicators need to be interpreted together with morphological, architectural and heritage-related information.

Another important reason for selecting Via Roma is the availability and diversity of urban information. The case study allows information originating from different sources and scales to be combined, including municipal building data, census information, urban-planning datasets, historical documentation and heritage-related classifications. These datasets provide complementary information but are not originally structured as a single building-level database. Via Roma therefore offers an appropriate testing ground for the data-integration component of the research, in which heterogeneous GIS information is processed, harmonized and associated with individual building identifiers before being transferred to the BIM environment.

At the same time, the case study presents the type of data incompleteness that commonly characterizes urban-scale energy assessment. Detailed information regarding the construction and current thermal properties of every building is not consistently available. This makes it possible to test an archetype-based approach in which available construction-period and building information is combined with TABULA documentation to estimate representative thermal properties where direct information is unavailable. The case study consequently reflects realistic conditions for district-scale analysis rather than assuming the availability of complete BIM or energy-model data for every building.

The scale of Via Roma also provides a useful intermediate condition between the individual-building and city scales. It is sufficiently large to demonstrate the potential of GIS-based analysis and automated information processing, while remaining sufficiently defined to permit the generation of building-level 3D objects and their enrichment within a BIM environment. The study can therefore investigate not only the transfer of GIS geometry into BIM, but also the preservation and enrichment of semantic information during this process.

Finally, Via Roma is suitable for evaluating the integration between GIS and BIM as a methodology rather than as a one-directional conversion process. GIS provides the spatial, demographic, morphological, planning and heritage context required to interpret the building stock, while BIM provides a structured three-dimensional environment in which building-level parameters and calculated indicators can be associated with individual objects. The resulting information can subsequently be returned to a geographically referenced visualization environment for communication and comparison. In this sense, the case study enables the research to examine GIS and BIM as complementary components of an integrated urban information framework.

For these reasons, Via Roma represents a particularly relevant case through which to test the proposed methodology. Its combination of historical significance, morphological complexity, heritage constraints, heterogeneous data availability and energy-retrofit requirements creates a realistic environment for assessing whether GIS–BIM integration can support the transition from fragmented urban datasets toward a building-level information model capable of informing retrofit analysis and decision-making.

3.3 Methodological Framework

The methodology developed for this research is structured around the integration of two complementary technological domains: a Geographic Information System (GIS) domain and a Building Information Modelling (BIM) domain, linked together through a dedicated GIS-to-BIM integration process. This dual-domain structure, summarized in the diagram below, reflects the underlying aim of this research: to represent the city in a way that is complete and meaningful for today's needs. A contemporary representation of the city can no longer be limited to its geometric and morphological form alone but should be capable of holding together the many dimensions that define urban life, social, economic, historical, and environmental among others. Energy performance is one of these dimensions, and it is the one adopted in this research as the specific lens through which the proposed GIS-to-BIM methodology is developed and tested, without this focus excluding the other aspects of the city that the same representation is meant to be able to accommodate.

Achieving this kind of multidimensional representation requires combining two domains that, individually, only capture part of the picture. The GIS domain is responsible for assembling and structuring the heterogeneous, urban-scale data needed to describe the building stock of the study area, geospatial and morphological data, socio-demographic and planning data, historical and regulatory data, and standardized building typology data, into a single, coherent, building-level database. The BIM domain, in turn, is responsible for translating this database into a spatial, parametric digital model, in which every building is represented not only through its geometry, but also through the semantic information attached to it, allowing any of these dimensions, in this case, energy performance, to be analyzed at the individual building scale. Neither representation, on its own, would be sufficient: GIS alone can describe the city at scale but lacks the object-based, parametric detail needed for a building-by-building assessment, while BIM alone is typically built one building at a time and lacks the urban-scale, multi-source data needed to characterize an entire historic district. The methodology adopted in this research treats the connection between these two domains as a structured, repeatable integration process, so that the urban-scale information assembled in GIS can be reliably carried into a building-scale, parametric BIM representation, capable of supporting energy performance analysis as demonstrated in this thesis, while remaining open, in principle, to the integration of other urban dimensions in future applications.

This methodology is further conceived as a decision-oriented framework rather than a purely technical exercise. For this reason, a virtual globe environment was deliberately chosen as the final destination of the workflow, rather than stopping at the BIM model itself: while the GIS-to-BIM integration is what makes a rich, building-level representation of the city possible, it is the virtual globe that makes this representation accessible and usable as a decision-making tool, by translating the technical outputs of the energy analysis into a shared, navigable, and

intuitive spatial interface. Through this virtual globe, the results of the analysis can be communicated to the different actors involved in the management and transformation of the built environment, urban planners, designers, residents, and researchers, each able to draw on the same city representation to inform their own decisions. In this sense, the methodology closes a cycle: data drawn from the real world is progressively structured, integrated, and enriched, in order to return to the real world, through the virtual globe, as an updated, multidimensional representation of the city, capable of informing concrete urban policies and retrofit priorities for the historic building stock of the Via Roma study area.

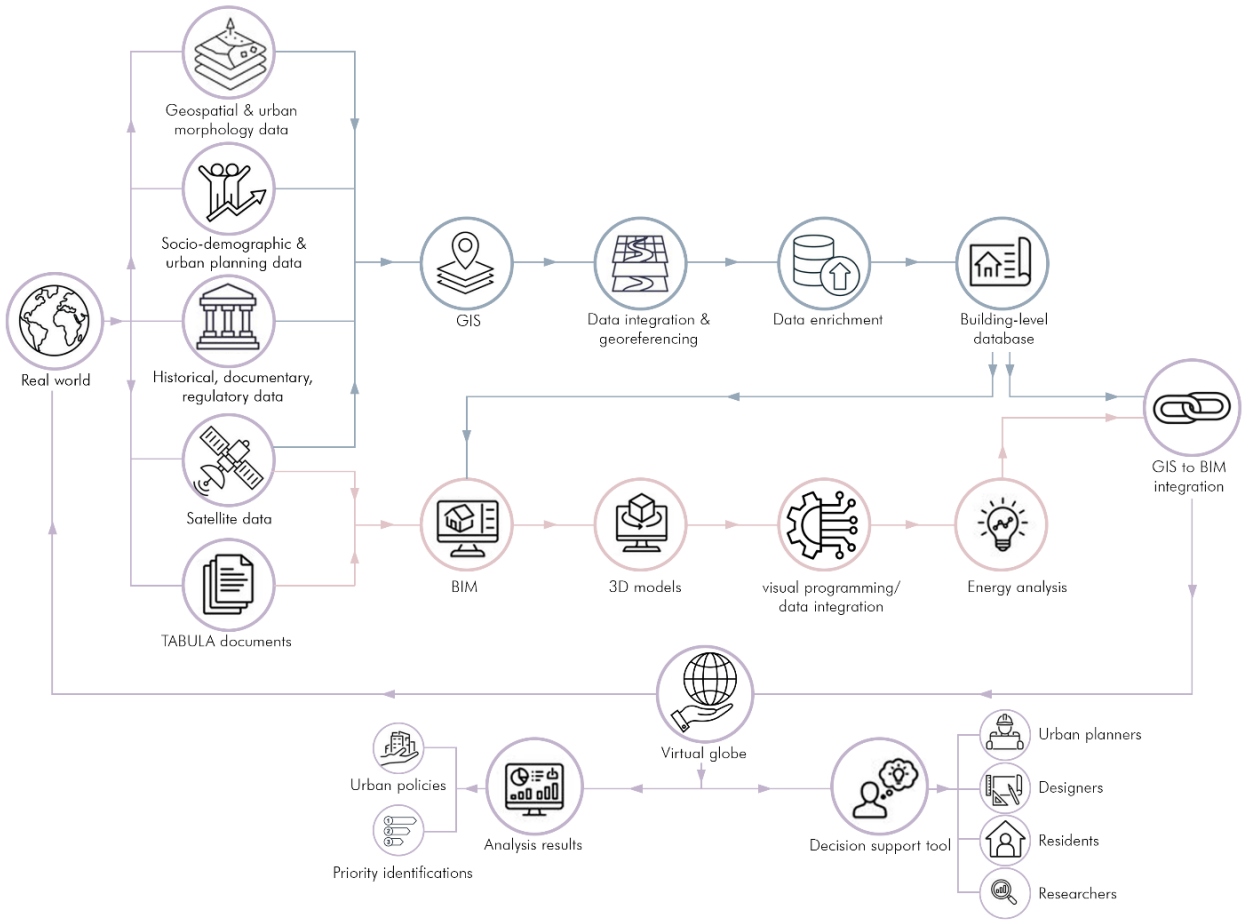


Figure 3.7 Methodological Framework Diagram

3.4 Heritage Regulations

Via Roma is subject to a layered system of heritage and planning protection that runs from national law down to the individual building. This section reconstructs that system in descending order of scale, from the general principles of national cultural-heritage law, through the regional and municipal planning instruments that implement them, to the specific classification, cartographic evidence and permitted-intervention regime that apply to the buildings forming the case study of this thesis. The section draws on the national Code of Cultural Heritage and

Landscape, the Technical Implementation Rules (N.T.A.) and technical annexes of Turin's General Zoning Plan (PRG), the explanatory and research volumes accompanying the plan's 1993 Progetto Definitivo, and the plan's own 1:1000 cartography of the historic center.

1. The National Framework

The primary source of heritage protection in Italy is Legislative Decree No. 42 of 22 January 2004, the *Codice dei Beni Culturali e del Paesaggio* (Code of Cultural Heritage and Landscape), which consolidated and replaced the earlier statutes of 1939 (Law No. 1089 on cultural assets and Law No. 1497 on landscape protection). The Code distinguishes two categories of protected assets: *beni culturali* (cultural assets, Part Two, Arts. 10–130) and *beni paesaggistici* (landscape assets, Part Three, Arts. 131–159). For an urban case study such as Via Roma, three provisions of the Code are of particular importance. First, Article 10(4)(g) extends the notion of cultural asset to "public squares, streets, roads and other open urban spaces of artistic or historic interest", allowing a street to be protected as a unitary urban artefact rather than only as a sum of individually listed buildings. Second, Articles 20–21 establish that cultural assets may not be altered, and that any works on them require prior authorization from the competent Superintendency. Third, Articles 45–47 introduce *tutela indiretta* (indirect protection), empowering the Ministry to impose distance, height and alignment requirements on buildings surrounding a protected asset, so as to preserve its setting, sightlines and visual context, the legal mechanism that can extend protection to an entire street front even where not every building on it carries an individual constraint. A parallel landscape-protection route exists under Article 136, which protects "groups of buildings that together compose a characteristic appearance of aesthetic and traditional value", subject to landscape authorization under Article 146.

2. The Regional and Municipal Planning Framework

Below the national Code, heritage protection is put into practice at the city level through Turin's Piano Regolatore Generale (PRG, General Zoning Plan). The current plan was designed by Gregotti Associati Studio (Vittorio Gregotti, Augusto Cagnardi and Pierluigi Cerri) and submitted to the city in 1993 [4], [5]. It was formally approved by the Piedmont Region on 21 April 1995 (Deliberazione n. 3-43091, published in the B.U.R. n. 21 of 24 May 1995), and has been updated several times since, most recently in a coordinated text dated 1 January 2023 [2], [3], [6]. This approval is the legal basis for everything discussed in the rest of this section.

The plan's Norme Tecniche di Attuazione (N.T.A., Technical Implementation Rules) put the Code into effect at city level. Article 7 of the N.T.A. defines the Zona Centrale Storica (ZCS, Historic Central Zone), the area within which Via Roma lies in its entirety, classified as an "urban settlement of historic-artistic character" under Article 24 of the Piedmont Regional Planning

Law. Within the ZCS, Article 7 classifies every building into one of six historic-value groups, summarized in the table below.

Table 3-1 The six building groups defined by Art. 7 of Turin's N.T.A.

Grp	Building group (N.T.A., Art. 7)	Relevance to the case study
1	**Edifici di gran prestigio** (Buildings of great prestige)	Royal residences, representative palaces, churches; not part of the Via Roma complex.
2	**Edifici di rilevante interesse** (Buildings of major interest)	Pre-existing noble palazzi bordering the axis.
3	**Edifici della costruzione ottocentesca della città** (19th-century construction)	Surviving pre-1930s fabric adjacent to the reconstructed stretches.
4	**Edifici del complesso di via Roma** (Buildings of the Via Roma complex)	The case-study buildings: the unitary inter-war reconstruction along Via Roma.
5	**Edifici del periodo tra le due guerre** (Inter-war period buildings)	Contemporary but architecturally independent inter-war infill.
6	**Edifici recenti** (Recent buildings)	Built after 1945; occasional post-war replacements within the blocks.

For each of the six groups, Article 7 further subdivides every building into four constituent parts, exterior facing public space, distribution system, courtyards and private fronts, and interior of the building bodies, and assigns each part, according to its architectural quality, one of three intervention-type codes: RES (restauro conservativo, conservative restoration), RIS (risanamento conservativo, conservation-based renovation) or RIE (ristrutturazione edilizia, building refurbishment).For Group 4, the street-facing fronts of the Via Roma buildings receive RIS with no RES option and no more permissive alternative, the strictest regime the plan applies to this group, while the distribution system, courtyards and interior admit the more flexible RIE.

The Annex A to the N.T.A., Definizione dei tipi di intervento (Definition of Intervention Types) [3], explains what each intervention type allows, from lightest to heaviest: ordinary maintenance, extraordinary maintenance, conservative restoration (RES), conservation-based renovation (RIS), building refurbishment (RIE), demolition, and demolition with reconstruction. If a building is also protected under national heritage law, any work must additionally follow the Superintendency's rules [3, Premessa, point 6].

The Via Roma buildings' street-facing fronts fall under risanamento conservativo (RIS). Under this rule, it is allowed to rebuild damaged masonry, replace parts of the front with matching materials, and make small changes to windows, shopfronts and roof dormers, but only as part of a design for the whole building front, not isolated changes. Decorative details cannot be removed or simplified, and the roof shape cannot be changed except in a few listed cases [3, §4.1]. This makes RIS stricter than ristrutturazione edilizia (RIE), which allows partial rebuilding of the front and small volume changes. But RIS is less strict than restauro conservativo (RES), which requires replacing everything exactly as it was and submitting a historical report [3, §3.0–

§3.1]. In short, Via Roma's fronts sit in the middle: protected enough to keep their historic character, but flexible enough to still work as a commercial street today.

Table 3-2 Intervention types applicable to Group 4 ("Edifici del complesso di via Roma") by building part.

Building part	Type	Permit
Exterior facing public space	RIS	Authorization
Distribution system	RIS / RIE	Authorization / permit
Courtyards & private fronts	RIS / RIE	Authorization / permit
Interior of building bodies	RIE	Full building permit

In practice, this means: any work on the street-facing side of a Via Roma building, the arcaded ground floor, shopfronts, upper windows, cornices and roofline, must follow the stricter risanamento conservativo rules [3, §4.1]. These rules apply to the whole front at once, and they protect the decorative details and the historic look of the street. Work on the inside, the courtyards, or technical upgrades can instead follow the more flexible ristrutturazione edilizia rules [3, §5].

If a building also has its own heritage protection under the Code, the Superintendency's approval is required on top of these city rules, and takes priority over them [1, Artt. 20–21]; [2, Art. 7.1]. Nearby buildings may also need separate checks under the Code's "indirect protection" rule (Articles 45–47), regardless of their own group classification [1, Artt. 45–47].

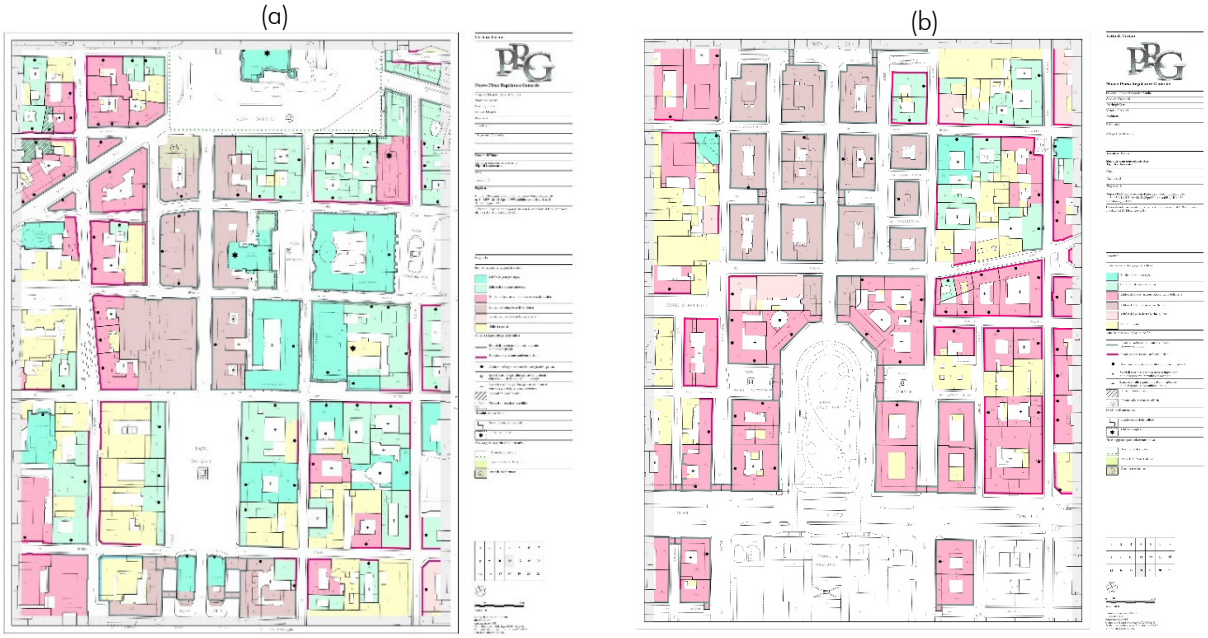


Figure 3.8 (a) PRG, Tavola n. 3, Foglio 11: building-type classification from Piazza Castello to Piazza San Carlo. Buildings coloured pink/magenta; (b) PRG, Tavola n. 3, Foglio 18: building-type classification from Piazza C.L.N. to Piazza Carlo Felice and Porta Nuova station.

3. Cartographic Classification of the Case-Study Area

The building-group classification described above is not only a textual provision of Article 7; it is mapped, building by building, in the plan's own 1:1000 cartography, *Zona urbana centrale storica. Tipi di intervento* (Historic Central Urban Zone. Intervention Types), Tavola n. 3 [6]. Figures 3.8(a) and 3.8(b) reproduce the two sheets of this map covering the full length of Via Roma: Foglio 11, from Piazza Castello to Piazza San Carlo, and Foglio 18, from Piazza C.L.N. to Piazza Carlo Felice and Porta Nuova station, corresponding respectively to the "1st stretch" and "2nd stretch" of the Via Roma complex identified in the 1993 research volume (§3.4.5).

4. Intervene actions sample of the Case-Study Area

The sources reviewed in this section do not present a single, consolidated list of technical or energy-related interventions; instead, such measures appear scattered across different articles and intervention types, often described only in passing. Table 3-3 brings these scattered references together into one schedule, matching each measure to the intervention type that governs it and to whether it is possible on the Via Roma buildings.

Table 3-3 Technical and energy-related interventions mentioned across the sources, matched to the intervention type required, and whether they are possible on the Via Roma buildings (public front = RIS; interior/courtyards = RIS or RIE).

Topic	What the sources say	Type	Possible on Via Roma?
Technical installations (general)	Should go inside the building or in the basement where possible. If placed outside, must be hidden or blended with the building's design and not be visible from public space.	RIS	Yes, if hidden
Solar panels / renewable energy	Not named directly, only "renewable energy systems on roofs": must not be visible from public or panoramic viewpoints; must use the best available technology.	RIS	Yes, if not visible
Roof insulation	Allowed, including full replacement of the roof covering, but materials and technique must match the building's character; roof height and shape must stay the same.	RIS	Yes, if shape kept
Wall insulation	Not mentioned by name. Possible if applied on the inside; if applied on the outside, it would change the appearance of the street-facing facade, which the sources protect at every level.	RIS	Yes, only if it does not change the street-facing facade
Green roofs	Not mentioned by name. Possible if it doesn't change the appearance of the street-facing facade, which the sources protect at every level.	RIS	Yes, only if it does not change the street-facing facade
Plant / technical rooms	Allowed, but must be placed in basements or attics, not visible from outside.	RIE	Yes, interior only
Lifts / elevators	New lifts are allowed inside the building, outside the stairwell, without damaging valuable spaces.	RIS / RIE	Yes
Windows and doors (fittings)	Can be replaced only with identical ones, or with modest changes as part of a whole-front project.	RIS	Yes, whole front only

Shopfronts and signage	Ground-floor shops are protected as part of the street's character. Can be changed only as part of a design for the whole building front.	RIS	Yes, whole front only
Attic / loft conversions	Using existing attic space is always allowed. Adding new floor levels needs a bigger type of intervention.	RIS / RIE	Yes, RIE if new floors
Underground garages	Allowed under conditions: access ramps must be inside the building or hidden, courtyard paving restored after.	RIS / RIE	Yes, under conditions
Rainwater systems (gutters, pipes)	Can be replaced only with identical materials and shapes.	RIS	Yes

The "Type" column shows the lightest intervention level under which the source allows that work. Since Via Roma's street-facing fronts are classified as RIS, anything achievable under RIS is possible there; items that only become possible under RIE (e.g. new floor levels, technical rooms) apply mainly to the interior, courtyards or distribution system, not the street front itself.

3.5 Technological Workflow

The methodology developed in this thesis is supported by a specific chain of software tools, in which each tool was adopted in response to a limitation encountered in the one preceding it. Presenting this chain of reasoning here serves as an introduction to the technological workflow as a whole, before each of its stages is examined in detail in the remainder of this chapter.

The starting point of the workflow is QGIS. Its adoption follows directly from the nature of the source data available for this research: the municipal building geometry, the census statistics, the heritage classification, and the topographic surface data existed as separate datasets, in different formats and at different spatial scales, with no single source providing a ready-to-use, building-level dataset. QGIS was chosen as the environment in which these heterogeneous sources could be brought together, since, being free, open-source, and capable of handling vector and raster data alike, it offered the flexibility required to clean, join, and reconcile these datasets into a single, coherent building-level database.

This database, however, could not be transferred to a BIM environment in its native GIS format. The shapefile structure in which vector GIS data is conventionally stored separates geometry and attribute information across several linked files, a structure well suited to a GIS environment but poorly suited to being read independently by external software. For this reason, once the building-level database had been finalized, it was exported not as a shapefile but as a single GeoJSON file, a lightweight, text-based format in which geometry and attributes are stored together, and which can therefore be parsed directly by a script without reliance on any GIS-specific library.

It is precisely this property that made the subsequent stage of the workflow possible. To bring the resulting dataset into Revit, Dynamo was selected as the integration tool, being the visual programming environment embedded directly within Revit, and consequently the only tool capable of both reading external data and generating native Revit geometry from it within the same environment in which the building model was ultimately required to reside. As the existing Dynamo packages designed for this type of GIS import proved unable to read the dataset reliably, Dynamo's capacity to execute a custom Python script as part of its visual graph was used instead, allowing the GeoJSON file to be parsed directly and translated into building geometry.

Revit, as the destination of this process, followed naturally from the choice of Dynamo, but it also provided a further capability essential to this research: a Shared Parameters mechanism through which every building element could carry its own set of attributes, rather than existing merely as an undifferentiated geometric shape. This mechanism is what allows the resulting model to function as a building-by-building information base, capable of supporting an individual energy assessment for each building of the study area.

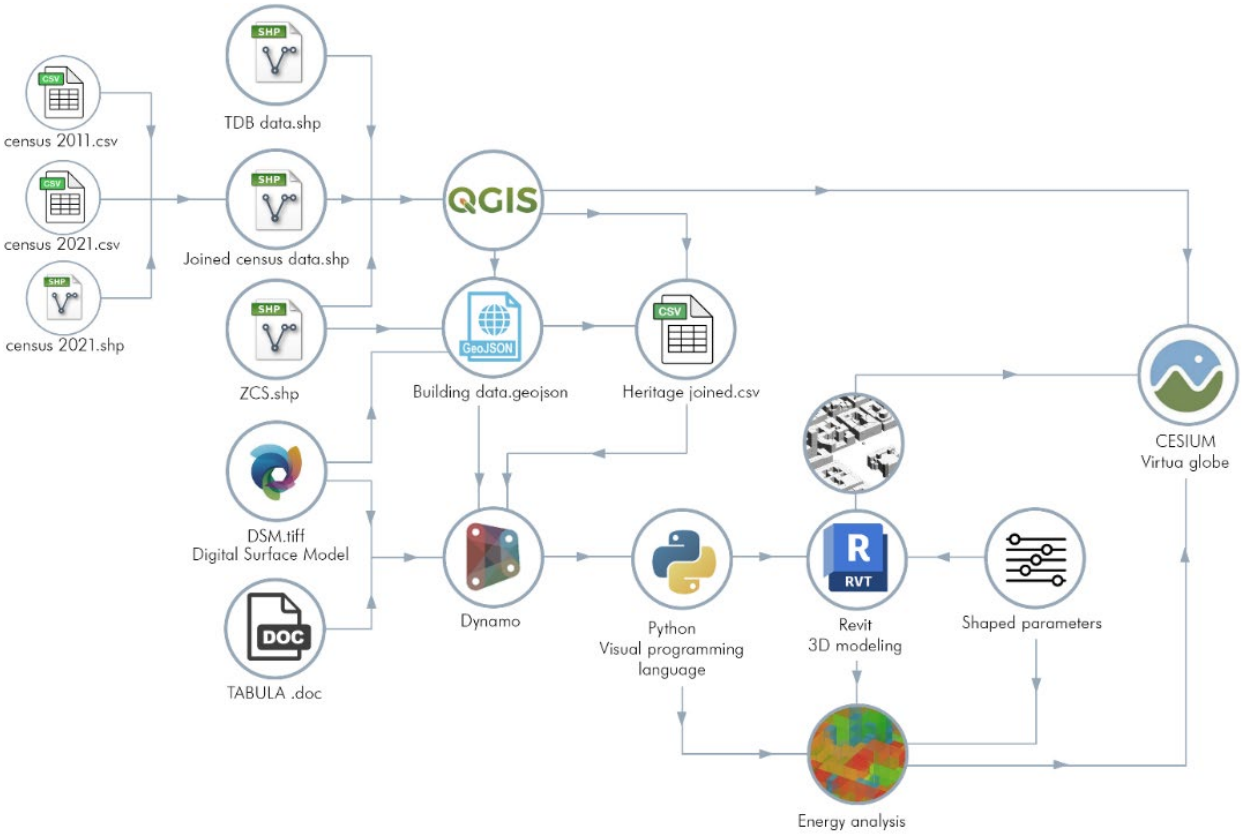


Figure 3.9 Technological Workflow Diagram

The final stage of the chain responds to a different requirement. Once the energy analysis had been completed, neither QGIS nor Revit offered a suitable means of communicating its results

to an audience beyond GIS or BIM specialists. Cesium was adopted to address this gap, as a virtual globe platform designed to display large-scale, georeferenced three-dimensional city data directly within a web browser. Publishing the results of the analysis through this platform is what allows the outputs of this research to extend beyond its technical pipeline, and to reach the actors actually concerned with the building stock under study.

3.6 Data Preparation

Before any building on Via Roma could be processed through the GIS-to-BIM pipeline, a range of different data sources had to be collected, checked, and brought into a common, usable format. This data came from several places at once, municipal GIS records, heritage classification tables, energy performance references, and the historic drawings and plans covered in earlier sections, and each source needed its own preparation before it could be combined with the others. This section walks through that preparation process, source by source, starting with the municipal GIS data that formed the base layer for everything else.

3.6.1. Municipal GIS Data

The data preparation process for this research began with the acquisition of the base geometric and semantic dataset for the building stock under study, sourced from the Geoportale of the City of Turin, specifically from the municipal Topographic Database (TDB). This dataset was retrieved in shapefile format, a vector data structure fully compatible with GIS software, and was subsequently imported into QGIS, which served as the primary environment for inspecting, cleaning, and processing the spatial data throughout this phase of the work.

The TDB was selected as the starting point of the dataset construction because it represents the most reliable and city-wide source of georeferenced building geometry available for the municipality, ensuring a consistent spatial reference for every building object considered in the study, a necessary condition for any building-scale energy analysis conducted at urban scale.

Since the scope of this research was limited to a specific area of the city rather than the entire municipal territory, the citywide TDB shapefile was clipped in QGIS to retain only the buildings falling within the district of Via Roma, an area that had been defined beforehand as the boundary of the case study. This clipping operation reduced the dataset to a manageable and analysis-relevant subset, ensuring that all subsequent processing steps, from attribute inspection to the integration of external data sources, were focused exclusively on the buildings of interest, and avoiding the unnecessary computational and organizational burden of handling the full city-scale dataset.

Upon opening the clipped shapefile in QGIS, the attribute table was examined to identify which building-level information was already available and which was still missing. Each building record in the dataset came with the following attributes:

1. Building ID – a unique identifier for each building, essential for linking this dataset to any other data source that would be integrated later in the workflow;
2. Height – the vertical extent of the building, a key parameter for volumetric calculations and envelope surface estimation;
3. Portico presence/effect – an attribute noting whether the building included porticoes, relevant for correctly reconstructing the building footprint and its exposed surfaces;
4. Number of floors – although present, this attribute was incomplete for a portion of the buildings, requiring later integration or estimation;
5. Building footprint – the 2D geometric outline of each building, from which volume, gross floor area, and heat-transfer surfaces can subsequently be derived;
6. Land use code – a classification attribute indicating the general function associated with each building, although present, this attribute was also incomplete for a portion of the buildings;
7. Eave elevation above sea level – the altitude of the roof eave line, useful for height verification and for supporting 3D reconstruction of the building volume;
8. Ground level elevation above sea level – the altitude at the base of the building, which, combined with the eave elevation, allows the true building height to be cross-checked and refined.

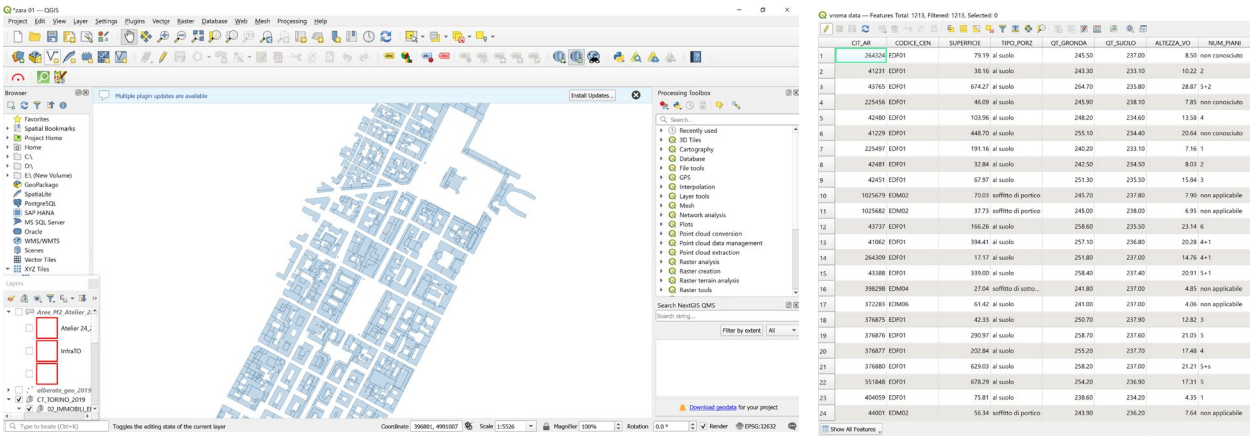
While this set of attributes provided a solid geometric and locational foundation, it was not sufficient, on its own, to support a building energy performance analysis. Two critical pieces of information were found to be missing entirely from the municipal GIS dataset:

- The actual use/function of each building (e.g., residential, educational, commercial, mixed-use), as opposed to the generic land use classification available; and
- The construction year (or construction period) of each building, which is one of the most influential parameters in determining the thermal characteristics of the building envelope.

These two gaps were particularly significant for the purposes of this project. The intended outcome of this phase of work was to build a complete, building-by-building dataset containing all the information required to conduct an energy analysis at the individual building level. Construction year is a fundamental input because it allows the thermal transmittance (U-values) of walls, roofs, and floors to be estimated according to the typical construction techniques and regulatory standards in force during that period, information that cannot be derived from geometry alone. Similarly, knowing the actual use of each building is indispensable, since energy demands profiles, internal gains, occupancy patterns, and operational schedules differ

substantially between residential, educational, commercial, or public building types, and these differences directly affect the accuracy of any energy simulation or benchmarking exercise.

For this reason, the municipal GIS/TDB dataset extracted from Geoportale Torino was treated as the geometric and spatial backbone of the building database being constructed, rather than as a complete dataset in itself. It provided the essential spatial identity of each building (position, footprint, height, and elevation references) and a unique building ID that would later serve as



(a) (b)

Figure 3.10 (a) QGIS File Created by TDB shp; (b) Attribute Table of TDB Parameters per Each Building

the key for integrating additional external data sources, specifically aimed at filling the construction year and building use gaps, into a single, unified building-level database suitable for energy performance analysis.

3.6.2. Census Data

Following the identification of the two major information gaps left by the municipal GIS dataset, building use and construction year, the next step of the data preparation process focused on finding a reliable external source capable of filling these gaps. This search led to the adoption of ISTAT data, the official statistical dataset published by the Italian National Institute of Statistics (Istituto Nazionale di Statistica). ISTAT is the public body responsible for conducting the national population and housing census in Italy, and it periodically releases detailed statistical information organized at the scale of census sections (sezioni di censimento), which are small, homogeneous territorial units used as the standard spatial unit for aggregating demographic, social, and building-related statistics across the country.

For this research, the most recent census dataset available for the Piemonte region, referring to the 2021 census, was downloaded. This dataset contains a wide range of statistical variables at the census-section scale, from which the following attributes were extracted as relevant to the objectives of this study:

1. Land use, providing further confirmation and refinement of the functional classification of the built environment;
2. Resident population, useful for characterizing occupancy levels within the study area;
3. Number of families, relevant for estimating the number of independent households per building;
4. Total dwellings, providing a measure of residential density and housing stock composition;
5. Residential buildings, indicating the share of buildings within each census section devoted to residential use.

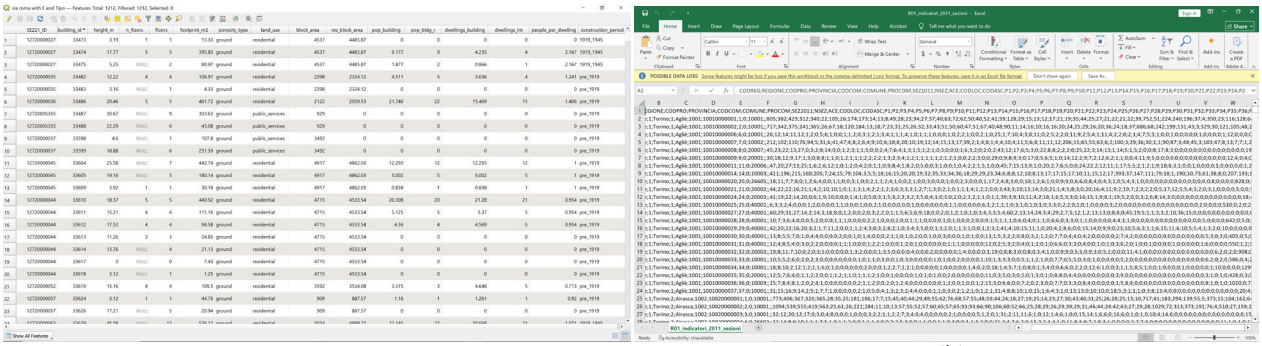
Although the 2021 census dataset provided valuable additional information, it still did not include one of the key parameters this study required: the construction year of buildings. To resolve this remaining gap, an earlier release of the census data was investigated, and it was found that the 2011 census sections (sezioni di censimento 2011) included a specific variable reporting the construction period of buildings, aggregated at the census-section scale. This made the 2011 dataset a necessary complement to the 2021 one, despite the difference in reference year, since it was the only available source providing this information at a level of spatial detail compatible with the rest of the study.

A further complication arose from the format in which these datasets were distributed: the 2021 census data was available both as a shapefile (SHP) and as a CSV table, while the 2011 dataset was available only in CSV format, without an associated geometry. To reconcile these different files, the census section identification code (sezioni ID) was used as the common key, since it was consistent across all the ISTAT datasets involved. Working in QGIS, the 2011 CSV table was therefore joined to the 2021 shapefile geometry through this shared identifier, allowing the construction period attribute to be linked to the correct census-section polygons and, consequently, to be positioned in space.

Once the ISTAT data, spanning both census years, had been consolidated into a single georeferenced layer, this layer was integrated with the building-scale dataset previously obtained from the municipal TDB (see Section 3.7.1). This integration was carried out through a spatial intersection in QGIS, overlaying the building footprints from the TDB with the census-section polygons from the ISTAT layer, so that each building could inherit the corresponding census-section attributes based on its geographic location.

At the end of this process, the resulting dataset finally contained all the parameters originally sought for the energy analysis: geometric and locational data from the TDB, together with land use, population, household, dwelling, and construction period information from the ISTAT census data. However, this integration also introduced an important limitation that had to be acknowledged and addressed in the subsequent phase of the work: while the TDB data was available at the individual building scale, the ISTAT census data was only available at the

census-section (block) scale. As a result, all buildings falling within the same census section were assigned identical values for population, dwellings, families, and construction period,



(a) (b)

Figure 3.11 (a) Attribute Table of Joined ISTAT and TDB Parameters Data per Building; (b) ISTAT 2011 CSV File of Piedmont

even though in reality these characteristics may vary from one building to another within the same section. This scale mismatch represented a methodological constraint of the dataset at this stage, and it required further refinement in the following steps of the data preparation workflow in order to disaggregate the block-level information down to the individual building level.

3.6.3. Heritage Data

Given that the case study area is located within the historic urban fabric of Turin, an additional data requirement emerged: the heritage protection status of each building, since this information directly influences the range of retrofit interventions that can realistically be proposed for the historic building stock. Buildings subject to strict architectural or historical protection constraints cannot be treated in the same way as ordinary buildings when defining an energy retrofit strategy, as regulatory limitations may restrict or entirely prevent interventions on the building envelope, such as facade insulation or window replacement. For this reason, it was necessary to research and identify a data source capable of describing the heritage classification of the buildings within the study area.

The investigation of this topic led to the identification of the ZUCS classification (Zone Urbanistiche di Conservazione e Salvaguardia), the municipal reference used by the City of Turin to regulate interventions within the historic urban tissue, in relation to the city's Piano Regolatore Generale (PRG). Within this framework, buildings are assigned to different protection categories according to their architectural and historical value, ranging from buildings of considerable prestige and historical interest, for which interventions are tightly constrained, to buildings that are simply part of the historic tissue without additional individual protection, for which more flexibility is allowed in terms of intervention.

While the corresponding official WFS services did not provide open bulk access to this data, a ZUCS building-level shapefile (edifici_della_zucs.shp) covering the relevant classification

categories was obtained and made available for the study area. This shapefile was inspected and found to contain, for each mapped building polygon, a heritage classification field indicating the protection category assigned by the municipality, expressed through a numeric group code and an associated descriptive label.

To integrate this heritage information into the building-level dataset already developed from the TDB and ISTAT sources, a spatial join was performed between the building footprints of the study area and the ZUCS polygons, based on geometric overlap rather than on a shared identifier, since the ZUCS shapefile did not use the same building ID system as the municipal TDB. For buildings intersecting more than one ZUCS polygon, the classification associated with the largest area of overlap was retained, in order to assign each building a single, representative heritage category rather than an ambiguous or duplicated one. The heritage classification obtained through this process was then simplified into a small number of protection tiers, better suited to guiding retrofit-strategy decisions later in the study, while remaining traceable back to the original municipal classification categories.

The outcome of this process was a CSV table listing, for every building within the study area, its corresponding heritage classification, using the same building ID adopted throughout the rest of the dataset as the join parameter. This structure allows the heritage information to be attached to the building-level database in exactly the same way as the other data sources described in the previous sections, ensuring that, at a later stage, the heritage protection status of each building can be directly linked to its energy performance results and used as a criterion for defining feasible and context-appropriate retrofit strategies.

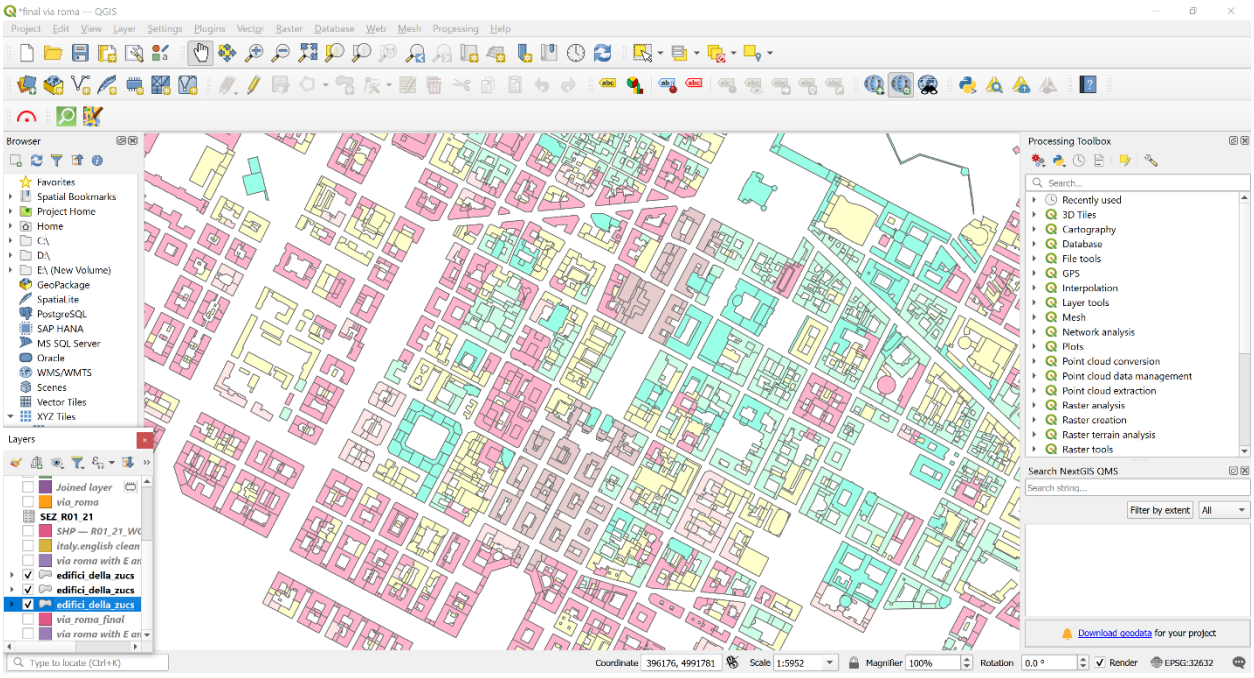


Figure 3.12 QGIS View of Via Roma, Colour Coded by Heritage Classification

3.6.5. TABULA Database

Beyond the geometric, census, and heritage information collected in the previous steps, the objective of this research required each building to eventually be associated with a set of energy-relevant parameters — thermal transmittance values, envelope construction typologies, and typical heat supply systems — that could not be derived directly from any of the datasets described so far. To obtain this information without having to survey or model every single building in detail, the study relies on the TABULA project (Typology Approach for Building Stock Energy Assessment), a European initiative that developed a harmonized method for classifying national residential building stocks into a limited number of representative building types, each associated with a full set of pre-calculated energy performance parameters. Because TABULA already provides these parameters for a structured set of Italian building archetypes, the purpose of this data collection stage was not to generate new energy data, but to gather the information necessary to correctly classify each building of the study area within the appropriate TABULA category, so that its corresponding envelope and system parameters could later be retrieved and applied in the energy assessment phase of the thesis.

TABULA defines a building typology as a classification of parameters commonly found in buildings, with particular emphasis on those parameters that are relevant to energy performance. According to the TABULA methodology, three main criteria are used to classify buildings within a national context:

- Location, related to the climatic area in which the building is situated. Where a country presents significant climatic variation, separate typologies are developed for each climatic zone rather than for the country as a whole;
- Construction period, related to the constructive principles, materials, and regulatory context in force at the time the building was built, since these directly determine the thermal performance of the envelope;
- Building size and shape, distinguishing buildings according to their volumetric and typological characteristics.

These two classification axes, construction period and building size, are combined into what TABULA calls the Building Typology Matrix, a grid in which each row corresponds to a construction-period class ("Building Age Class") and each column corresponds to a size category ("Building Size Class"). Each cell of this matrix identifies a single, distinct building type, to which a representative set of geometric, envelope, and system parameters is assigned.

For Italy, three climatic areas were defined on the basis of heating degree-days: the Mediterranean Zone (up to 2,100 HDD), the Middle Climatic Zone (2,100 to 3,000 HDD), and the Alpine Zone (more than 3,000 HDD). The Italian Building Typology Matrix was developed specifically for the Middle Climatic Zone, which represents the large majority of

Italian municipalities and is the zone within which the city of Turin, and consequently the case study area of this thesis, falls.

Within this matrix, the Italian building stock is classified along eight Building Age Classes, each reflecting a distinct period of construction practice and, from Class VI onward, a distinct phase of national energy regulation:

Class I (up to 1900), Class II (1901–1920), Class III (1921–1945), Class IV (1946–1960), Class V (1961–1975), Class VI (1976–1990), Class VII (1991–2005), Class VIII (after 2005).

In parallel, four Building Size Classes are defined, based on building geometry, number of apartments, and number of floors:

- Single-family house: a detached or semi-detached single dwelling of one or two floors;
- Terraced house: a single dwelling of one or two floors, attached to neighbouring dwellings;
- Multi-family house: a small building with a limited number of apartments (up to roughly 15 apartments over 2–5 floors, or 16–20 apartments over 2–4 floors);
- Apartment block: a larger building with a higher number of apartments.

Each cell of the resulting matrix, combining one age class and one size class, is populated with a reference building type derived either from statistically representative real buildings, where sufficiently detailed data was available (particularly for multi-family houses and apartment blocks up to Class VII), or from statistically constructed "archetypes", synthetic average buildings representing the typical characteristics of a given category, where individual representative buildings could not be identified, based on the analysis of Energy Performance Certificate databases for the Piedmont region.

The relevance of this classification framework for the present study lies precisely in the fact that, once a building can be correctly assigned to one cell of the Italian TABULA matrix, all the corresponding energy-relevant parameters associated with that building type, typical wall, roof, and window constructions and their thermal transmittance values, as well as typical heat generation systems, become available for use in the subsequent energy assessment. This is the reason why, at this stage of the data collection process, particular attention was paid to gathering exactly the two parameters that the TABULA classification requires as inputs: the construction period of each building, obtained from the ISTAT census data described in Section 3.6.2, and the building size/typology, derivable from the geometric attributes already collected from the municipal TDB (footprint, height, and number of floors) described in Section 3.6.1. Only by ensuring that both of these parameters were available at the building level was it possible to proceed, later in the workflow, to systematically map each building of the Via Roma study area onto its corresponding TABULA building type, and thereby retrieve the envelope and system data needed to carry out the building energy performance assessment.

3.7 Data Processing

Once the raw datasets described in the previous section had been collected and spatially joined into a single building-level layer, the resulting database was still far from ready to be used for GIS to BIM workflow. Because the data originated from four independent sources, each with its own encoding, naming conventions, spatial scale, and level of completeness, the combined dataset contained inconsistent attribute names, missing or conflicting values, and information recorded at different spatial resolutions. This section describes the processing stage in which the raw, merged dataset was cleaned, standardized, and transformed into a coherent, building-by-building database ready for simulation.

3.7.1. Attribute Harmonization

Following the collection and spatial integration of the municipal GIS, census, and heritage datasets described in Section 3.6, the resulting building layer contained a number of attributes inherited from different sources, each retaining its own naming convention and level of spatial detail. Before any classification or energy-related processing could be carried out, it was therefore necessary to consolidate these attributes into a single, unified GIS layer, with one clean and clearly defined attribute table containing exactly the parameters required for the subsequent steps of the analysis.

This harmonization process involved reviewing the fields carried over from the TDB and ISTAT census layers, removing redundant or unused columns, renaming the retained fields consistently, and documenting the meaning of each one, so that the final dataset could be read and used unambiguously in the following stages of the work. The attributes retained in the harmonized layer, and their definitions, are as follows:

- Building ID – unique identifier of each building, inherited from the municipal TDB and used throughout the workflow as the key linking this GIS layer to any external table;
- Sezioni ID – the identifier of the census section (sezione di censimento) each building falls within, inherited from the ISTAT layer and kept as a reference to trace back which block-level census data was assigned to each building;
- Footprint – the 2D building outline, from which plan area, perimeter, and heat-transfer surfaces are derived;
- Height – vertical extent of the building, used together with the footprint to estimate building volume and envelope area;
- Number of floors – number of storeys of each building, used to relate height to floor-to-floor dimensions and to support the building-size classification required by TABULA;
- Portico presence – attribute indicating whether the building includes ground-floor porticoes, relevant for correctly identifying exposed versus sheltered envelope surfaces;

- Land use – the function associated with the building (e.g., residential, commercial, mixed-use), used to characterize occupancy and energy demand profiles;
- Construction period – the construction year class of the building, required as one of the two key inputs for the TABULA building classification.

A specific issue had to be resolved during this harmonization step, related to the two attributes that were only available from ISTAT at the census-section (block) scale rather than at the individual building scale: land use and construction period. Since each census section could, in principle, contain more than one type of land use or more than one construction period among its buildings, simply assigning the section's raw values to every building risked introducing inconsistencies where a section contained mixed information. To resolve this, for each census section, the most frequently occurring value, i.e., the value characterizing the majority of buildings within that block, was identified separately for land use and for construction period, and this dominant, representative value was then assigned uniformly to all the buildings belonging to that census section. This majority-based approach ensured that, despite the scale mismatch between the building-level geometry and the block-level census data, every building in the harmonized layer was assigned a single, coherent value for both land use and construction period, consistent with the general character of the block it belongs to, while avoiding contradictory or fragmented values within the same building record. All other attributes in the layer, being already available directly at the building scale from the TDB, did not require this adjustment.

At the end of this process, the outcome was a single QGIS layer containing one clean, well-documented attribute table, in which every building in the Via Roma study area was described by exactly the set of parameters listed above, ready to be used as the input for next steps described in the following sections.

3.7.2. Parameters Estimation

Once the attribute table had been harmonized and reduced to a clean, consistent set of building-level parameters (see Section 3.7.1), the next step of the data processing workflow focused on enriching this dataset with a series of derived parameters that were not directly available from any of the original sources, but could be calculated from the geometric and attribute information already collected. These calculations were carried out directly within the QGIS attribute table, using field-calculator expressions applied to the existing footprint, height, and floor attributes of each building, resulting in a substantially strengthened dataset in which every building of the Via Roma study area is described by a more complete and internally consistent set of geometric and demographic parameters.

The first group of parameters added at this stage concerns the geometric characterization of each building, required as a basis for the subsequent envelope and energy calculations. Specifically, the following quantities were computed for every building:

- Perimeter – calculated directly from the building footprint geometry, representing the total length of the building's external boundary at ground level;
- Envelope area – estimated by combining the building perimeter with its height, in order to approximate the total exposed vertical surface of the building envelope, in addition to the roof and ground floor surfaces derived from the footprint;
- Volume – calculated by multiplying the building footprint area by its height, providing the gross building volume used as a basis for later energy demand calculations;
- Block area – calculated for each census section/block as the sum of the footprint areas of all the buildings falling within it, providing the spatial denominator later used to disaggregate block-level census data down to the individual building scale.

A second issue addressed at this stage concerned the buildings for which the number of floors was missing or incomplete in the original municipal dataset (see Section 3.6.1). Since this parameter is required both for the TABULA building-size classification and for cross-checking building geometry, a simple estimation method was applied to fill these gaps: for every building lacking a reliable floor count, the number of floors was estimated by dividing the building height by an assumed average storey height of 3.5 meters, a value considered representative of typical floor-to-floor heights in the historic and early-to-mid-twentieth-century residential building stock of the study area. The result of this division was rounded to the nearest whole number of floors, allowing a floor count to be estimated consistently for every building in the dataset, including those originally missing this attribute.

Finally, since the demographic attributes obtained from the ISTAT census, resident population and number of dwellings, were only available at the census-section (block) scale, a proportional disaggregation method was applied in order to distribute these block-level totals down to the individual building scale. For each building, its share of the total block area was calculated as the ratio between its own footprint area and the total block area computed in the previous step. This ratio was then used as a weighting factor to redistribute the block's total resident population and total number of dwellings proportionally across all the buildings belonging to that block, so that larger buildings, occupying a greater share of the block's footprint, were assigned proportionally larger shares of the block's population and dwellings, while smaller buildings received correspondingly smaller shares. This area-weighted disaggregation provided a more realistic, building-specific estimate of population and dwelling counts than would have been obtained by simply repeating the same block-level value for every building, as had been the case immediately after the initial spatial join described in Section 3.6.2.

As a result of these calculations, the dataset was substantially strengthened: each building in the study area is now described not only by its original geometric and classification attributes, but also by a consistent set of derived geometric parameters (perimeter, envelope area, volume, block area), a complete floor count, and building-specific estimates of resident population and dwellings. This enriched, building-by-building dataset provided the necessary foundation for the subsequent building classification and envelope estimation steps of the data processing workflow.

3.7.3. Final GIS Database

At the end of the attribute harmonization and parameter estimation steps described in the previous sections, the building layer developed in QGIS reached its final form: a single, spatially consistent GIS database in which every building within the Via Roma study area is described by a complete and coherent set of attributes, combining original data from the municipal TDB and the ISTAT census with the derived geometric and demographic parameters calculated in Section 3.7.2. At this stage, the dataset was considered ready to move beyond the GIS environment and to support the next phase of the methodology: the integration between the GIS database and the Building Information Model (BIM) developed in Revit.



Figure 3.13 Schematic View of Data Parameters Organized in GIS Database Level

To enable this transition, the final GIS layer was exported from QGIS in GeoJSON format. This format was chosen because it preserves both the geometry and the full attribute table of each building in a single, lightweight, text-based file, and because it is directly readable through the Dynamo visual programming environment used within Revit. The GeoJSON export therefore functions as the bridge between the GIS domain and the BIM domain: it carries forward, in a structured and machine-readable form, every parameter prepared during the data preparation and data processing stages of the workflow, including building ID, footprint geometry, height, number of floors, land use, construction period, portico presence, and the estimated population, dwellings, perimeter, envelope area, and volume, so that this information can be read directly into Dynamo and used to generate and populate the corresponding building elements in the Revit model.

3.8 Data Integration

Once the final GIS database had been completed and exported in GeoJSON format (see Section 3.7.3), the focus of the methodology shifted from data preparation and processing to the actual integration between the GIS environment and the Building Information Model (BIM). This section describes how the building-level dataset developed in QGIS was brought into Revit through Dynamo, how the geometric and attribute information was used to generate and populate the corresponding building elements in the BIM environment, and how the resulting model was structured to support the subsequent building energy performance assessment. In this sense, Section 3.8 represents the point at which the two parallel domains of the methodology, the geographic, block-scale representation of the urban fabric, and the detailed, object-based representation of individual buildings, are brought together into a single, coherent digital model of the Via Roma study area.

3.8.1. Dynamo as a Bridge

Before arriving at the workflow described in this section, several existing GIS-to-BIM interoperability packages available for Dynamo were tested as potential solutions for importing the GeoJSON dataset into Revit. None of these packages, however, proved capable of reliably reading the structure of the exported file or of correctly translating its geometry and attributes into Revit elements. For this reason, the import step was ultimately built as a custom solution, using a Python script node within Dynamo to read and parse the GeoJSON file directly, bypassing the limitations encountered with the pre-existing packages. In this role, Dynamo does not act simply as a modelling tool, but as the actual bridge that carries the building dataset prepared in GIS across into the BIM environment, translating the GeoJSON file exported at the end of Section 3.7.3 into native Revit geometry.

The Dynamo bridge developed for this purpose begins with a File Path node, pointing to the final GeoJSON file exported from QGIS at the end of the data processing stage (see Section

3.7.3). This file path is passed to a FileSystem.ReadText node, which reads the entire content of the GeoJSON file and outputs it as a single text string. This string is then fed into a Python Script node, where a custom Python script parses the GeoJSON structure, extracting the list of building features contained in the file, together with their geometric coordinates and associated attributes. The output of this script is a structured list, in which each item corresponds to one building, returning for each of them the specific pieces of information needed for the subsequent geometry-generation step, namely the building footprint coordinates and the building height.

At this stage of the workflow, only these two parameters, footprint and height, were used to generate the three-dimensional representation of each building in Revit. The footprint coordinates extracted from the GeoJSON were used to reconstruct the building's ground-floor polygon as a closed curve, while the height value was used to define the extrusion vector applied to that curve, through a Vector.ByCoordinates node, oriented vertically (with the x and y components set to zero and the z component driven by the building height) and combined with the footprint curve in a Curve.ExtrudeAsSolid node. This operation produced a solid representing the raw building volume, without any further architectural detail. The resulting solid was assigned to a Generic Models category and converted into Revit geometry through a DirectShape.By.Geometry node, which generates a non-parametric, direct-shape element in the Revit model for each building processed.

The outcome of this first Dynamo bridge was therefore a raw, purely volumetric 3D model of the Via Roma study area within Revit, in which every building appears as a simple extruded solid corresponding to its actual footprint and height, but without any parametric building information, such as construction period, land use, or envelope typology, yet attached to it. This raw geometric model represented an important intermediate milestone of the GIS-to-BIM integration process, confirming that the building geometry could be correctly and automatically reconstructed in Revit directly from the GeoJSON dataset, before proceeding, in the following steps of the workflow, to enrich these raw DirectShape elements with the full set of parametric attributes prepared during the data preparation and processing stages.

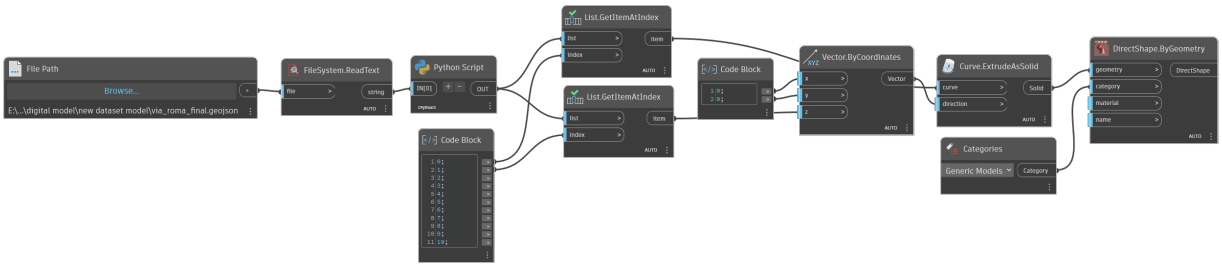


Figure 3.14 Dynamo Script for Importing GeoJSON File Containing Integrated Parameters from GIS Database for Preparing Solid 3D Model

3.8.2. Shared Parameters

Once the raw, non-parametric building geometry had been generated in Revit through the Dynamo bridge described in Section 3.8.1, the next step of the GIS-to-BIM integration process consisted of transferring the full set of building-level attributes prepared in QGIS (see Sections 3.6 and 3.7) into the Revit model itself. For this purpose, each attribute carried by the GeoJSON dataset was defined as a Shared Parameter in Revit, bound to the Generic Models category used for the DirectShape building elements, so that every building in the model could store and display its own set of GIS-derived attributes directly within its Revit element properties.

The parameters defined and populated at this stage can be grouped into two categories, according to their origin. The first group consists of attributes imported directly from the GeoJSON file, without any additional calculation, corresponding to the fields already established during the data preparation and processing stages:

Building ID, Height, Number of floors, Land use, Porosity type, Construction period, Population per building, Dwellings per building, People per building, and Footprint.

The second group consists of a set of morphological parameters, which were not read directly from the GeoJSON file, but calculated within the Dynamo graph itself once the building geometry had been generated in Revit, in order to further characterize the geometric properties of each building. These parameters are:

- Volume: the gross building volume, calculated from the extruded solid geometry of each building;
- Envelope area: the total exposed surface area of the building envelope, calculated from the perimeter, footprint, and height of the extruded solid;
- S/V ratio: the surface-to-volume ratio of the building, obtained by dividing the calculated envelope area by the calculated volume, and used as a key morphological indicator of the building's compactness and expected heat-loss behavior.

Each of these parameters, whether imported directly from the GeoJSON file or calculated within Dynamo, was written into the corresponding Revit element using Element.SetParameterByName nodes, one for each parameter and each building, so that every DirectShape element generated in the earlier step of the workflow was systematically populated with its complete set of attributes. As a result of this process, the raw geometric model obtained in Section 3.8.1 was transformed into a fully parametric, information-rich BIM model: selecting any individual building within the Revit environment and inspecting its Properties panel now displays the complete set of GIS-derived and morphology-derived parameters described above, directly attached to that specific building element. This building-by-building availability of parametric information within Revit constitutes the foundation on which the subsequent building

classification, envelope estimation, and energy performance assessment steps of the methodology is built.

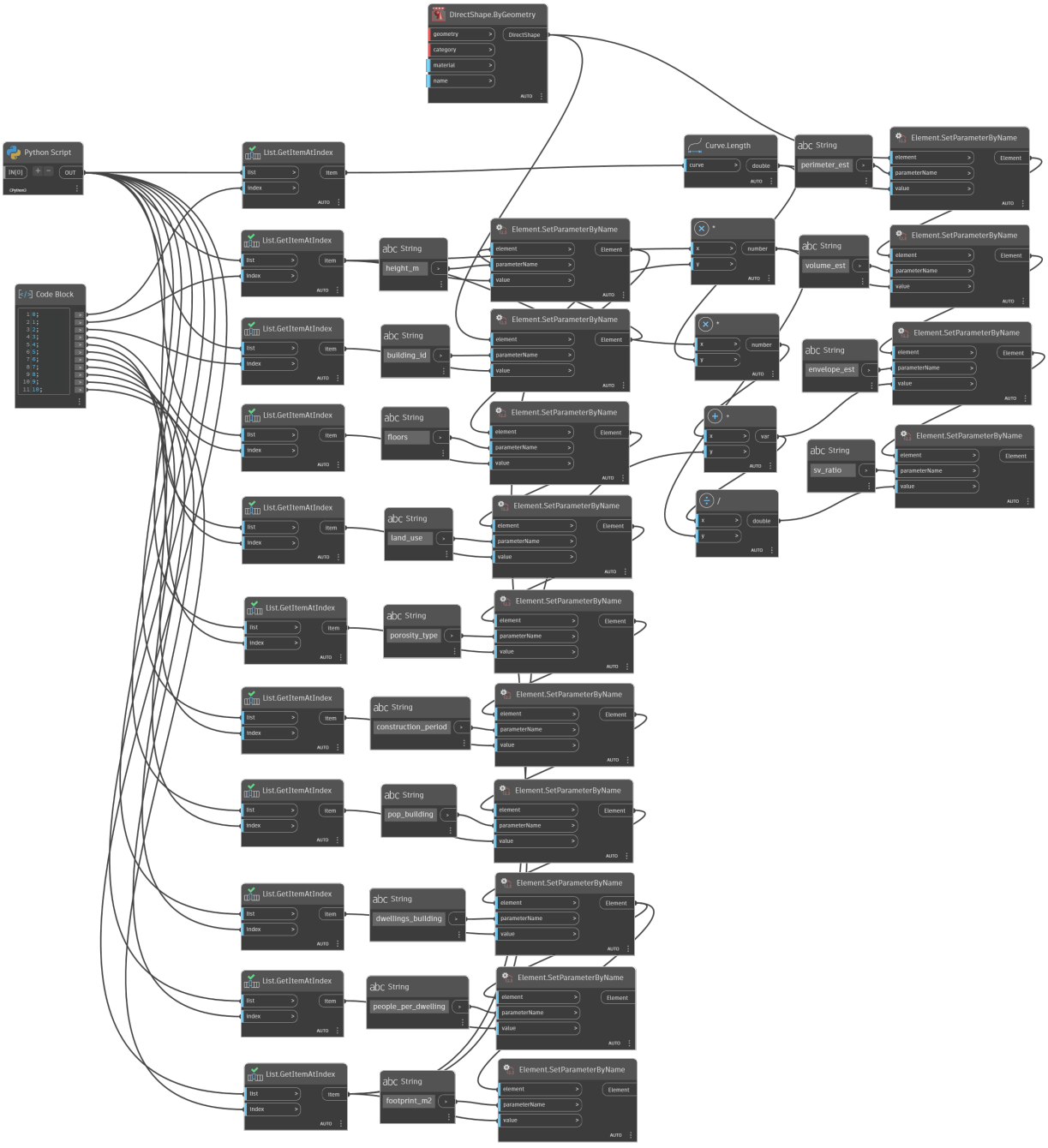


Figure 3.15 Dynamo Script for Enriching Solid 3D Model by Defining All Parameters for Each Building in Revit Workspace

3.8.3. BIM Model Generation

Once the Dynamo bridge had reconstructed the building geometry in Revit (Section 3.8.1) and the Shared Parameters had been defined and populated for every building (Section 3.8.2), the outcome of this stage of the methodology was a complete, building-by-building Building Information Model of the Via Roma study area. Each building of the case study area is represented in Revit as an individual DirectShape element, geometrically consistent with its footprint, height, and volume as derived from the municipal TDB, and carrying the full set of GIS-derived and morphology-derived parameters described in Section 3.8.2 directly attached to it.

Unlike the raw, purely volumetric model obtained at the end of Section 3.8.1, this model is fully parametric: every building element can be individually selected within the Revit environment, and its associated attributes — Building ID, height, number of floors, land use, porosity type, construction period, population, dwellings, people per building, footprint, volume, envelope area, and S/V ratio — are immediately available through the Properties panel, without requiring any additional lookup in the original GIS dataset. In this sense, the BIM model generated at this stage functions as a digital replica of the building stock of the study area, in which geometric representation and semantic information coexist within a single, coherent Revit file.

This building-by-building BIM model represents the completion of the GIS-to-BIM integration process described translating the dataset prepared during the data preparation and processing stages (Sections 3.6–3.7) into a spatial, queryable, and information-rich digital model, ready to support the building classification, envelope estimation, and energy performance assessment steps that follow in the remainder of the methodology.

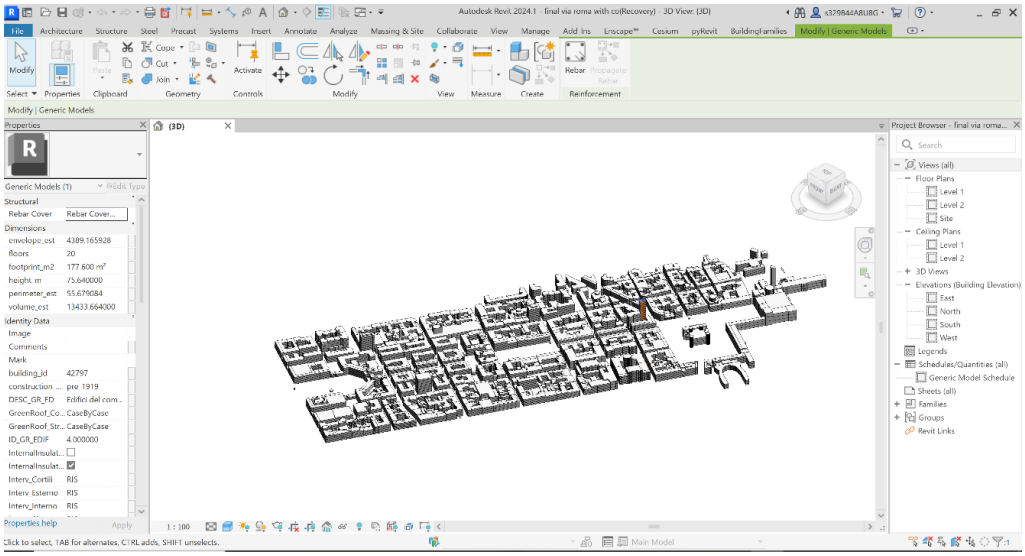


Figure 3.16 Enriched 3D Model in Revit Workspace with Associated Values for Each Building in Properties

3.8.4. Data Validation

Because the Dynamo graph generates and populates every building in the study area within a single execution, rather than building by building, the reliability of the entire GIS-to-BIM workflow described in Sections 3.8.1–3.8.3 depends on geometry and attributes remaining correctly matched throughout the process. This correspondence is preserved automatically: since each building feature in the GeoJSON file stores its geometry and its full set of attributes together, in the same ordered position, both the geometry-generation branch and the attribute-writing branch of the graph read from this list using the same index, so the n-th solid generated in Revit is always populated with the n-th building's attributes. This indexed correspondence, keyed ultimately to each building's unique Building ID, is what allows the workflow to be re-run after any correction to the source GIS dataset without risk of attributes being assigned to the wrong building.

To confirm that this correspondence held true in practice, a validation step was carried out once the Revit model had been fully populated. A sample of buildings, selected by their Building ID, was manually cross-checked: for each sampled building, the parameter values displayed in the Revit Properties panel, height, floors, land use, construction period, population, dwellings, footprint, and the calculated morphology parameters, were compared against the corresponding record in the original GeoJSON and QGIS attribute table. As a further, independent check, the same sampled buildings were also verified against the building information published on Geoportale Torino's own mappe interattive (interactive maps) service, cross-referencing attributes such as height, land use, and construction period directly against the municipality's official building records. This double-checking, against both the processed dataset and the original municipal source, confirmed that the geometry generated in Revit and the attributes attached to it corresponded correctly to the same building, with no shifting or mismatching of values across the model.

In addition to this attribute-level check, the overall completeness of the model was verified by comparing the total number of building elements generated in Revit against the total number of building features present in the final GeoJSON file, confirming that every building of the Via Roma study area had been successfully translated from GIS into the BIM environment. Together, these checks validated the GIS-to-BIM integration pipeline as accurate, in correctly matching geometry to attributes; consistent, against the authoritative municipal source; and complete, successfully carrying the entire building stock of the study area from QGIS into a fully parametric Revit model.

3.9 Urban Energy Assessment

Building on the validated BIM model of the Via Roma study area (Section 3.8), this section describes the methodology used to estimate the heating demand of each building and express it through comparable energy indicators.

The assessment follows the quasi-steady-state approach developed within the TABULA project (Section 3.6.5), balancing heat losses against useful heat gains using standardised parameters linked to each building's construction period and typology, chosen for its consistency with the classification already adopted and its suitability to an urban-scale assessment of many buildings.

Two types of inputs feed into this calculation: parameters adopted directly from TABULA based on each building's archetype (Section 3.9.2), and parameters calculated specifically for the study area. These feed into the heating demand framework and calculation, expressed through the energy indicators.

3.9.1. Heating Demand Framework

The calculation of the heating demand of the buildings of the Via Roma study area is based on the standard reference method developed within the TABULA project (Loga, Diefenbach & Stein, 2012), which is in turn derived from the European standard EN ISO 13790:2008, "Energy performance of buildings, Calculation of energy use for space heating and cooling", later revised and integrated into the ISO 52016-1:2017 series. This standard defines a quasi-steady-state, monthly or seasonal energy balance method for estimating the useful energy need for space heating of a building, based on the balance between the heat lost by the building and the useful share of the heat gained by it over the heating season.

This calculation method, rather than a fully dynamic hourly simulation, was selected for three main reasons, consistent with both the TABULA methodology (Loga, Diefenbach & Stein, 2012) and with comparable urban-scale energy studies carried out for the city of Turin (Mutani & Todeschi, 2020). First, the seasonal method requires a comparatively small number of standardized input parameters, envelope areas, U-values, and a limited set of climatic and usage boundary conditions, which matches well with the type of building-level data that could realistically be prepared for an entire urban district within the GIS-to-BIM database described in Sections 3.6–3.8, rather than the highly detailed geometric and system information a dynamic simulation would require for every building. Second, the method is explicitly designed by TABULA to be applied to whole building typologies and building stocks rather than to single, individually surveyed buildings, making it directly compatible with the archetype-based classification adopted in Section 3.9.2. Third, being based on a small number of transparent, tabulated formulas, the method allows the calculation to be run in a fast, replicable, and easily

verifiable way across the entire building stock of the study area, which would not be practical with a computationally intensive dynamic model.

Within this framework, the total heat transfer of the building over the heating season, Q_{ht}, corresponding to its heating energy demand, is calculated as the sum of its heat transfer coefficients by transmission and by ventilation, multiplied by the heating degree-days of the location:

$$Q_{ht} = (H_{tr} + H_{ve}) \cdot HDD \cdot 24 \cdot 10^{-3}$$

where:

- Q_{ht} – the building's total heat transfer (heating energy demand) over the heating season, in kWh;
- H_{tr} – the building's heat transfer coefficient by transmission, in W/K;
- H_{ve} – the building's heat transfer coefficient by ventilation, in W/K;
- HDD – the heating degree-days of the location, in K·day, a standard climatic indicator that already expresses the accumulated temperature difference between indoor and outdoor conditions over the heating season;
- 24 – the conversion factor from days to hours;
- 10^{-3} – the conversion factor from Wh to kWh, so that Q_{ht} is expressed in kWh.

The heat transfer coefficient by transmission, H_{tr}, accounts for the heat lost through the opaque and transparent components of the building envelope (walls, roof, ground floor, windows, and doors), and is calculated, following EN ISO 13790:2008, as:

$$H_{tr} = \Sigma(U_i \cdot A_i \cdot b_{tr,i}) + \Delta U_{tb} \cdot \Sigma A_i$$

where:

- U_i – the thermal transmittance (U-value) of envelope component i, in $W/(m^2K)$;
- A_i – the area of envelope component i, in m^2
- $b_{tr,i}$ – an adjustment factor that reduces the effective heat loss for components not directly facing the external environment;
- ΔU_{tb} – a thermal bridging correction, in $W/(m^2K)$, applied to the total envelope area, following the standard TABULA reference approach (Loga, Diefenbach & Stein, 2012);
- ΣA_i – the total envelope area of the building, in m^2, obtained by summing the areas of all envelope components.

The heat transfer coefficient by ventilation, H_{ve}, accounts for the heat loss through the air exchanged between the conditioned space and the outdoor environment, and is calculated, following EN ISO 13790:2008, as:

$$H_{ve} = 0.34 \cdot n_{air} \cdot V_c$$

where:

- 0.34 – the volumetric heat capacity of air, in $Wh/(m^3K)$;
- n_{air} – the air change rate of the building, in air changes per hour (h^{-1});
- V_c – the conditioned (heated) volume of the building, in m^3, obtained from the conditioned floor area and the building height.

The specific calculation method applied to the buildings of the Via Roma study area, reflecting the local climate and construction practices of the city of Turin.

3.9.2. Building Archetypes

Applying the heating demand framework described in Section 3.9.1 to every building of the Via Roma study area requires, as an input, the thermal transmittance (U-value) of each building's envelope components, a parameter that could not be measured or surveyed individually for every building within the scope of this research, and that was, in any case, never recorded as such in any of the data sources described in Section 3.6. This is precisely the kind of gap that the use of building archetypes is intended to address. Rather than requiring detailed, building-by-building envelope surveys, an archetype-based approach allows a building to be assigned standard, literature- and statistics-based envelope and system parameters on the basis of a small number of easily obtainable characteristics, in this case, its construction period and its size, making it possible to extend an energy assessment from a handful of surveyed buildings to an entire urban district.

The use of archetypes is further justified by the specific nature of the Via Roma study area. As discussed in Section 3.6.3, a significant share of the buildings of this area fall under the ZUCS heritage classification, and were built within a relatively narrow historical window associated with the major urban reconstruction of the Via Roma complex. Buildings sharing the same construction period and a comparable size are also likely to share comparable structural and constructive principles, wall thickness, materials, floor-to-floor heights, roof types, since they were built according to the technical practices and regulations in force at the time. It is therefore reasonable, for this specific study area, to assume that the buildings of the Via Roma district can be meaningfully grouped into a limited number of representative archetypes, and that the results obtained for a given archetype can be considered representative of every building sharing that same archetype, for the purposes of a district-scale energy assessment.

For this reason, the archetype adopted in this research is not a custom classification developed specifically for the study area, but the reference Building Typology Matrix already defined by the TABULA project for the Italian residential building stock (Loga, Diefenbach & Stein, 2012; see also Section 3.6.5), which classifies buildings according to two parameters: their construction period, grouped into eight Building Age Classes, and their size, grouped into four Building Size Classes (single-family house, terraced house, multi-family house, apartment

block). Each cell of this matrix, combining one age class and one size class, corresponds to a distinct building type, for which TABULA provides standard envelope construction types and reference U-values, derived for the Piedmont region from the statistical analysis of the regional Energy Performance Certificate database (Ballarini et al., 2014).

Assigning each building of the Via Roma study area to its corresponding TABULA building type required determining, for every building, its Building Age Class and its Building Size Class from the attributes already available in the GIS-to-BIM database described in Sections 3.7 and 3.8. This classification was implemented as a Python script embedded in the Dynamo bridge (see Section 3.8.1), which reads, for each building, its construction period and its number of dwellings, and returns the corresponding TABULA archetype code, written back into the Revit model as a Shared Parameter (see Section 3.8.2). The Building Age Class of each building was determined directly from its construction period attribute, already classified, during the census data processing described in Section 3.6.2 and Section 3.7.1, according to the same eight age classes defined by TABULA for Italy.

The Building Size Class of each building, on the other hand, is not an attribute directly available in the database, and had to be derived, since TABULA defines it primarily in terms of the number of dwellings per building rather than in terms of directly measurable geometric quantities. Following the same criterion adopted in the statistical analysis carried out for the Piedmont region within the TABULA project itself (Ballarini et al., 2014), the number of dwellings estimated for each building (see Section 3.7.2) was used to determine its size class according to the following rule:

Size class = SFH if $Nd \leq 2$; MFH if $3 \leq Nd \leq 15$; AB if $Nd \geq 16$

where:

- Nd – the estimated number of dwellings of the building (see Section 3.7.2);
- SFH – Single-Family House, assigned to buildings with one or two dwellings;
- MFH – Multi-Family House, assigned to buildings with between three and fifteen dwellings;
- AB – Apartment Block, assigned to buildings with sixteen or more dwellings.

The Terraced House size class, also defined by TABULA, was not adopted in this classification, consistently with the same simplification applied by Ballarini et al. (2014) to the Piedmont regional building stock, since no reliable statistical criterion was available to distinguish terraced houses from single-family houses on the basis of dwelling count alone, and since this building type is, in any case, not representative of the dense, multi-storey urban fabric of the Via Roma study area.

Once both the Building Age Class and the Building Size Class had been determined for a given building, the two were combined by the Python script to identify the corresponding cell of the Italian TABULA Building Typology Matrix, and the resulting archetype code was written to the building's Shared Parameters in Revit. Through this archetype code, each building of the Via Roma study area became associated with a complete set of standard envelope construction types and reference U-values, which are described in detail, together with the actual, building-specific values calculated from them, in Section 3.9.3.

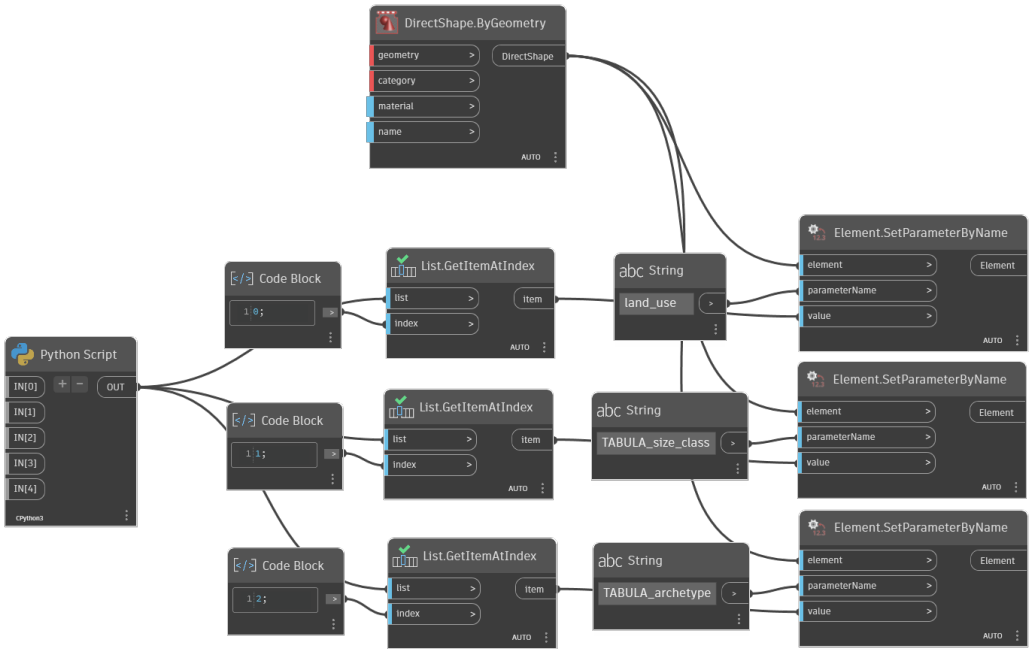


Figure 3.17 Dynamo script for creating Tabula archetype per each building

3.9.3. Envelope Parameter Derivation

Once every building of the Via Roma study area had been assigned to its corresponding TABULA archetype (Section 3.9.2), the two remaining inputs required to apply the heating demand framework of Section 3.9.1 could be derived: the thermal transmittance (U-value) of each envelope component, and the exposed envelope area through which each building loses heat. This section describes how each of these two parameters was obtained.

The U-values of the roof, external walls, ground floor, and windows of each building were not measured or surveyed individually, but assigned from the standard reference values already established by TABULA for the Italian residential building stock, specifically for the Piedmont region, on the basis of the statistical analysis of the regional Energy Performance Certificate database (Ballarini, Corgnati & Corrado, 2014). These reference values, tabulated for each combination of Building Age Class and Building Size Class of the Italian TABULA matrix (see Section 3.9.2), express the typical thermal transmittance associated with the construction techniques and materials in use during a given period, differentiated by envelope component:

Ui = U_TABULA (component_i, age_class, size_class)

where:

- Ui – the thermal transmittance assigned to envelope component i (roof, wall, floor, or window) of the building, in W/(m²K);
- U_TABULA – the lookup of the standard TABULA reference U-value for the given envelope component, Building Age Class, and Building Size Class, as tabulated for the Piedmont region by Ballarini, Corgnati & Corrado (2014).

This assignment was implemented as part of the Python script embedded in the Dynamo bridge (Section 3.8.1): once a building's age class and size class had been determined, the script retrieved the corresponding wall, roof, floor, and window U-values from the TABULA reference table, and wrote each of them into the building's Shared Parameters in Revit (Section 3.8.2), so that every building of the study area carries its own set of archetype-derived U-values, ready to be used in the transmission heat transfer calculation.

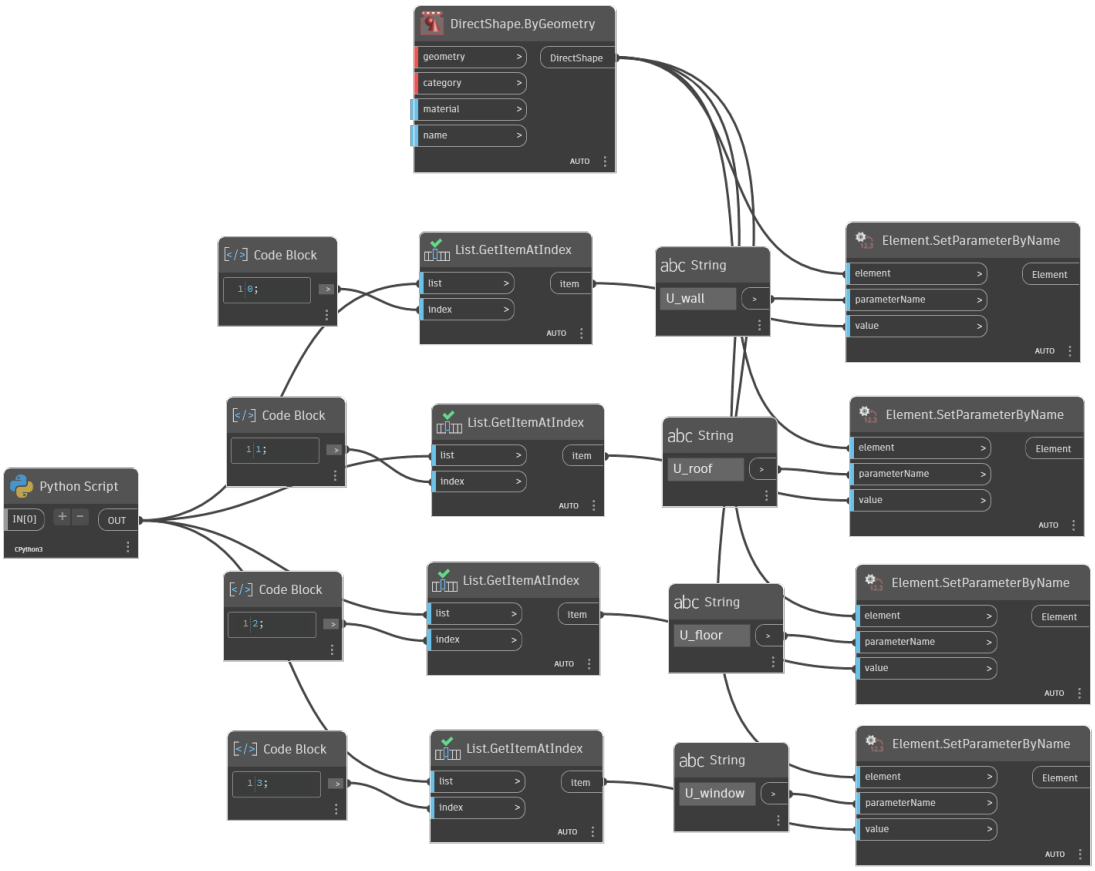


Figure 3.18 Dynamo script for associating U value per each building

The second parameter required by the heating demand framework is the exposed envelope area of each building — that is, the actual surface area of roof, wall, floor, and window through which heat is lost to the outside environment. Unlike the U-values, this parameter is building-specific rather than archetype-based, and its calculation required a distinct step in the workflow, which was carried out not in Revit but back in the GIS environment. This decision reflects a specific, practical consideration: identifying which portions of a building's perimeter are actually exposed to the outside air, as opposed to share with an adjacent building along a party wall, a condition common throughout the dense, continuous urban fabric of the Via Roma study area, is a spatial operation more directly and efficiently carried out in a GIS environment, using the building footprints and their mutual adjacency relationships, than it would be by working directly with the solid geometry already generated in Revit.

For this reason, the exposed envelope area of each building was calculated in QGIS, working on the same building footprint layer used throughout Sections 3.6 and 3.7, by identifying, for every building, the share of its perimeter that borders open space or streets rather than a neighbouring building, and combining this exposed perimeter with the building height to obtain the exposed wall area, in addition to the roof and ground floor areas obtained directly from the footprint. The resulting values were exported from QGIS as a Geojson file, using the building ID already adopted throughout the entire database (see Section 3.6.1) as the join key, in the same way as the heritage classification table described in Section 3.6.3.

This Geojson file was then imported into Dynamo and joined to the enriched Revit model, the same model already populated with the archetype classification and U-values described above, using the building ID as the common key, following the same indexed-correspondence logic already applied throughout the GIS-to-BIM integration (see Section 3.8.3). This step effectively closes a loop within the overall workflow: the exposed envelope area, which could not be efficiently calculated within the BIM environment, is derived instead in GIS and brought back into the same Revit model it originated from, so that every building ends up carrying both its archetype-derived U-values and its GIS-derived exposed envelope area within the same set of Shared Parameters, ready to be combined in the transmission heat transfer calculation.

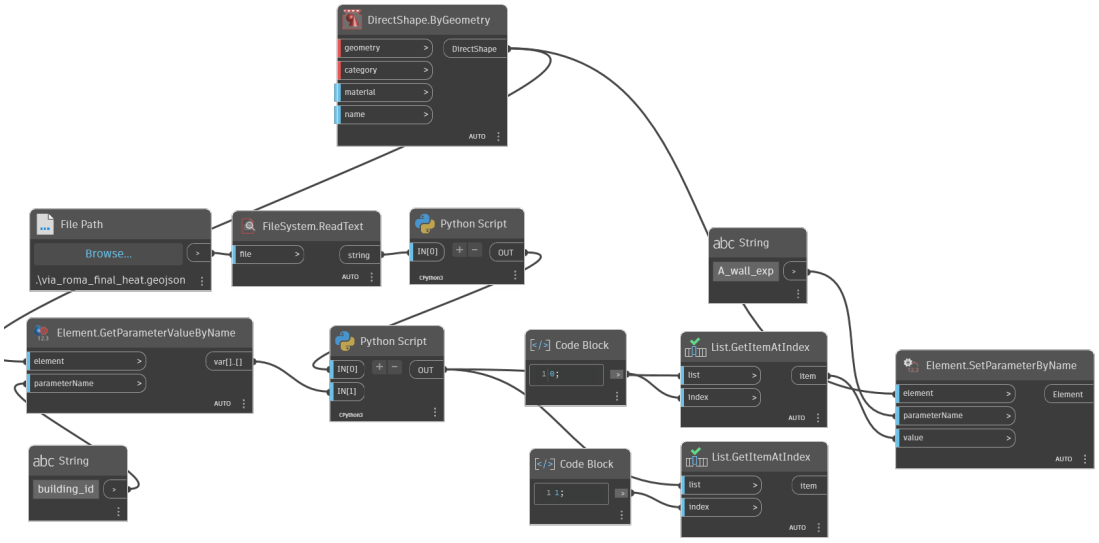


Figure 3.19 Dynamo script for importing envelope exposed area per each building

3.9.4. Calculations and Energy Indicators

Before the heating demand framework of Section 3.9.1 could be applied, one further building-specific parameter had to be derived: the conditioned (referenced) floor area, AC,ref, defined by TABULA (Loga, Diefenbach & Stein, 2012) as the internal, heated floor area enclosed by a building's thermal envelope, and used both to normalise the final heating performance results and to estimate the conditioned volume, Vc, required by the ventilation term Hve (Section 3.9.1). Since AC,ref is not directly available from the GIS database, it was derived from each building's gross floor area (footprint × number of floors, see Section 3.7.2) through a conversion coefficient fn, reducing it to a net, usable floor area on the basis of a typical internal wall thickness associated with the building's construction period, following the approach adopted by Mutani & Todeschi (2020) for the Turin residential building stock:

$$A_{C,ref} = f_n \cdot A_{gross}$$

where fn is the construction-period-dependent conversion coefficient (Mutani & Todeschi, 2020) and A gross is the building's gross floor area, in m^2 (Section 3.7.2). This calculation was carried out through the same Python script used for the archetype classification and U-value assignment (Sections 3.9.2–3.9.3), and the resulting AC,ref was written into each building's Shared Parameters in Revit (Section 3.8.2).

With these building-specific inputs available, the remaining parameters needed to complete the calculation are fixed for the whole study area, depending on Turin's climate and on standard reference assumptions rather than on individual buildings. These were already introduced in Section 3.9.1, and are summarized here as applied in the calculation:

- Heating degree-days: HDD ≈ 2,617 K·day, corresponding to the climatic zone E of Turin (UNI 10349-3:2016; Mutani & Todeschi, 2020);
- External surface heat resistance: Rse = 0.04 m^2K/W (UNI 10349:2016; Mutani & Todeschi, 2020);
- Thermal bridging correction: ΔUtb, applied as a surcharge on the building's total envelope area, following the standard TABULA reference approach (Loga, Diefenbach & Stein, 2012);
- Adjustment factors for non-external components: btr,floor = 0.8 and btr,roof = 0.9 (Mutani & Todeschi, 2020);
- Volumetric heat capacity of air: ρa·ca = 0.34 $Wh/(m^3K)$, the standard reference value (EN ISO 13790:2008);
- Air change rate: nair, a standard value adopted for the residential building stock of Turin (Mutani & Todeschi, 2020);
- Standard room height: hroom, used together with the conditioned floor area to estimate the conditioned volume of each building (Mutani & Todeschi, 2020).

With both sets of parameters available, Htr, Hve, and Qht were calculated for every building through a Python script embedded in the Dynamo bridge.

The resulting values of Htr, Hve, and Qht are written back into the Revit model as further Shared Parameters, following the same procedure already described for the other building-level attributes in Section 3.8.2, so that, for every building of the Via Roma study area, these three quantities can be read directly from its Properties panel in Revit.

In addition to these three heat transfer terms, a fourth, normalized indicator is calculated and attached to each building: the specific heating energy demand, EPh, obtained by dividing the total heat transfer Qht by the building's conditioned floor area (see Section 3.9.1):

EPh = Qht / AC,ref

where:

- EPh – the specific heating energy demand of the building, expressed in $kWh/(m^2·year)$, the standard indicator used to express and compare the heating performance of buildings independently of their size.

Unlike the absolute value of Qht, EPh allows buildings of different sizes and typologies to be directly compared on a common basis, consistently with its widespread use as a reference indicator in building energy studies (Mutani & Todeschi, 2020).

Every building of the Via Roma study area is therefore associated, within its Revit Shared Parameters, with four outputs: Htr, Hve, Qht, and EPh. These constitute the direct output of the

urban energy assessment described in this chapter, further discussed and mapped in Chapter 4.

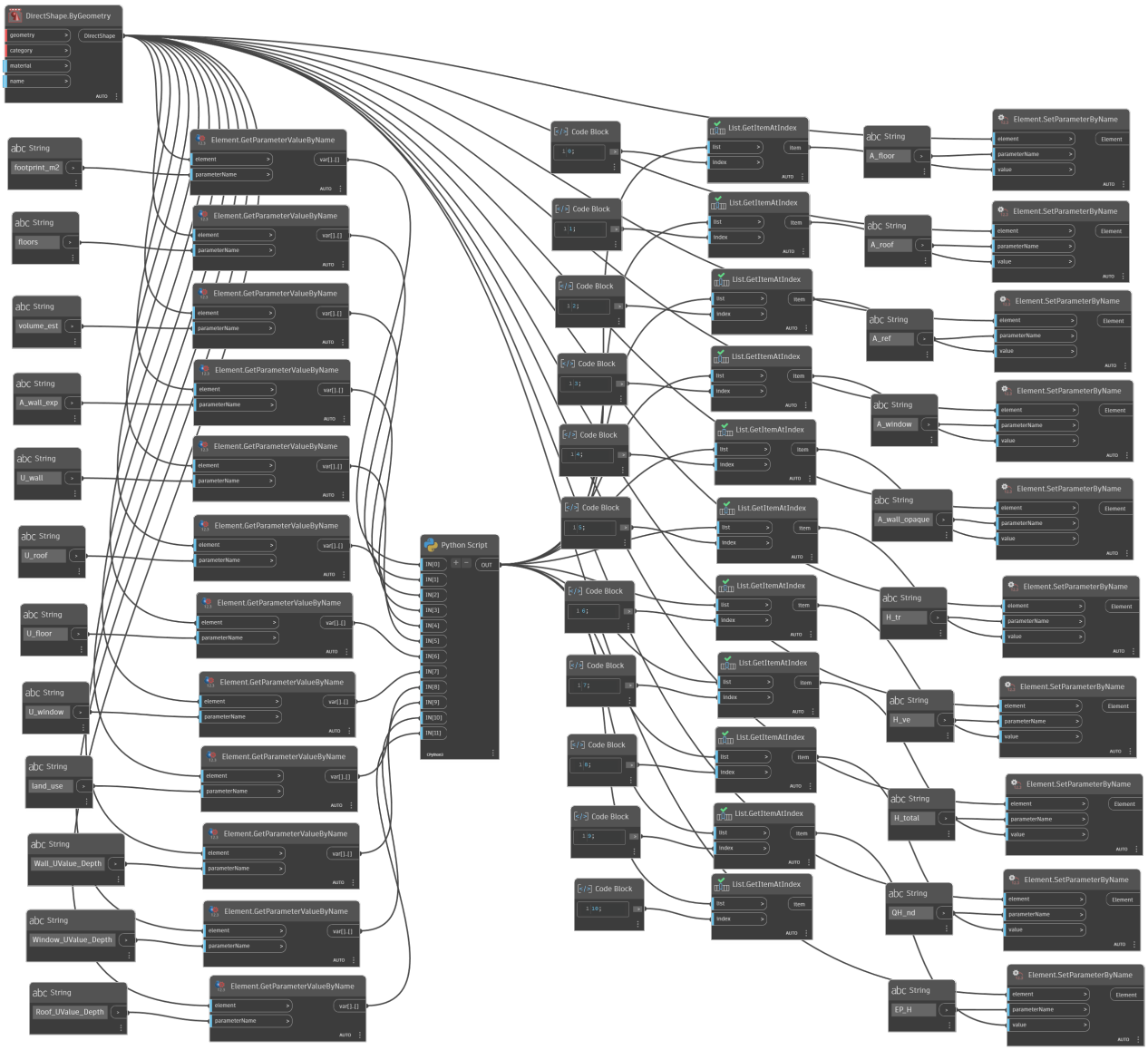


Figure 3.20 Dynamo script for heating demand calculation for Via Roma district

3.10 Heritage-Based Retrofit Assessment

The preceding sections of this chapter developed two parallel strands of the Via Roma database: a heritage classification of every building, derived from its ZUCS group and the associated Article 7 intervention regime (Section 3.4, Section 3.6.3), and a set of energy performance indicators, Htr, Hve, Qht and EPh, calculated for every building under existing conditions (Section 3.9). Taken separately, neither strand is sufficient to support a retrofit decision. The energy indicators identify which buildings perform poorly, but say nothing about whether their envelope can legally be altered; the heritage classification identifies which buildings are constrained, but says nothing about how much energy is actually at stake. This section brings the two strands together, translating the heritage regime established in Section 3.4 into a set of building-specific, measure-specific retrofit constraints, and using those constraints to determine, for every building of the study area, which envelope interventions are feasible, to what standard they can be carried out, and how urgently they should be prioritised. The result is a heritage-aware retrofit assessment in which energy need and legal feasibility are evaluated jointly, rather than one being considered independently of the other.

3.10.1. Heritage Constraints

The heritage classification introduced in Section 3.6.3 associated every building of the study area with a ZUCS protection group, obtained through a spatial join between the building footprints and the ZUCS building-level shapefile. For the purposes of the present section, this classification needed to be developed further: rather than a single descriptive protection tier, each building required an explicit, machine-readable statement of which type of intervention, restauro conservativo (RES), risanamento conservativo (RIS) or ristrutturazione edilizia (RIE), applies to each of its four constituent parts, exterior facing public space, distribution system, courtyards and private fronts, and interior of the building bodies, following the classification already introduced in Section 3.4 (Table 3-1).

The source dataset for this step is the same ZUCS building-level shapefile (edifici_della_zucs.shp) used in Section 3.6.3, obtained from the City of Turin's own open-data catalogue, the Geoportale del Comune di Torino (geocatalogocoto), where it is published as an ESRI Shapefile under a CC-BY 4.0 licence. As already noted in Section 3.6.3, the corresponding WFS service did not provide open bulk access to this data, and the shapefile itself was therefore obtained directly through the catalogue's own download record for the "Edifici della ZUCS" layer, rather than through a live web service. Each polygon of this dataset carries a numeric group code, ID_GR_EDIF, corresponding to the six building groups defined by Article 7 of Turin's N.T.A. (Table 3-1).

Deriving the four part-specific intervention codes for each building required stepping back into QGIS, working on the same spatially joined layer produced in Section 3.6.3. Rather than

retaining only the simplified protection tier used earlier, the full ID_GR_EDIF value was carried forward and used as the key of a lookup table reproducing, group by group, the intervention type assigned to each of the four building parts by Article 7 and its accompanying Allegato A. Where a group's own intervention regime distinguishes between sub-categories not resolvable from the ZUCS attributes alone, the most restrictive intervention type among them was retained for that part, a conservative simplification consistent with the treatment already adopted elsewhere in the data-processing stage of this methodology (Section 3.7). Buildings falling outside the ZUCS boundary, and therefore lacking a matched polygon, were assigned the most restrictive intervention type, RES, across all four parts as a conservative fallback, pending manual verification. The outcome of this step was, for every building of the study area, four new attributes, Interv_Esterno, Interv_SistemaDistributivo, Interv_Cortili and Interv_Interno, each populated with one of the three intervention codes.

As with the heritage classification produced in Section 3.6.3, this enriched table was exported from QGIS as a CSV file, using the same Building ID already adopted throughout the database as the join key. This CSV was then imported into the Dynamo bridge already established for the model in Section 3.8, following the same pattern used for the Shared Parameters populated in Section 3.8.2: a File Path node pointing to the CSV, read through a Data.ImportCSV node, matched to the corresponding building elements by Building ID, and written into the Revit model as four further Shared Parameters, Heritage Group and its four part-specific intervention codes. As a result, selecting any building within the Revit environment now exposes not only the general GIS-, morphology- and energy-derived attributes already available through Sections 3.8 and 3.9, but also the specific heritage constraint governing each of its constituent parts, providing the building-level basis on which the retrofit matrix of Section 3.10.2 is constructed.

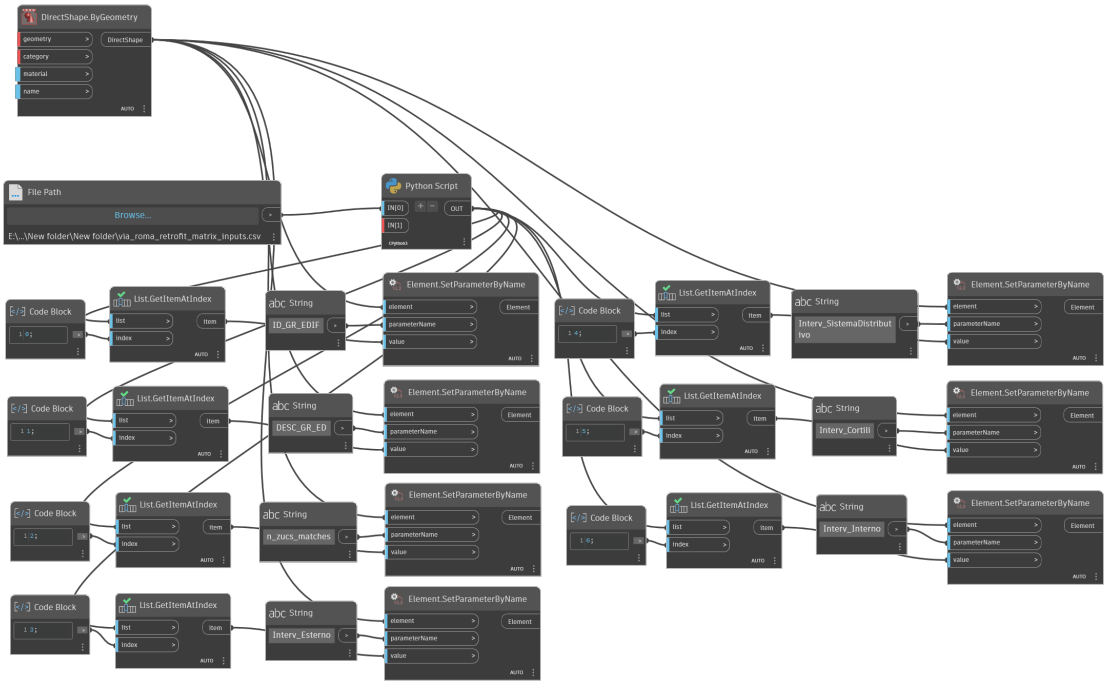


Figure 3.21 *Dynamo Script for Importing Heritage Intervention Parameters and Writing Them as Shared Parameters in Revit*

3.10.2. Envelope Retrofit Matrix

Section 3.10.1 gave every building an intervention code, RES, RIS or RIE, for its street-facing front (Interv_Esterno) and for its other three parts. This code alone does not say what can actually be built, since wall insulation, window replacement and roof insulation are each affected differently by the same code. This section turns the code into a straightforward feasibility answer, per building and per measure, following the logic already set out in Table 3-3 (Section 3.4).

- **Wall insulation**: Insulating a wall on a heritage-protected front can be done in two ways: on the inside face, where nothing about the street-facing appearance changes, or on the outside face, where it can still be compliant provided the façade is rebuilt out to look exactly as it did before, render, mouldings, window-reveal depths and all. Both routes are permitted in principle wherever the front is RIS or RIE, since neither RES-level protection applies; where the front is RES, wall insulation is blocked outright. In this study, the internal route is treated as the default path to feasibility under RIS or RIE, since it avoids any judgement call about whether the rebuilt façade genuinely reads as unchanged, and - because the regulation restricts what the façade may look like, not how thick a layer may be behind it - it is treated as reaching the Advanced refurbishment level with no intermediate cap. External insulation is not excluded, but is flagged as a case-by-case exception under RIS or RIE rather than assumed by default, reflecting that

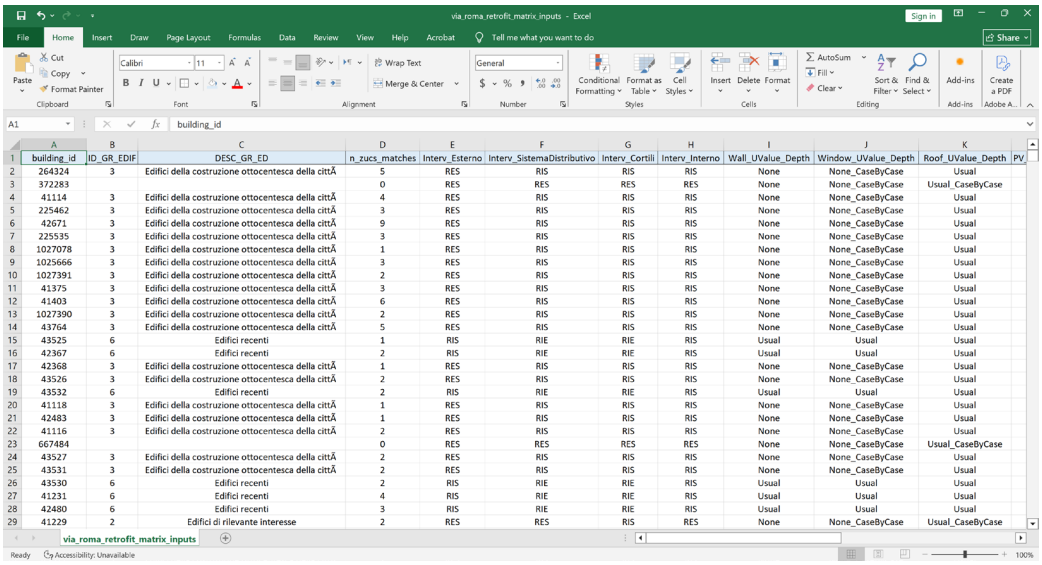
its compliance depends on execution quality rather than being guaranteed by the intervention code alone.

- Window replacement: Windows sit in the same street-facing part, Esterno, and follow the same threshold: blocked at RES, feasible at RIS or RIE. Unlike wall insulation, a window cannot be hidden - replacement is, by definition, visible. Table 3-3 accordingly limits it to units that stay close to the original appearance, or that are installed as part of one coordinated design for the whole front. This measure is therefore capped at the Standard refurbishment level even where feasible, reflecting that visible ambition, not hidden thickness, is what constrains it.

- Roof insulation: Table 3-3 treats roof insulation under the same street-facing part as wall and window, permitting full replacement of the roof covering under RIS provided the roof's height and shape are kept unchanged. Following the same logic already applied to walls, this measure is treated as feasible primarily through insulation added under the existing covering, from the attic side, where it alters nothing visible from the street; this route is treated as reaching the Advanced level wherever the front is RIS or RIE, and blocked at RES. As with wall insulation, replacing the covering material itself in a way that visibly departs from the original is not excluded, but is flagged as a case-by-case exception rather than assumed feasible by default.

Running this logic across the study area produced three feasibility outcomes per building, written into Revit as Shared Parameters, Wall_UValue_Depth, Window_UValue_Depth and Roof_UValue_Depth, using the same Dynamo import procedure set up in Section 3.10.1. Each parameter takes one of two values where feasible, Standard or Advanced, or None where blocked, with a case-by-case flag retained separately where the visible route may still apply.

Combining the three parameters gives each building an overall label: Fully feasible (all three measures reach their respective ceiling), Fully constrained (all three blocked), and Partially feasible (a mix of the two). This label is the envelope retrofit matrix referred to in the section title - a single, building-by-building summary of what can legally be retrofitted, grounded in the heritage constraints of Section 3.10.1 and the intervention logic of Section 3.4.



building_id	ID_GR_EDIF	DESC_GR_ED	n_zucs_matches	Interv_Esterno	Interv_SistemaDistributivo	Interv_Cortili	Interv_Interno	Wall_UValue_Depth	Window_UValue_Depth	Roof_UValue_Depth	PV
264324	3	Edifici della costruzione ottocentesca della cittÃ	5	RES	RIS	RIS	RIS	None	None_CaseByCase	Usual	
372283			0	RES	RES	RES	RES	None	None_CaseByCase	Usual_CaseByCase	
41114	3	Edifici della costruzione ottocentesca della cittÃ	4	RES	RIS	RIS	RIS	None	None_CaseByCase	Usual	
225462	3	Edifici della costruzione ottocentesca della cittÃ	3	RES	RIS	RIS	RIS	None	None_CaseByCase	Usual	
42671	3	Edifici della costruzione ottocentesca della cittÃ	9	RES	RIS	RIS	RIS	None	None_CaseByCase	Usual	
225535	3	Edifici della costruzione ottocentesca della cittÃ	3	RES	RIS	RIS	RIS	None	None_CaseByCase	Usual	
1027078	3	Edifici della costruzione ottocentesca della cittÃ	1	RES	RIS	RIS	RIS	None	None_CaseByCase	Usual	
1025666	3	Edifici della costruzione ottocentesca della cittÃ	3	RES	RIS	RIS	RIS	None	None_CaseByCase	Usual	
1027391	3	Edifici della costruzione ottocentesca della cittÃ	2	RES	RIS	RIS	RIS	None	None_CaseByCase	Usual	
41375	3	Edifici della costruzione ottocentesca della cittÃ	3	RES	RIS	RIS	RIS	None	None_CaseByCase	Usual	
41403	3	Edifici della costruzione ottocentesca della cittÃ	6	RES	RIS	RIS	RIS	None	None_CaseByCase	Usual	
1027390	3	Edifici della costruzione ottocentesca della cittÃ	2	RES	RIS	RIS	RIS	None	None_CaseByCase	Usual	
43764	3	Edifici della costruzione ottocentesca della cittÃ	5	RES	RIS	RIS	RIS	None	None_CaseByCase	Usual	
43525	6	Edifici recenti	1	RIS	RIE	RIE	RIS	Usual	Usual	Usual	
42367	6	Edifici recenti	2	RIS	RIE	RIE	RIS	Usual	Usual	Usual	
42368	3	Edifici della costruzione ottocentesca della cittÃ	1	RES	RIS	RIS	RIS	None	None_CaseByCase	Usual	
43526	3	Edifici della costruzione ottocentesca della cittÃ	2	RES	RIS	RIS	RIS	None	None_CaseByCase	Usual	
43532	6	Edifici recenti	2	RIS	RIE	RIE	RIS	Usual	Usual	Usual	
41118	3	Edifici della costruzione ottocentesca della cittÃ	1	RES	RIS	RIS	RIS	None	None_CaseByCase	Usual	
42483	3	Edifici della costruzione ottocentesca della cittÃ	1	RES	RIS	RIS	RIS	None	None_CaseByCase	Usual	
41116	3	Edifici della costruzione ottocentesca della cittÃ	2	RES	RIS	RIS	RIS	None	None_CaseByCase	Usual	
667484			0	RES	RES	RES	RES	None	None_CaseByCase	Usual_CaseByCase	
43527	3	Edifici della costruzione ottocentesca della cittÃ	2	RES	RIS	RIS	RIS	None	None_CaseByCase	Usual	
43531	3	Edifici della costruzione ottocentesca della cittÃ	2	RES	RIS	RIS	RIS	None	None_CaseByCase	Usual	
43530	6	Edifici recenti	2	RIS	RIE	RIE	RIS	Usual	Usual	Usual	
41231	6	Edifici recenti	4	RIS	RIE	RIE	RIS	Usual	Usual	Usual	
42480	6	Edifici recenti	3	RIS	RIE	RIE	RIS	Usual	Usual	Usual	
41229	2	Edifici di rilevante interesse	2	RES	RES	RIS	RES	None	None_CaseByCase	Usual_CaseByCase	

Figure 3.22 envelope retrofit matrix in CSV file

3.10.3. Envelope Retrofit

Section 3.10.2 established, for every building, whether its wall, window and roof could be retrofitted, and to which of two levels, Standard or Advanced, each was allowed to reach. This section carries that classification one step further, converting it into an actual improved U-value for each envelope component, and into the corresponding reduction in heating demand that this improvement produces.

Before doing so, one further component must be introduced that has not featured in the retrofit matrix so far: the floor. Wall, window and roof were each assessed against one of the four building parts defined by Article 7, exterior facing public space, distribution system, courtyards, or interior, since each of these elements is visible, or partially visible, from one of those vantage points, and is therefore addressed, directly or indirectly, by the heritage regulation. The floor slab occupies none of these positions: it faces neither the street nor the courtyard nor the building interior in any way that heritage protection is concerned with. For this reason, floor insulation was not subjected to the same feasibility test as the other three measures, and was instead treated as available to every building of the study area, regardless of its heritage group, at both the Standard and the Advanced refurbishment level.

The two refurbishment levels themselves are drawn directly from the TABULA project, which was already used in Section 3.9 as the source of each building's existing envelope U-values. In addition to these existing values, TABULA defines two standardised improvement targets for the Italian building stock, referred to as the Standard and Advanced refurbishment packages. Unlike the existing U-values, which vary from one building to another according to its construction period, these two targets are fixed at a national level: the same Standard U-value,

and the same Advanced U-value, apply to every building of a given component, irrespective of when it was built. The Standard package corresponds to the level of envelope improvement expected of ordinary retrofit practice, while the Advanced package corresponds to the considerably more ambitious level associated with regional energy-incentive schemes, and consequently reaches lower, more performant U-values for every component. The specific target values adopted in this study, obtained from the Italian TABULA dataset, are reported in Table 3-4.

Table 3-4 TABULA Standard and Advanced Refurbishment Target U-Values

Envelope Component	Standard (W/m²K)	Advanced (W/m²K)
Wall	0.32	0.24
Window	2.00	1.70
Roof	0.27	0.21
Floor	0.28	0.21

With both the feasibility classification of Section 3.10.2 and the target values of Table 3-4 available, the improved U-value of each building was calculated component by component. For wall, window and roof, floor, the existing U-value was replaced with the corresponding Standard or Advanced target wherever Section 3.10.2 classified that component as feasible at that level, and left unchanged wherever it was classified as None. Because this substitution was carried out independently for each of the four components, a single building may combine, for instance, an improved floor and window with an unretrofitted wall, if that is the specific combination its own heritage classification permits; the resulting set of U-values is therefore particular to that one building, rather than a single improvement applied uniformly across the whole study area.

Once this building-specific set of improved U-values had been established, the heating demand method already applied to the existing condition in Section 3.9.1 was run twice more for every building: once substituting the Standard-level U-values, and once substituting the Advanced-level U-values, while every other input to the calculation, envelope areas, climatic data, and internal gains, was held identical to the existing-condition run, so that any difference in the result could be attributed to the envelope retrofit alone. This produced, for each building, two further values of specific heating energy demand, $EP_{h,Standard}$ and $EP_{h,Advanced}$, alongside the existing value, EP_h, already obtained in Section 3.9. To allow these three values to be compared directly, each retrofit scenario was also expressed as a percentage reduction relative to the existing condition, following Equations:

1) $\Delta EP_{h,Standard}\ (\%) = (EP_h - EP_{h,Standard}) / EP_h \times 100$

2) $\Delta EP_{h,Advanced}\ (\%) = (EP_h - EP_{h,Advanced}) / EP_h \times 100$

A building whose wall, window and roof are all classified as None under Section 3.10.2 still shows a zero reduction in both scenarios, a building with no heritage restriction on any of its four components instead shows the largest reduction the study allows, bounded only by the Advanced targets of Table 3-4. Every other building fall between these two extremes, according to the specific combination of components its own heritage classification permits.

All five resulting indicators, EPh, EPh-Standard, EPh-Advanced, ΔEPh -Standard and ΔEPh-Advanced, were written into the Revit model as further Shared Parameters, following the same Dynamo-based procedure already used throughout Sections 3.8 to 3.10. As a result, every building of the Via Roma study area is now associated, within its own Properties panel, not only with its current energy performance but with the specific, heritage-aware improvement it could realistically achieve under both refurbishment levels.

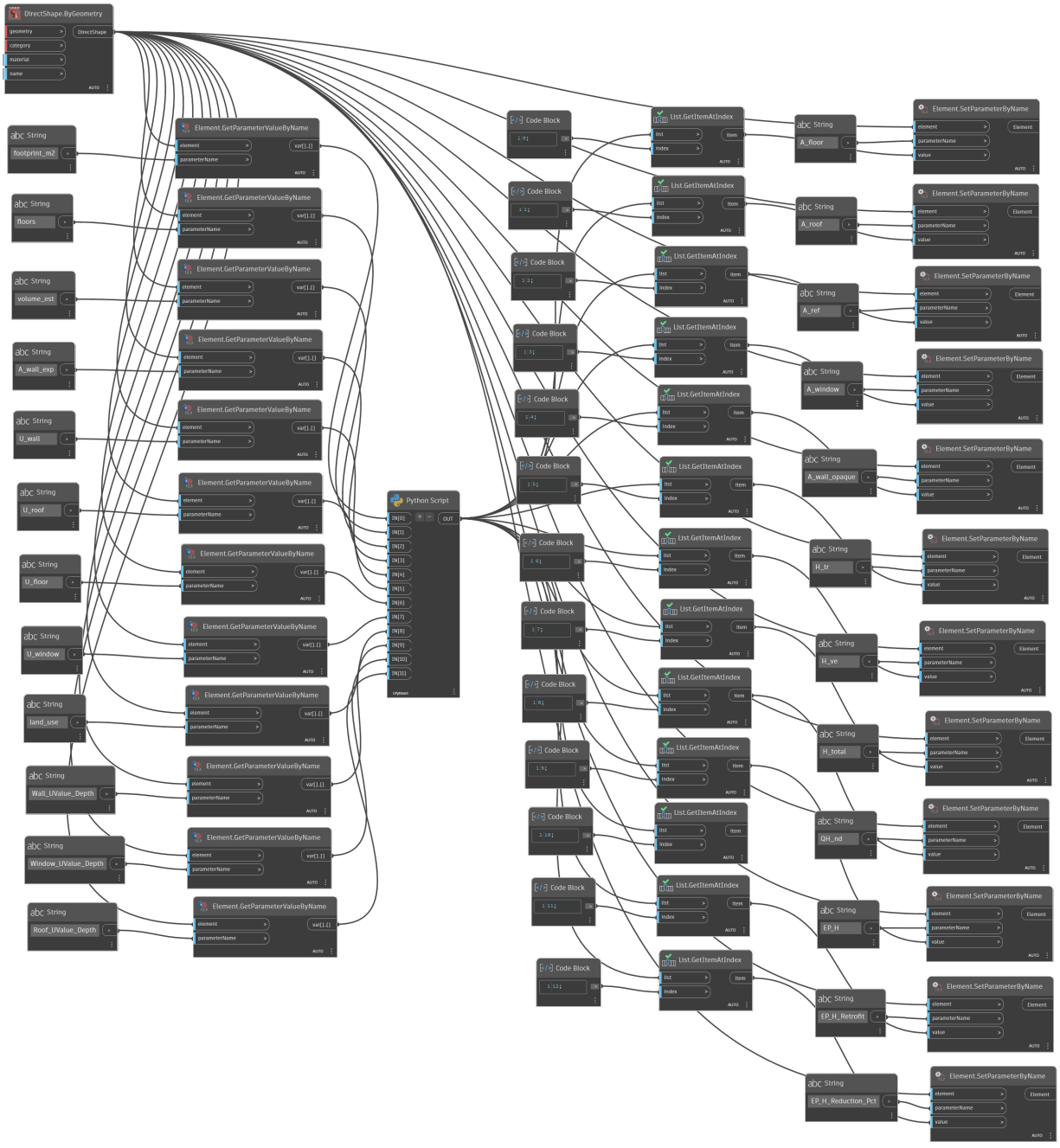


Figure 3.23 Dynamo Script for Calculating Standard and Advanced Retrofit Scenarios

3.10.4. Priority Classes

The final step of the heritage-based retrofit assessment consists of using the results of Sections 3.10.2 and 3.10.3 to divide the buildings of the study area into a small number of priority groups, providing a starting point for a retrofit roadmap: which buildings should be addressed first, which can reasonably wait, and which offer little to be gained from intervention at all. As with the parameters described in Sections 3.10.1 to 3.10.3, this final classification was computed for every one of the 1,212 buildings of the study area and written into the Revit model as a further Shared Parameter, so that each building's priority group is available directly from its Properties panel alongside its heritage classification, its feasibility label, and its existing and retrofitted energy indicators.

As already argued at the start of this section, ranking buildings by existing energy performance alone is not a sound basis for prioritisation, since a considerable share of the worst-performing buildings are also the most heritage-constrained, and can only be improved marginally regardless of intervention. The classification adopted here therefore combines two criteria, rather than relying on either alone: how poorly a building currently performs, and how much of that performance can actually be recovered given its heritage classification.

Each criterion was first reduced to a simple three-level rank. Existing performance was ranked using the same EPh bands already used elsewhere in this study: a rank of 3 for buildings with EPh at or above 200 kWh/m^{2}yr, 2 for buildings between 100 and 200 kWh/m^{2}yr, and 1 for buildings below 100 kWh/m^{2}yr. Feasibility was ranked using the three-way classification already established in Section 3.10.2: a rank of 3 for buildings classified as Fully feasible, 2 for Partially feasible, and 1 for Fully constrained. Each building's two ranks were then added together to give a single combined score. Since each rank runs from 1 to 3, the combined score can range from 2, when both ranks are at their lowest, to 6, when both ranks are at their highest. A score of 2 means the building already performs well and is also fully constrained by heritage rules — the least urgent case. A score of 6 means the opposite: the building performs poorly and faces no heritage restriction at all — the most urgent case for retrofit.

This scale was, in turn, collapsed into three priority groups, to keep the resulting classification easy to read and to map:

- High priority (score 5 or 6) — buildings combining poor or moderate existing performance with a favorable, or fully favorable, feasibility classification: the buildings where retrofit would do mostly good and faces the fewest heritage obstacles, and which should therefore be addressed first.
- Medium priority (score 4) — buildings where either performance or feasibility is only moderate, representing a genuine but less urgent case for intervention.

- Low priority (score 2 or 3) — buildings that are either already performing reasonably well, or are heavily heritage-constrained, or both: buildings where retrofit is either less necessary or, in practice, barely achievable, and which can reasonably be left until later.

Applied to the full study area, this classification distributed the 1,212 buildings of Via Roma into 582 High priority buildings, 347 Medium priority buildings, and 283 Low priority buildings. This three-group split gives the study area a first, defensible answer to the question posed at the beginning of Section 3.10: not simply which buildings perform worst, and not simply which buildings are least constrained, but which buildings offer the most to be gained from a heritage-compatible retrofit, and should therefore come first in any phased retrofit strategy for the district.

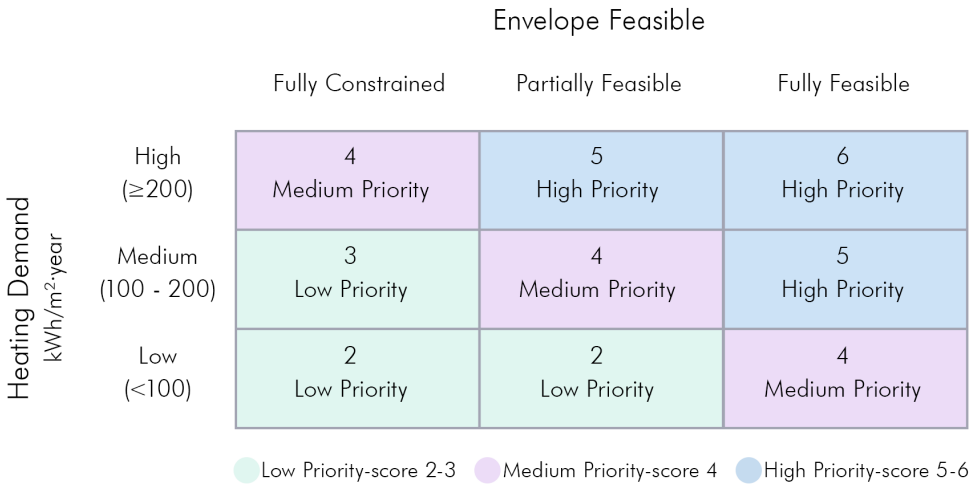


Figure 3.24 priority matrix

3.11 Roof-Based Assessment

The heritage-based retrofit assessment presented in Section 3.10 was, by design, able to proceed without any explicit three-dimensional roof geometry. Wall, window and floor could each be represented as a single U-value attribute per building, retrieved from an archetype table and, where feasible, replaced with a Standard or Advanced target — a calculation that requires knowing a building's envelope area, but not the actual shape of its roof. Up to this point, in other words, every building in the BIM model could carry a complete set of energy and heritage attributes while still being represented, geometrically, as a simple extruded volume with a flat top. Generating an actual, building-specific roof surface was pursued as a separate objective from this energy assessment: an attempt to raise the geometric detail, or Level of Detail (LOD), of the model itself, closer to what a genuine as-built BIM representation of the district would require, rather than a flat placeholder standing in for a roof. This section

documents the sources tried in pursuit of that geometry, why each one fell short, and why, as a result, higher-LOD roof geometry could ultimately be produced for only part of the study area.

- Regione Piemonte Geoportale, 5-metre DSM

The first elevation dataset tried was the Digital Surface Model already available through the Regione Piemonte Geoportale, the same portal used elsewhere in this study for the ZUCS heritage shapefile (Section 3.10.1). This dataset, however, is published at 5-metre resolution. Over a historic urban block such as Via Roma, where individual roof slopes and ridgelines are frequently only a few metres wide, a 5-metre cell is too coarse to register the slope of a roof pitch at all; adjacent cells routinely span the ridge and the eave of the same roof, or bridge two entirely separate buildings, making any building-level slope calculation unreliable from the outset. Nevertheless this file added to Gis data base to examine the possibility of getting roof data and create the model in revit but This source was accordingly set aside as insufficient for the purpose.

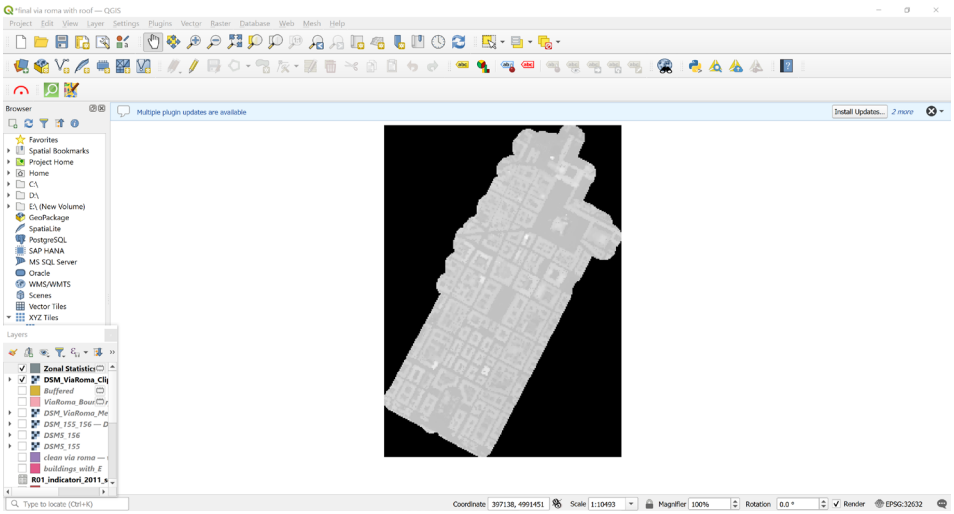


Figure 3.25 5-Metre Resolution DSM Raster (Regione Piemonte Geoportale) Clipped to the Via Roma Study Area

- National 1-metre LiDAR DSM (Geoportale Nazionale / data.europa.eu)

The second dataset tried was a 1-metre resolution DSM published on the national open-data portal (data.europa.eu), sourced from the Geoportale Nazionale of the Italian Ministry of the Environment, and derived from an airborne LiDAR survey carried out under the national Piano Straordinario di Telerilevamento Ambientale. At 1-metre resolution, this dataset is fine enough, in principle, to resolve individual roof pitches. In practice, however, its coverage is incomplete over the study area: the underlying LiDAR survey was flown primarily along river corridors and flood-risk zones rather than as uniform urban coverage, and only a subset of the Via Roma block falls within its acquired extent. Where coverage was present, this dataset was used to

drive the automated roof-generation workflow described below; where it was absent, no roof geometry could be produced.

- Google Earth / Google Maps satellite

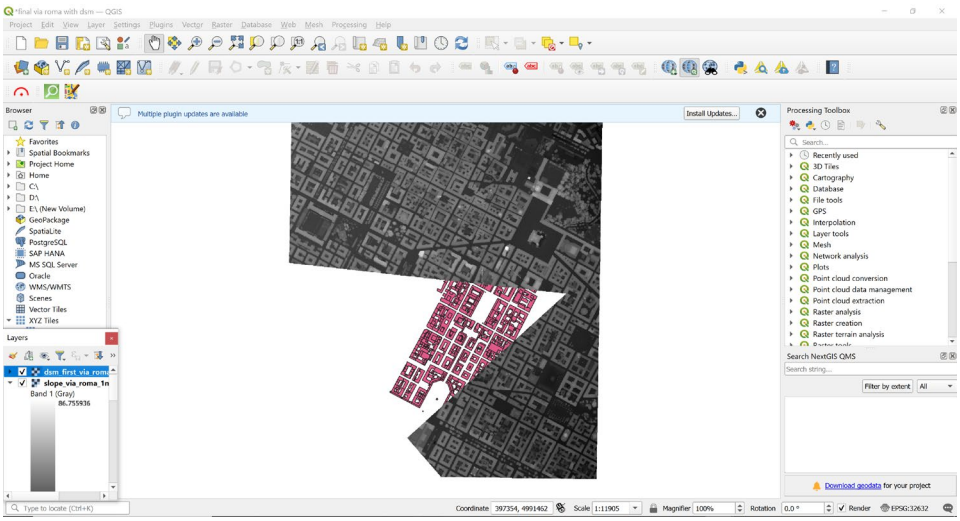


Figure 3.26 1-Metre National LiDAR DSM and Derived Slope Raster (data.europa.eu / Geoportale Nazionale), Overlaid on the Via Roma Study A rea

A third possible source, extracting roof outlines and slope information from Google Earth's satellite and 3D imagery, was considered and deliberately not pursued, on legal rather than technical grounds. Google's own terms of service for these products explicitly prohibit the kind of extraction this would have required: the Google Maps Platform terms state that users may not trace or digitise building outlines from satellite basemap imagery, may not create three-dimensional building models from Google's 45° aerial imagery, and may not build terrain models from elevation values obtained through Google's services, while the Google Earth end-user terms separately prohibit mass-downloading content or using it to construct a new mapping-related dataset. Since the roof-generation workflow of this thesis would have needed to do precisely this, digitise roof outlines and derive slope from imagery to build a new geometric dataset, using Google Earth as a source would have breached these terms. This source was therefore excluded from the workflow entirely, rather than attempted and later discarded.

- OpenStreetMap

As a lower-effort supplementary check, the OpenStreetMap roof:shape tag was queried for the Via Roma extent using the QuickOSM plugin in QGIS, on the possibility that even partial crowd-sourced coverage could reduce reliance on the DSM. This tag was found to be effectively empty for the study area, and provided no usable coverage.

Of the 1,212 buildings of the study area, the 1-metre national DSM provided usable coverage for 501, giving a set of elevation and slope points over each of these building footprints (Figure 3.25). Translating these points into an actual closed roof surface, the geometry-generation step of the Dynamo workflow, did not succeed: the script was able to sample and process the underlying DSM points, but consistently failed to construct a valid roof form from them, regardless of building shape. The result, for every building attempted, was a set of raw elevation points sitting over the model rather than an actual three-dimensional roof volume. Neither Google Earth, excluded on legal grounds, nor OpenStreetMap, exhausted without result, offered a way around this. In total, therefore, no building in the study area ultimately received higher-LOD roof geometry through this workflow; the attempt is documented here as a data-and-tooling limitation encountered at the geometry-generation stage, rather than as a partial success.

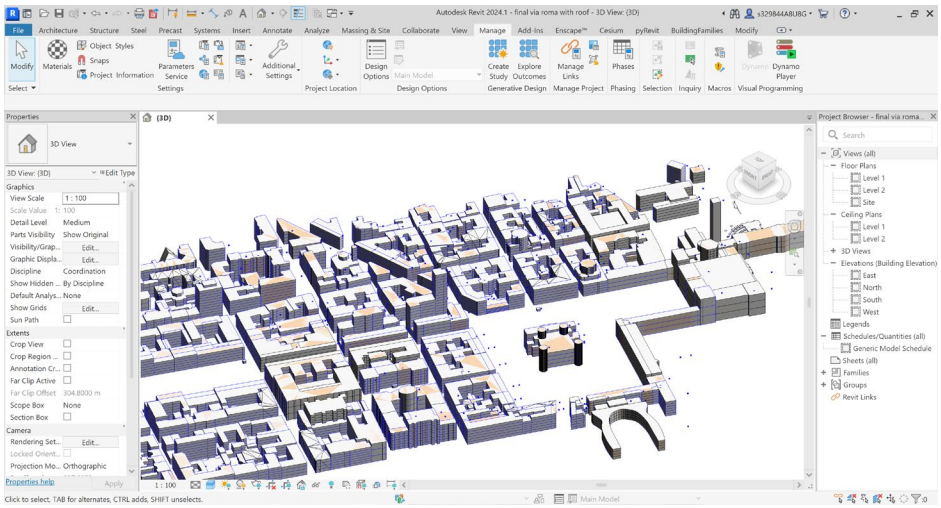


Figure 3.27 Revit 3D View of the Via Roma BIM Model Showing Imported DSM Elevation Points Distributed Over Building Roofs, With No Corresponding Roof Surface Generated

3.12 Building-Scale Detailed Model

Section 3.11 set out to raise the geometric detail of the Via Roma model at district scale, generating an explicit roof volume for every one of its 1,212 buildings, and found that the elevation data available could not support this at the scale attempted. That outcome does not mean a higher level of detail is without value to this methodology; it means that achieving it automatically, across an entire historic district, was not possible with the data sources available. To demonstrate what a genuinely higher LOD does enable, once achieved, this section shifts scale: rather than attempt partial roof coverage across all 1,212 buildings, a single representative block of Via Roma, the Torre Littoria block, was instead modelled at a

substantially higher level of detail than the rest of the district, and used as a case study for the kind of analysis that level of detail makes possible.

Unlike the course, Direct Shape-based massing used for the other 1,211 buildings of the study area, this single block was not built through this thesis's own GIS-to-BIM pipeline. A dedicated Revit model of the Torre Littoria block was instead created directly at a much higher level of detail, capturing individual facade elements and architectural features that the district-wide massing does not represent, reconstructing this degree of detail manually for one building rather than automating it across the full district, since doing so for all 1,212 buildings fell outside the scope of this thesis. This model provided the starting point for a further, building-scale energy analysis, described below, in which a photovoltaic retrofit was added directly onto its south-east-facing facade.

Onto this higher-LOD model of the Torre Littoria block, a photovoltaic retrofit was added as a sample building-level energy analysis, modelled directly onto the block's south-east-facing facade as 297 individual PV panel elements, each 1 by 0.5 metres, giving a panel area of 0.5 m^2 apiece and a total active panel area of 148.5 m^2 across the facade. Since these panels are a generic modelled family, labelled by dimension rather than by a real manufacturer datasheet, they carry geometry but no inherent power rating; converting this geometry into an actual energy estimate required stating an explicit efficiency assumption rather than reading one off the model. A conversion efficiency of 20%, within the typical range for standard monocrystalline modules, was adopted, corresponding to roughly 200 Wp of rated capacity per square metre of panel area at standard test conditions. Applied to the total panel area, this gives an installed capacity of approximately 29.7 kWp for the modelled facade.

With an installed capacity established, the actual annual electricity output of the facade was estimated using PVGIS (Photovoltaic Geographical Information System), the European Commission Joint Research Centre's free solar-resource and PV-performance tool, queried for Via Roma's own coordinates. The facade was modelled in PVGIS as a fixed, vertical surface, a tilt of 90 degrees, at an azimuth of −45 degrees in PVGIS's convention, corresponding to a south-east orientation, using the PVGIS-SARAH3 solar radiation database and the tool's default system loss assumption of 14%. This returned an annual in-plane irradiation of approximately 1,133 kWh/m^2 for this specific orientation and tilt, which, combined with the installed capacity and total system losses of approximately 25%, produced an estimated annual output of roughly 25,300 kWh for the modelled installation. As with the assumed panel efficiency, this figure should be read as a defensible estimate grounded in a real irradiation dataset for the correct location and orientation, not as the output of a certified, product-specific PV yield simulation.

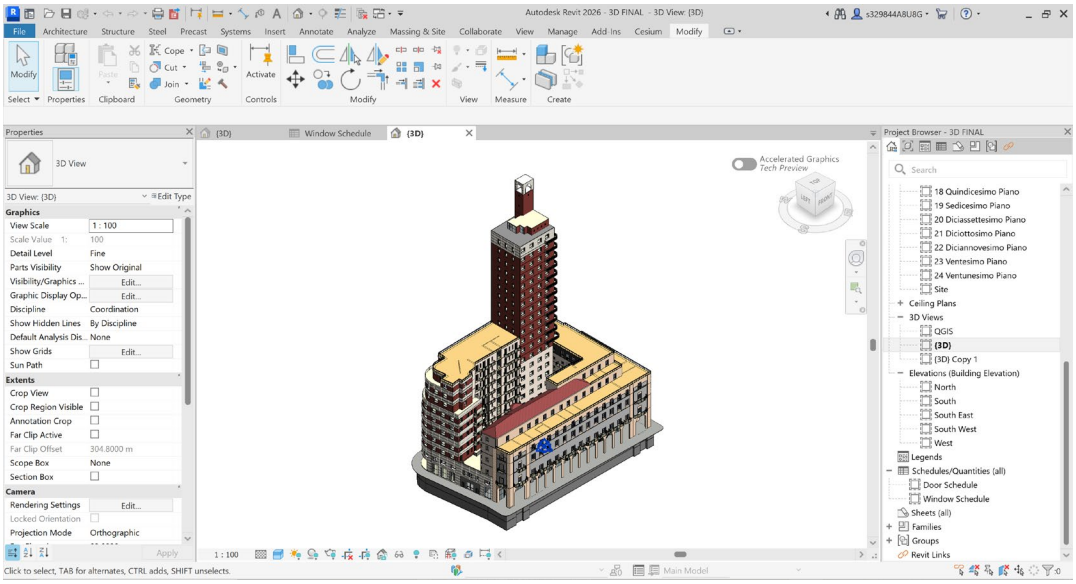


Figure 3.28 Revit Model of the Torre Littoria Block

3.13 Decision Support Visualization

Every stage described so far in this chapter, from the data preparation of Section 3.7 through the heritage-based retrofit assessment of Section 3.10, produced its results inside the Revit environment, attached to each building as a Shared Parameter. This is an appropriate format for building the model and for verifying results building by building, but it is not, on its own, a practical way for someone without Revit, a professor, a municipal planner, a heritage officer, to explore the results of the study across all 1,212 buildings of Via Roma at once. This section describes the final stage of the methodology: publishing the BIM model to the web as an interactive, browsable viewer, so that the outcomes of the preceding sections can be inspected spatially, building by building and layer by layer, without requiring specialist software.

- Publishing the model

The starting point for this stage was the same Revit model already populated with heritage, energy and retrofit parameters throughout Sections 3.8 to 3.10. Rather than exporting this model as a static file, it was published as a 3D Tiles dataset to Cesium ion, Cesium's cloud-based asset-hosting platform, using the Cesium for Revit add-in already installed alongside the Dynamo pipeline. This add-in reads the Revit model directly from within the Revit environment and uploads it as a tiled, web-streamable dataset, assigning it a unique asset ID that a web application can subsequently reference and load. This step converts the model from a file that must be opened in Revit into an asset that can be streamed into any modern web browser, without the recipient needing Revit, Dynamo, or any Autodesk license at all.

- Reconnecting the attribute data

The 3D Tiles format priorities geometry and rendering efficiency over carrying every Shared Parameter as embedded metadata, so the building-level dataset used throughout the rest of this study, the same table already exported to CSV and re-imported at each stage of Sections 3.8 to 3.10, was exported once more, this time as the definitive attribute source for the web viewer. Each row of this CSV retains the same Building ID used as the join key throughout the entire pipeline, allowing the web viewer to associate every tile of the published 3D model with its corresponding heritage classification, energy indicators and retrofit parameters, in exactly the same way Dynamo associated CSV rows with Revit elements in Section 3.8.2.

- Building the web viewer

The viewer itself was built using CesiumJS, the open-source JavaScript library underlying the Cesium ion platform, as a single self-contained web application. On loading, the application requests the published tile set by its asset ID and streams it into an interactive 3D globe, while separately loading the building-level CSV into memory and indexing it by Building ID, so that any tile clicked in the 3D view can be resolved, client-side, to its full row of heritage, energy and retrofit data without a further server request.

- Thematic layers

Rather than displaying the model with a single, fixed appearance, the viewer was built to let the user switch between a set of thematic map layers, each recoloring every building according to one of the attributes established earlier in this chapter: heritage protection group (Section 3.6.3), existing specific heating demand EPh (Section 3.9), envelope retrofit feasibility (Section 3.10.2), existing CO2 emissions, and retrofit priority group (Section 3.10.4). To keep these layers legible and consistent with one another, a single canonical color convention, was applied across every categorical layer, so that a user switching between, each layer is accompanied by its own on-screen legend, explaining the specific categories or value bands it represents.

- Click-to-inspect panel

Beyond coloring the model, the viewer was built to respond to direct interaction: clicking any building opens a details panel reporting that building's full attribute set, its heritage group and intervention codes, its existing and retrofitted EPh values, its envelope feasibility label, and its retrofit priority group, resolved instantly from the pre-indexed CSV data described above. This allows a single building to be investigated in depth without leaving the map view, complementing the district-wide picture given by the thematic layers with a building-specific one.

- Publishing and integrating the detailed block

Because 3D Tiles publishing through the Cesium for Revit add-in operates per Revit model rather than per building, the higher-LOD Torre Littoria block described in Section 3.12 could

not simply be folded into this same district-wide tileset; it was published separately, as its own Cesium ion asset, in both its as-built and PV-retrofitted states. Within the viewer, this block is exposed as a distinct, toggleable layer: selecting it flies the camera to its location and lets the user switch between the block's existing state and its PV-retrofitted state, while the corresponding building in the coarse, district-wide tileset is dimmed for that duration, so that two overlapping representations of the same block are never visible at once. A dedicated stats panel accompanies this toggle, reporting the panel count, total area, assumed efficiency, installed capacity, and PVGIS-derived annual output already established in Section 3.12, alongside the irradiation and loss assumptions behind them, so that a user inspecting this block can see not only the retrofit itself but the reasoning and data source behind its estimated performance.

- District-wide dashboard

Finally, a separate dashboard panel was built alongside the map view itself, aggregating the same building-level data into district-wide summary statistics and charts, total existing and potential heating demand across the whole study area, the distribution of buildings across EPh bands and feasibility categories, and a phased retrofit roadmap projecting cumulative energy and CO2 savings if buildings were retrofitted progressively over time, in order of priority class. Where the map view and click panel answer the question "what is the situation at this specific building", the dashboard is intended to answer the complementary question, "what is the situation across the district as a whole, and what would a phased retrofit strategy achieve" — giving the viewer both the granular, building-by-building detail the rest of this chapter was built to produce, and a summarised, decision-oriented view of what that detail adds up to across Via Roma.

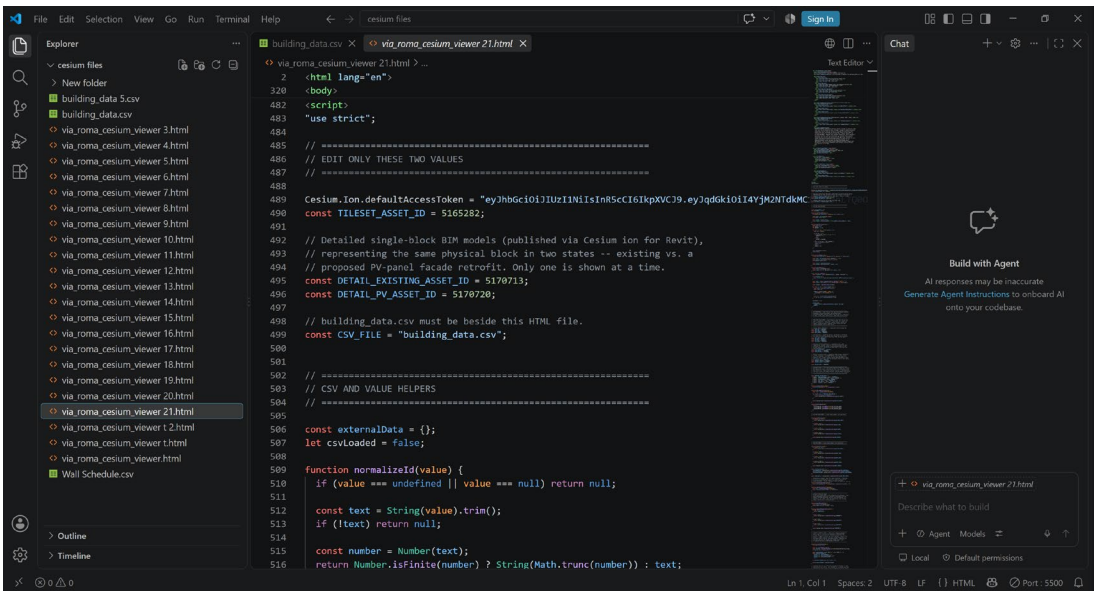


Figure 3.29 Viewer Source Code Showing the District-Wide Tile set Asset ID, the Two Detailed-Block Asset IDs (Existing and PV-Retrofitted States), and the Linked building_data.csv File

Chapter 4: Results

Chapter 3 set out the methodology by which a historic urban district, Via Roma in Turin, could be represented as a single, coherent GIS-to-BIM model: linking parcel-level geographic data to building-level parametric elements, layering heritage regulation, energy performance and retrofit feasibility onto every building of the study area, and, where the underlying data proved insufficient, documenting that limitation openly rather than masking it with an assumption the data could not support. This chapter reports what that methodology actually produced, and evaluates whether it delivers on the objectives set out in Chapter 1.

4.1 Analysis Results

This section presents the results of the methodology developed in Chapter 3, applied to the full 1,212-building stock of the Via Roma study area. Results are presented in four stages, moving from the smallest unit of the model outward: first the single-building detail available through the viewer's click-to-inspect panel, then the district-wide thematic map layers built from that same per-building data, then the aggregated, district-wide statistics reported in the dashboard, and finally the higher-LOD, single-block detail available for the Torre Littoria case study. This ordering mirrors how a user is likely to actually explore the model, starting from curiosity about one building and building outward to the district as a whole, rather than presenting the results as a set of disconnected tables.

- Building-level detail

The click-to-inspect panel. Selecting any one of the 1,212 buildings in the viewer opens a details panel reporting its full attribute set as established throughout Chapter 3: its building base data, heritage group and four part-specific intervention codes (Section 3.10.1), its existing, Standard-retrofit and Advanced-retrofit EPh values (Sections 3.9 and 3.10.3), its existing and retrofitted CO2 emissions, and its retrofit priority charts (Section 3.10.3). This is the finest-grained result the study produces: a single building can be inspected in full, without needing to consult Revit or a spreadsheet, confirming that every parameter computed across Sections 3.8 to 3.10 is retrievable, correctly joined, and legible at the point where a user would actually want it.



Figure 4.1 Building Details Panel, Showing Heritage, Energy and Retrofit Attributes for a Single Building

- **District-wide thematic layers**

Stepping back from a single building to the full study area, the viewer's thematic map layers recolour all 1,212 buildings simultaneously by each of the attributes shown in the details panel above, making it possible to read the same information spatially rather than one building at a time.

1. The existing state (heritage classification layer) colors every building by its ZUCS protection group (Section 3.6.3), showing that the majority of Via Roma's frontage falls within the more protected groups, with lighter or no protection concentrated in a smaller number of infill and post-war buildings.



Figure 4.2 *Heritage Classification Layer, Cesium Viewer*

2. Heating demand layer (Existing EPh layer) colors every building by its existing specific heating demand, EPh, calculated for each building in Section 3.9, answering the simplest question a user might ask: how much energy does this building currently need to heat itself, per square metre, per year? Mean existing EPh is 236.96 kWh/m²·yr, while the median is noticeably lower, at 176.42 kWh/m²·yr, indicating that a smaller number of particularly high-demand buildings pull the average upward, while the typical building performs somewhat better than that average alone would suggest.

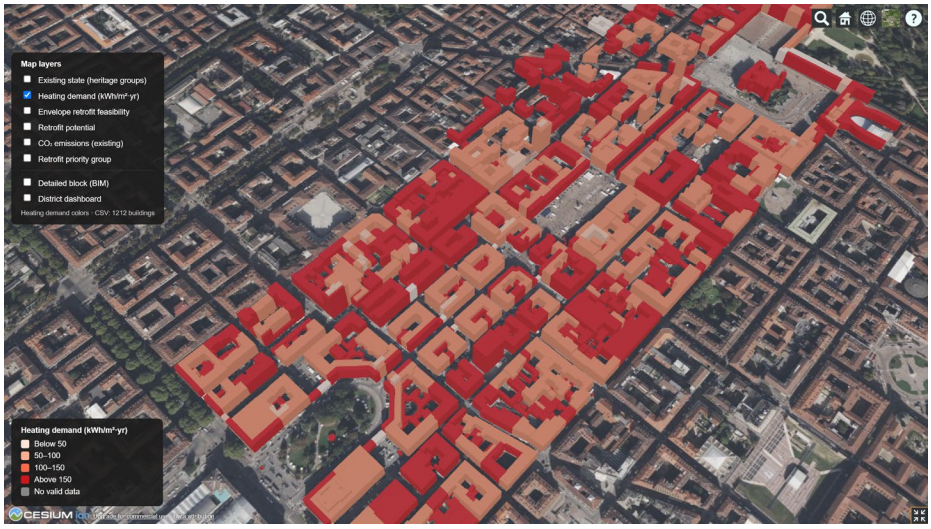


Figure 4.3 Existing Heating Demand Layer, Cesium Viewer

3. Envelope feasibility layer shows the result of Section 3.10.2's analysis: each building's heritage intervention codes, combined with the wall, window and roof feasibility logic developed there, collapsed into a single practical label per building — Fully feasible, Partially feasible, or Fully constrained. It answers a more actionable question than the heritage layer alone: not just how protected is this building, but what can actually be done to it. Across the district, 478 buildings (39.4%) are Fully feasible, 294 (24.3%) Partially feasible, and 440 (36.3%) Fully constrained.

This is the point of building feasibility as its own analytical layer rather than simply coloring the heritage layer again: it reflects heritage rule and physical building geometry acting together, which is what actually determines whether a retrofit measure is possible, not the heritage classification on its own.

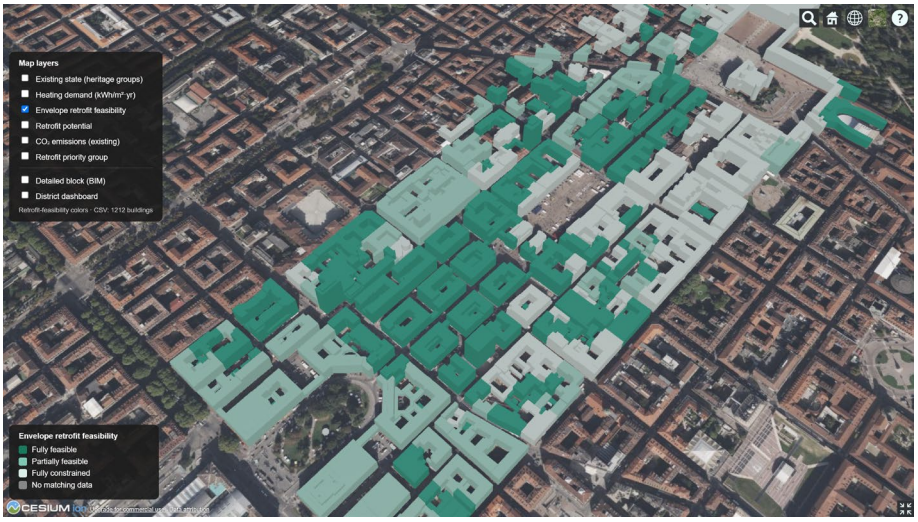


Figure 4.4 Envelope Feasibility Layer, Cesium Viewer

4. Retrofit potential layer colors every building by its achievable percentage reduction in EPh under the Advanced refurbishment scenario, the result of substituting each building's feasible components with the improved U-values established in Section 3.10.3. Where the feasibility layer shows what is legally possible, this layer shows what that possibility is actually worth in energy terms — turning a legal category into a single, comparable number for every building in the district. This is where feasibility and energy need visibly meet. Fully feasible buildings reach a mean reduction of 51.4%; Fully constrained buildings reach only 4.1%, a figure produced entirely by the floor retrofit applied unconditionally in Section 3.10.3, since wall, window and roof remain unavailable to them. The result is a roughly twelve-fold gap between the two groups — buildings that are free to retrofit fully recover more than half their heating demand, while buildings locked by heritage protection recover barely a twentieth of it.

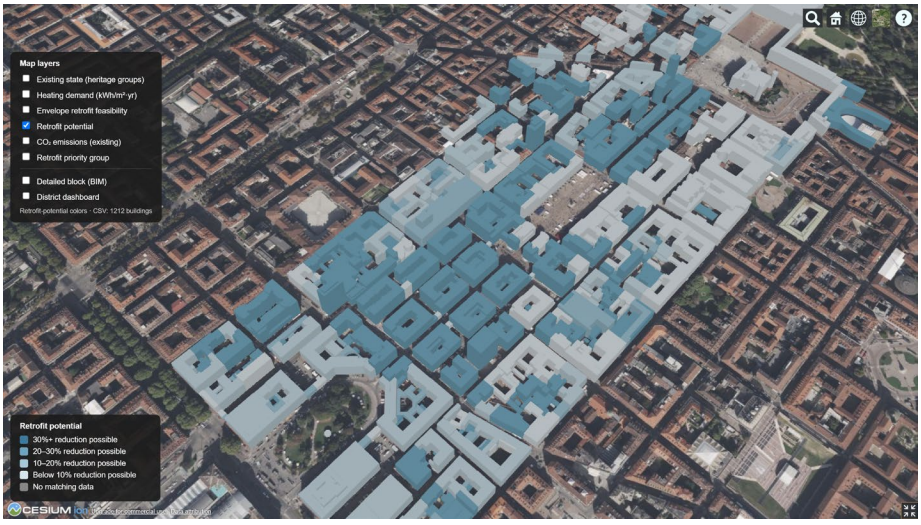


Figure 4.5 Retrofit Potential Layer (% EPh Reduction, Advanced Scenario), Cesium Viewer

5. CO2 emissions layer colors every building by its existing, Standard and Advanced-retrofit CO2 emissions, calculated by applying the EPISCOPE national heat-supply emissions factor to the same heating demand figures already established in Section 3.9 and 3.10.3. Because CO2 emissions here are derived directly from EPh through a fixed factor, this layer's spatial pattern closely mirrors the retrofit potential layer, but it reframes the same result in a unit more directly meaningful to policy and reporting: not kWh saved, but kilograms of CO2 avoided per square metre. Presenting this as its own layer, rather than leaving CO2 implicit in the energy figures, makes the district's retrofit potential legible in the terms a municipal climate target or reporting framework is actually expressed in.

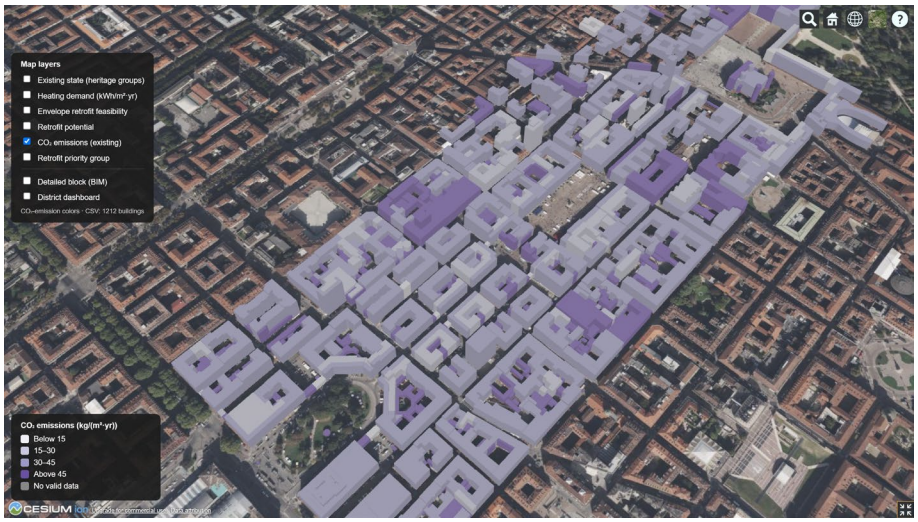


Figure 4.6 Existing C02 Emissions Layer, Cesium Viewer

6. Retrofit priority layer colors every building by the combined severity-and-feasibility score of Section 3.10.4, translating the energy and feasibility layers above into a single, actionable recommendation: which buildings to address first. Across the district, 582 buildings (48.0%) fall into the High-priority class, 347 (28.6%) into Medium, and 283 (23.3%) into Low. Compared against the feasibility layer, this shows that priority is not a simple re-labelling of poor performance: a poorly performing but heavily constrained building is deliberately excluded from the High-priority group, since little can actually be achieved for it, ensuring the resulting roadmap directs attention toward buildings where energy need and legal opportunity genuinely coincide. In this way, the layer functions as a practical starting point for a phased retrofit strategy across the district, indicating not simply which buildings perform worst, but which ones a retrofit programme should realistically begin with first.

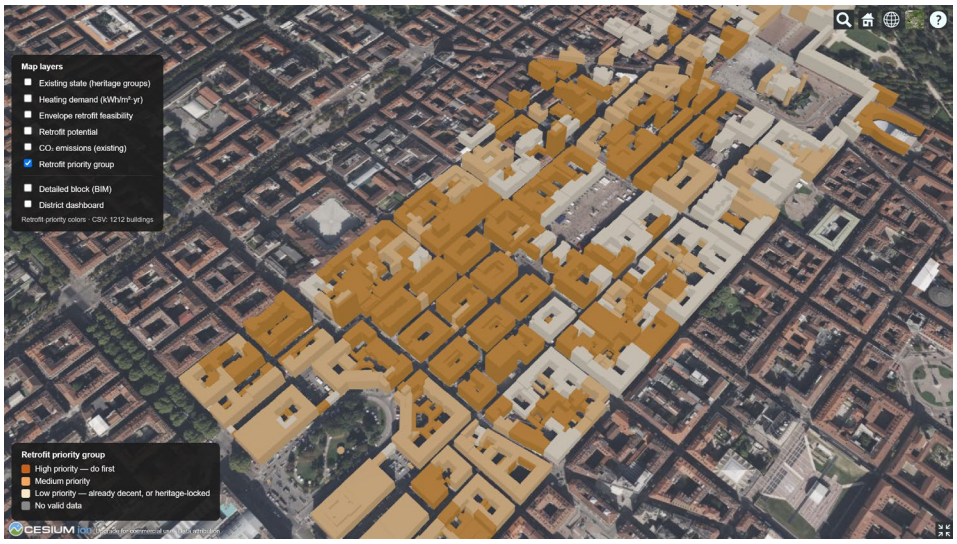


Figure 4.7 Retrofit Priority Layer, Cesium Viewer

- District-wide dashboard

Beyond the spatial layers, the dashboard panel aggregates the same per-building data into district-wide totals and charts. Existing heating demand across the study area totals approximately 53.0 million kWh/yr; under the Standard scenario this falls to approximately 39.7 million kWh/yr, a 25.2% district-wide reduction, and under the Advanced scenario to approximately 38.6 million kWh/yr, a 27.2% reduction.

The dashboard also presents a phased retrofit roadmap, projecting cumulative energy and CO2 savings across three milestone years, 2030, 2040 and 2050, if the district were retrofitted progressively rather than all at once. This roadmap assumes a cumulative retrofit rate of approximately 2% of district floor area per year, consistent with the EU Renovation Wave strategy's target of doubling the annual renovation rate through 2050, reaching cumulative floor-area shares of roughly 10%, 30% and 50% by each respective milestone. Rather than retrofitting buildings in a fixed or arbitrary order, buildings are selected at each milestone using the same priority classification established in Section 3.10.4, filling High-priority buildings first, then Medium, then Low, with existing EPh breaking ties within a tier; each retrofitted building is assumed to reach its own Advanced-scenario value once addressed. Applying this method, the projected cumulative savings reach approximately 15,100 MWh/yr and 3,644 tCO2/yr by 2030, 40,900 MWh/yr and 9,866 tCO2/yr by 2040, and 53,800 MWh/yr and 12,955 tCO2/yr by 2050, the final milestone corresponding closely to the full district-wide Advanced-scenario total reported above, once every building in the stock has been addressed. Because the roadmap prioritises by the combined severity-and-feasibility score rather than by poor performance alone, it deliberately avoids spending early retrofit effort on heavily heritage-constrained buildings that read badly on EPh but can only ever improve marginally, concentrating early-phase gains instead on buildings where the two criteria genuinely align.



Figure 4.8 District Dashboard Panel, Cesium Viewer

- **Building-scale detail:** The Torre Littoria block.

Where the results above summarize the district using the course, DirectShape-based model, the higher-LOD Torre Littoria block described in Section 3.12 demonstrates what the same viewer can show once a single building is modelled in greater detail. Toggling this block to its existing state shows its as-built facade; toggling to its PV-retrofitted state shows the 297-panel installation modelled on its south-east-facing facade, with an accompanying stats panel reporting a total panel area of 148.5 m^2, an assumed 20% conversion efficiency, an installed capacity of approximately 29.7 kWp, and a PVGIS-derived estimated annual output of approximately 25,300 kWh. This result sits outside the district-wide feasibility and priority figures reported above, since it was produced through a separate, building-specific analysis rather than the automated district-wide pipeline, but it illustrates concretely the kind of higher-resolution, building-specific analysis that pipeline cannot currently support at scale, a direction Section 4.3 returns to.

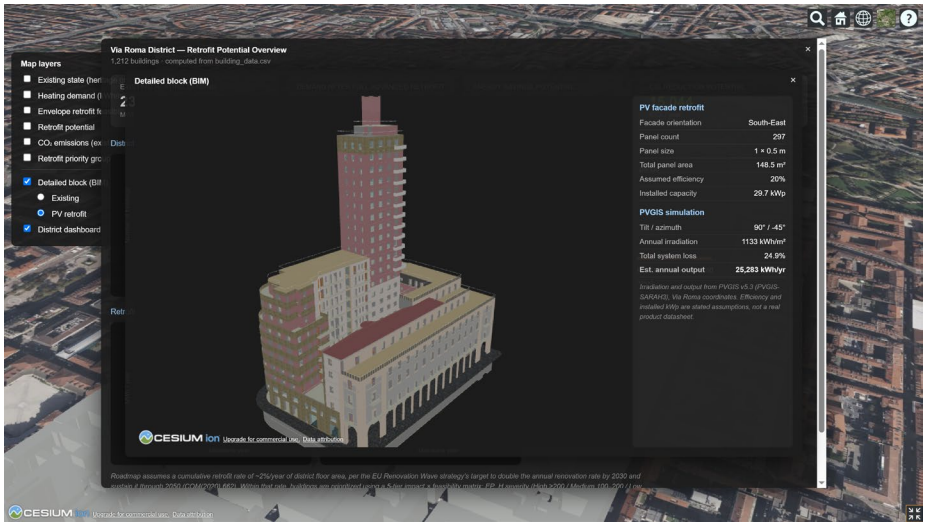


Figure 4.9 Torre Littoria Block — PV-Retrofitted State with Stats Panel, Cesium Viewer

4.2 Decision Support Evaluation

Chapter 1 framed this thesis as an attempt to introduce a new way of mapping the city: one that could hold geographic, regulatory, physical and performance information about a historic district together, in a single representation, rather than scattering that information across separate systems built for separate purposes. Section 4.1 showed what that representation actually contains once built. This section asks the more fundamental question behind it: does representing Via Roma this way genuinely change what mapping a historic district can do, and does it hold up against the specific questions and gaps Chapter 1 identified in how cities are currently mapped.

The starting problem, as Section 1.2 laid it out, was that GIS and BIM represent the city on two different logics that were never designed to meet. GIS maps a district the way a planner or a heritage authority actually needs it, as a continuous territory of parcels, regulatory zones and footprints, legible at the scale of a whole city. BIM represents a building the way an architect or engineer needs it, as an assembly of individual, parametric construction elements, legible at the scale of a single structure. Neither representation is wrong for its own purpose; the difficulty this thesis set out to address is that a historic district like Via Roma cannot be understood, or managed, from either logic alone. Deciding whether a specific building can be retrofitted requires the district-scale knowledge only GIS holds, its heritage designation, its position within a protected block, alongside the building-scale detail only BIM holds, its envelope construction, its actual energy performance. Via Roma's own building stock makes this concrete: a building's retrofit potential in this study was never a property of its energy performance alone, nor of its heritage status alone, but of the two considered together, which is precisely the kind of question a district mapped in only one of these two logics could not answer on its own terms.

The methodology developed in Chapter 3 responds to this by treating the city not as two separate maps to be consulted side by side, but as a single, layered representation, in which every building carries its geographic, regulatory and performance information simultaneously, and in which that information can be added to, corrected or extended over time rather than fixed at the moment of survey. Whether this actually succeeds as "a new way of mapping the city," rather than simply a more elaborate way of producing the same two separate maps, is the real test of the first two research questions posed in Section 1.3. The evidence for it lies less in any single number reported in Section 4.1 than in what the resulting model allows a user to ask of Via Roma that a conventional GIS layer or a conventional BIM file, used alone, could not: which buildings are both energy-poor and free of heritage restriction, and therefore worth prioritising; which buildings look energy-poor but are, in practice, barely improvable once their protection status is taken into account; and which parts of the district could, in principle, support a genuinely deeper form of representation, as the Torre Littoria case study demonstrates, once the underlying data allows it. These are not questions a purely geographic map or a purely architectural model could pose, because each, on its own, is missing exactly the half of the picture the other holds. That the resulting Via Roma model can pose them is the clearest evidence that integrating GIS and BIM did more here than combine two file formats; it changed what could be asked of the district in the first place, and the fact that new layers, and an entirely new higher-detail block, could be folded into this same representation after the fact, without redesigning it, is what distinguishes it from a fixed, single-use snapshot of the kind Section 1.3's second research question was concerned with.

The third research question, how robust such a representation remains when the real data behind it is incomplete or uneven, is where Via Roma proved to be the right kind of test case, because its data was never complete, and the methodology's response to that incompleteness is itself part of the result, not a caveat attached to it afterward. Where the municipal heritage dataset did not extend to every building in the study area, the methodology did not simply omit those buildings from the district's regulatory picture; it fell back on the most protective classification available, keeping every building represented, if conservatively, rather than silently absent. Where the heritage regulation itself left genuine room for interpretation, as it does over whether an external wall intervention can ever be considered unchanged in appearance, the methodology did not resolve that ambiguity by assumption; it carried the ambiguity itself into the representation, as a flagged, reviewable condition rather than a hidden default. And where the elevation data needed to represent Via Roma's roofscape in genuine three dimensions turned out not to exist, at a usable resolution or with sufficient coverage, across the district, the methodology did not quietly substitute a simplified stand-in and present it as complete; it left that part of the city's representation incomplete, and said so. This is a direct answer to the gap identified in Section 1.2, that existing GIS-to-BIM workflows respond to missing data with one uniform simplification regardless of how much evidence is actually available: Via Roma's

representation instead treats different kinds of missingness differently, using the same contextual and regulatory knowledge, the district's own heritage rules, to decide how to fill each gap, rather than applying a single rule everywhere.

The fourth research question, whether this representation of the city can actually be handed to someone who is not a GIS or BIM specialist, is where the stakes of this whole exercise are clearest, since a representation of a historic district that only its own creator can read has not really solved the problem Chapter 1 set out. Here, the Via Roma model was deliberately built to be opened and explored without any of the specialist software used to construct it, letting a heritage officer, a planner, or simply an interested resident move through the district and ask it questions directly, rather than requesting an export or a report from someone who can operate the underlying tools. This is a genuine, structural step toward answering RQ4, and it is worth stating plainly rather than modestly: for the first time in this methodology, the city's layered representation is something a non-technical user can actually stand inside, rather than something described to them secondhand. It is not, however, a complete answer. The representation was built to be explored, but it has not yet been placed in front of the kind of user it was built for and observed in use, so its accessibility remains a claim grounded in its design, not a result confirmed by watching someone unfamiliar with Via Roma actually navigate it. Nor can that same non-specialist user extend the representation themselves, add a new building, correct a misclassified one, without returning to the same specialist pipeline that built it in the first place; the city can be read by anyone, but it can still only be rewritten by the same few tools that wrote it.

Beyond these four research questions, a further set of practical limitations sits underneath this evaluation, ones that do not map neatly onto any single question but shape how far the resulting representation can actually be trusted or reused as it stands. The district-wide model remains only as complete as the public data available to build it, and that data was, at several points across Chapter 3, simply not there: the ZUCS heritage shapefile did not extend to every building, the national elevation data did not cover the district uniformly, and no source, public or commercial, offered roof-level detail at the resolution this study actually needed. Where the methodology responded to these gaps with visible, reasoned fallbacks rather than silent omissions, that response is itself evidence of a sound approach, as argued above; but it does not change the underlying fact that the representation of Via Roma built here is only as detailed, and in places only as accurate, as the data that happened to be publicly available at the time it was built, not as detailed as the district actually is. This is most visible in the uneven level of detail across the model itself: the great majority of the 1,212 buildings are still represented as simplified massing, with only a single block modelled and analysed at a genuinely higher level of detail, so a user comparing two adjacent buildings in the viewer is, in a real sense, comparing two different depths of representation, not two consistent ones.

A second, more practical limitation concerns the model's own weight and performance. A 3D Tiles dataset covering 1,212 buildings, streamed alongside a CSV of building-level attributes and, where enabled, a second, higher-detail block layered on top, is not a small file to move through a browser, and nothing in this thesis formally tested how the viewer performs on a slower connection, an older device, or a mobile browser, all of which a genuinely public-facing decision-support tool would eventually need to handle gracefully rather than simply working on the machine it was developed on.

A third limitation concerns how alive this representation actually is, as opposed to how alive it was designed to be. Chapter 1 framed the goal as an evolving model, one that could keep pace with data, regulations and questions that continue to change after the model itself is built. What this thesis demonstrates is that the architecture tolerates that kind of change, new layers and a new block were both added successfully after the district-wide model was complete, but every one of those additions was still a manual act carried out by the same person who built the original pipeline. Nothing in this study establishes what happens when the underlying heritage regulation is amended, when a building is actually retrofitted and its true post-retrofit performance becomes available, or when the model needs to be kept current over years rather than assembled once for a thesis; a living, continuously updated version of this representation remains an aspiration this study argues for, not one it has tested.

Weighed against the four questions Chapter 1 posed, and the limitations named above, this thesis's account of itself has to be equally direct in both directions. It offers real, demonstrated evidence that integrating GIS and BIM produces a genuinely different, more capable representation of a historic district than either could produce alone, and that this representation can absorb real-world data gaps without collapsing into a single, uniform simplification, which is a direct and substantiated response to two of the central problems identified in the literature. It does not claim to have solved mapping the city once and for all: the representation remains only as extensible as the technical pipeline behind it allows, only as complete as the public data available to build it, only as detailed as one representative block out of 1,212 buildings, and its accessibility to genuinely non-technical users remains a design intention that has not yet been tested against a real one. Those limits, not any shortfall in the numbers reported in Section 4.1, mark the honest edge of what this particular case study, Via Roma, can be said to have proven, and are exactly where the next section turns.

4.3 Future Developments

Beyond what Section 4.2 already covered, this methodology and the Via Roma model built from it point toward several broader directions for how cities could be represented and

managed going forward, extending well past what a single thesis, on a single district, was able to test.

The most immediate direction lies in the building-level parameter structure developed here: a single identifying key, carried consistently from GIS through to BIM, capable of joining any attribute back to its correct building without loss or ambiguity. This structure was proven in this thesis for heritage classification, energy performance and retrofit feasibility, but nothing about it is specific to those three domains. The same key could carry structural condition data, fire safety compliance, accessibility standards, seismic risk, or flood exposure, each layered onto the same underlying model using the same pipeline already established here, rather than requiring a new integration method to be designed from scratch every time a city needs to track a new concern. In this sense, what this thesis actually produced is less a single-purpose energy tool than a general pattern for attaching any building-level information to a district-scale representation, one that other studies, and other municipal departments, could adopt directly for their own domains without starting over.

The retrofit roadmap presented in this thesis, similarly, represents only one fixed scenario among many that the same underlying model could support. A natural extension is turning this from a single projection into an actual interactive planning tool, letting a municipality test different retrofit rates, different funding allocations, or different prioritisation rules, and see the resulting district-wide energy and emissions outcomes reflected immediately, rather than working from one predetermined set of assumptions. Such a tool would let planning decisions be tested against the model before being committed to, rather than the model simply reporting on decisions already made elsewhere.

More broadly still, this thesis points toward a different way of thinking about how a city's digital representation should be built in the first place: not as a single, complete deliverable produced once and then left fixed, but as a structure that can keep being added to over time, growing in both depth and coverage as better data, further analysis, or new civic priorities become available. This matters because complete, uniformly detailed data about a real historic district essentially never exists at the moment a project like this begins; a methodology that insists on completeness before anything can be built will, in practice, never get built at all. What this thesis demonstrates instead is that a representation can begin with whatever is genuinely available, however partial, and still function as a usable, honest model of the city, one that grows toward completeness rather than waiting for it. This principle, arguably more than any single result in Chapter 4, is what future work on this methodology should carry forward: build with the data that exists, document clearly where it runs out, and treat the resulting gaps as a known frontier for the next iteration of the model, not as a flaw to be hidden.

Finally, the central achievement this thesis argues for is not specific to Via Roma, or to Turin, or to any one regulatory context. It is an integrated, heritage-aware approach to representing

the city, one capable of holding regulatory, physical and performance information together in a single, coherent structure, and of remaining genuinely useful even where the underlying data is incomplete, which is the normal condition of any real historic district, not an exceptional one. Testing this same approach on other historic districts, each with their own heritage frameworks, their own data availability, and their own retrofit pressures, is what would carry it from a single validated case study toward a genuinely reusable way of representing and managing historic cities more widely. If it holds up under those different conditions, what this thesis will have offered is not simply a model of Via Roma, but a transferable way of building the next one, for any city facing the same tension between preserving what it has and adapting to what it now needs.

Chapter 5: Conclusions

What this thesis aimed to build was a workflow that could link parcel-level geographic data, census records, heritage classifications, and the TABULA archetype database into a single parametric BIM model and that's what it delivers. Each of Via Roma's 1,212 buildings now carries its heritage constraints and its energy performance as one joined set of attributes, rather than as scattered data across separate GIS layers and BIM files that never spoke to each other.

Applied to a real sustainability question, how much of a building's energy performance can actually be improved once heritage constraint is accounted for, the workflow produced a result that neither GIS nor BIM alone could have shown. That's not a minor achievement, it reshapes what retrofit can realistically apply on a street like Via Roma. And because the result was delivered through a browser-accessible viewer, it wasn't left sitting in a specialist's file format - it became available, at least by design, to the planners and heritage officers who would actually need to act on it.

Measured against the four gaps this thesis set out to address, the picture is mixed, and it's worth being honest about that. The semantic and data-loss problem was genuinely resolved - a single identifying key carried consistently from GIS all the way through to the final viewer. The tendency to fall back on coarse simplification whenever data goes missing was also directly addressed, through graded, reasoned responses to different kinds of missing data rather than one blunt default. The absence of a universal integration method was never something a single case study could realistically resolve, and this thesis doesn't pretend otherwise. What it offers instead is a reproducible pattern, tested and shown to hold under real conditions. The challenge of maintaining consistent detail across district and building scale is only partly answered: achievable in principle, demonstrated in parts, but not yet uniform across the whole district.

Taken together, these results support the thesis's central claim: integrating GIS and BIM does more than merge various file formats. It changes what can actually be asked of a historic district, while staying honest about where the underlying data, and the model itself, is still incomplete. This thesis doesn't claim to be finished, effortlessly extensible, or proven usable by non-specialists; those remain open questions for future work. What it has shown is that a coherent, adaptable, heritage-aware representation of a real historic district is achievable under real conditions, not just ideal ones. That's a foundation worth building on, for Via Roma and, if the pattern holds, for the historic districts that will face this same statement in the years to come.

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