

POLITECNICO DI TORINO

Master's degree in Digital Skills for Sustainable Societal Transitions

MASTER's Degree Thesis

Urban Digital Twin: Assessing Municipal Geodata Readiness for 3D City Modelling

Multi-scale QGIS–PostGIS Approach Using the Turin Building Dataset



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Abstract

The increasing availability of 3D city models and UDTs has expanded the range of urban data for planning, governance, climate-oriented decision-making, and digital transformations. However, the development of such systems not only depends on a current visualization platform but also on the availability of the underlying geographical data. Many municipal datasets are official and spatially detailed but created for mapping, administrative management, or territorial reference. Their instant reuse for semantic 3D city modeling and UDT-oriented interoperability is therefore not automatic.

The goal of this thesis is to evaluate the potential of an existing dataset of municipal buildings for the transition from GIS-based representation to standard-oriented 3D city modeling and future UDT procedures. The research is mostly focused on dataset preparation rather than constructing a whole UDT platform. It examines the extent to which the provided data can support semantic richness, interoperability, scalability, and geometric completeness.

The methodology follows a multi-scale approach, from the context of institutional geodata to the assessment at the district scale and the reconstruction at the building scale. The Turin building dataset is processed using the QGIS software, giving special attention to the volumetric layer and its height-related characteristics. Derived fields such as `height_m`, `has_height`, `building_id`, `part_id`, `ngsi_entity`, and `partOf` are created to evaluate LoD1-like extrusion potential, identify data restrictions, and support Building/BuildingPart reconstruction. The reconstructed data is then imported into PostgreSQL/PostGIS, storing the parent building and its parts in a spatial relational database, and the data is verified with SQL queries. GeoJSON and NGSI-LD-style JSON outputs are produced in an attempt to evaluate possible future web-based and interoperability-oriented reuse.

The results indicate that the data set is suitable for basic 3D city modeling if proper geometry and trustworthy height values are available. But its applicability to standard-oriented and UDT-oriented workflows is limited. The major limitations include the lack of height information, fractured object representation, scattered semantic properties, limited parent-child relationships, and lack of support for higher levels of detail. These limitations preclude the dataset from being utilized as a structured 3D or interoperable data model. The Building/BuildingPart refactoring and the PostGIS prototype demonstrate that these restrictions can be overcome by systematic interpretation, derived identifiers, relational geographical storage, SQL-based validation, and organized export.

Based on a study, cleaning, reorganization, and enrichment, the thesis concludes that the existing municipal GIS data can be a viable basis for 3D city modeling and future UDT development. But this is one of the terms. The fundamental contribution of the research is the implementation of a repeatable QGIS-PostGIS process that incorporates institutional geodata, object-based reconstruction, spatial database representation, export in the style of GeoJSON/NGSI-LD, and interactive 3D display. The result shows that the output is not only visible but also structured and queryable and might be scaled for future interoperable urban digital systems.

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Abbreviation

Abbreviation	Full term	Meaning in this thesis
2D	Two-dimensional	Conventional planar spatial representation, such as maps and footprints.
2.5D	Two-and-a-half-dimensional	Spatial data with height or elevation attributes, but not full 3D object structure.
3D	Three-dimensional	Representation of objects with horizontal and vertical dimensions.
API	Application Programming Interface	A technical interface that allows software systems to exchange data or functions.
BDTRE	Base Dati Territoriale di Riferimento degli Enti	The regional territorial reference database used for institutional and multi-scale geodata context.
BIM	Building Information Modelling	Digital modelling approach focused on detailed building information, geometry, and components.
CSI	Consorzio per il Sistema Informativo	The institutional source of the <i>edificato</i> dataset used for building-related analysis.
DBMS	Database Management System	Software used to store, manage, query, and organize data.
EPSG	European Petroleum Survey Group	Standard code system used to identify coordinate reference systems.
ETSI	European Telecommunications Standards Institute	Standardization body responsible for the NGSI-LD specification.
FIWARE	Future Internet Ware	Open-source ecosystem for smart applications and context information management.
GIS	Geographic Information System	System for managing, analysing, and visualizing geospatial data.
GML	Geography Markup Language	XML-based language used for geographic information exchange.
GeoJSON	Geographic JavaScript Object Notation	JSON-based format for encoding geographic features and attributes.
INSPIRE	Infrastructure for Spatial Information in Europe	European framework for spatial data infrastructure, metadata, and geodata interoperability.
IoT	Internet of Things	Network of physical devices and sensors capable of producing and exchanging data.
JSON	JavaScript Object Notation	Lightweight data format used for structured data exchange.
LEED	Leadership in Energy and Environmental Design	Sustainability certification system for buildings.
LoD	Level of Detail	Degree of geometric and semantic detail in a 3D city model.
NGSI-LD	Next Generation Service Interface – Linked Data	ETSI standard for representing context information through entities, properties, and relationships.

OGC	Open Geospatial Consortium	International organization developing geospatial standards such as CityGML.
OSM	OpenStreetMap	Open-source geographic database often used as basemap or contextual geodata.
QGIS	Quantum Geographic Information System	Open-source GIS software used for data processing, mapping, and 3D visualization.
Qgis2threejs	QGIS to Three.js exporter	QGIS plugin used to export interactive 3D web models.
RDBMS	Relational Database Management System	Database system that organizes data into related tables.
SDI	Spatial Data Infrastructure	Institutional and technical framework for managing, publishing, and accessing spatial data.
SQL	Structured Query Language	Language used to create, query, and manage relational databases.
UDT	Urban Digital Twin	Digital representation of an urban system that can support data integration, analysis, simulation, and decision-making.
URL	Uniform Resource Locator	Web address used to access online resources.

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CHAPTER

Introduction

Framing the transition from municipal GIS data to 3D city modelling and Urban Digital Twin readiness.

1.1 From Urban Models to Digital Representation

Cities have always necessitated representational structures for planning, governance, analysis, and transformation. Through the organization of spatial information regarding land, buildings, infrastructure, and administrative boundaries, traditional maps, cadastral plans, statistical records, and later Geographic Information Systems (GIS) have facilitated urban decision-making. Nevertheless, representations that transcend two-dimensional cartography are becoming more necessary in response to the contemporary urban challenges. For the purposes of climate adaptation, energy transition, infrastructure management, emergency response, and public-service planning, the city must be comprehended as a multifaceted system of physical objects, spatial relationships, and evolving processes (Ketzler et al., 2020; Lei et al., 2023).

Three-dimensional city models offer a significant step forward in this evolution since they provide a vertical dimension to urban depiction. In addition to being depicted as map features, buildings, roads, terrain, vegetation, water bodies, and infrastructures can also be represented as spatial objects with height, volume, morphology, and relationships. Therefore, 3D city models are advantageous for decision support, environmental assessment, planning communication, simulation, and visualization (Biljecki et al., 2015; Kolbe et al., 2005).

The primary concern examined in this thesis is not solely the visualization of existing data in three dimensions. The fundamental issue is whether the existing municipal data are adequately structured to facilitate this change. Numerous authoritative datasets were developed for administrative mapping, cadastral reference, spatial planning, or traditional GIS applications. While they may possess useful spatial information, they do not inherently provide the geometric completeness, semantic structure, object hierarchy, or interoperability essential for 3D city modeling and Urban Digital Twin-oriented operations (Ferré-Bigorra et al., 2022; Noardo et al., 2020).

The future of workflows focused on Urban Digital Twins depends on structured, queryable, and reusable urban data, which is essential for visualization and other uses in various software contexts. This thesis examines the function of spatial relational databases in the transition from GIS layers to interoperable urban entities. PostgreSQL is an open-source object-relational database management system, descended from the POSTGRES project at the University of California, Berkeley. It can handle a range of features such as transactional integrity, foreign keys, triggers, multiversion concurrency control and extension. PostGIS is the spatial database extender for PostgreSQL providing support for geographic objects allowing location queries to be run in SQL.(PostGIS Project, 2026; PostgreSQL Global Development Group, 2026).

Figure 1.1 depicts the continuous trajectory from institutional GIS data to 3D city modeling readiness, spatial database representation, and future Urban Digital Twin interoperability, encapsulating the overall logic of this transformation.

Continuous standard-oriented transformation path

From institutional GIS data to spatial database representation and future Urban Digital Twin interoperability

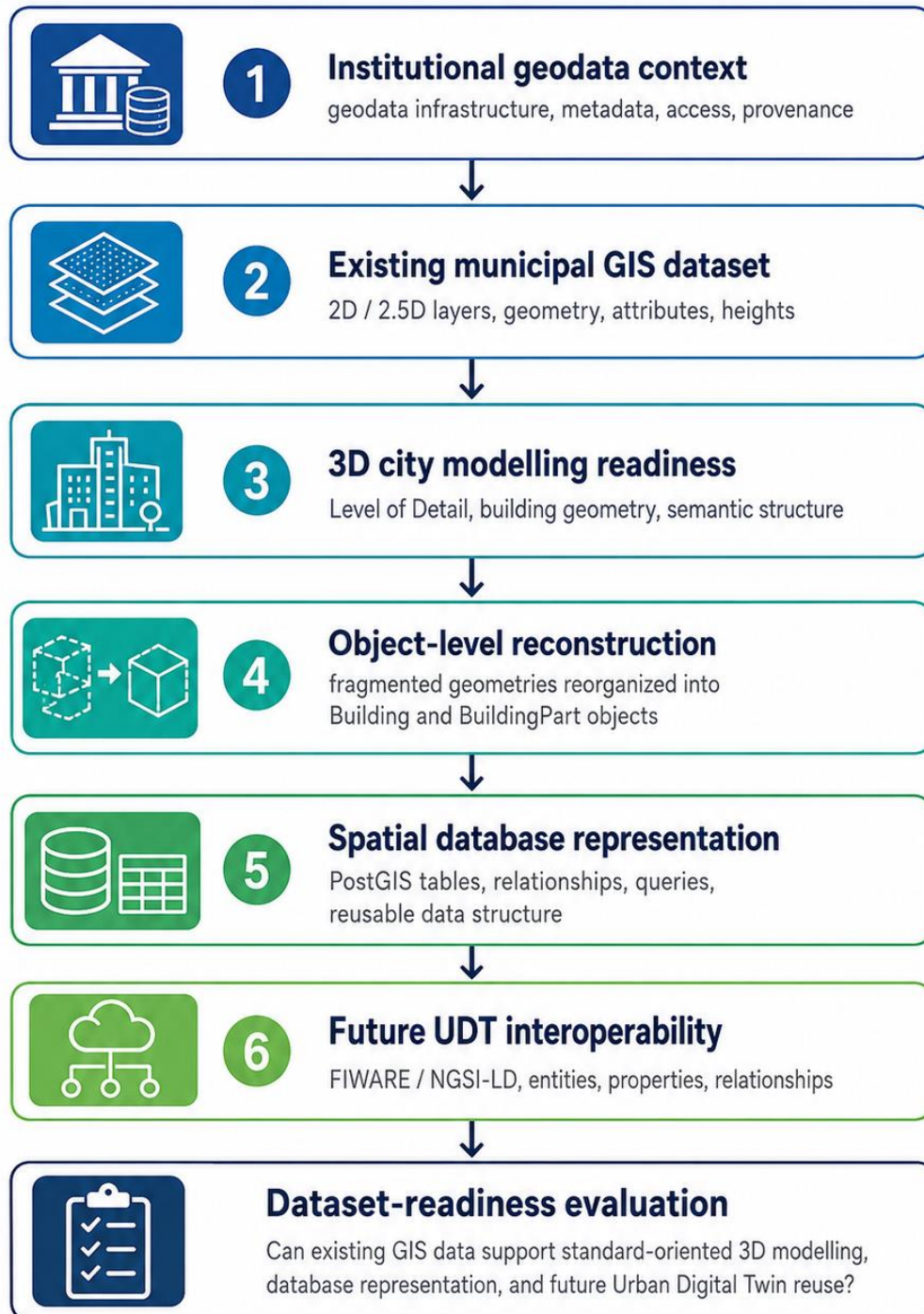


FIGURE 1.1 CONTINUOUS STANDARD-ORIENTED TRANSFORMATION PATH FROM INSTITUTIONAL GIS DATA TO SPATIAL DATABASE REPRESENTATION AND FUTURE URBAN DIGITAL TWIN INTEROPERABILITY. SOURCE: AUTHOR'S ELABORATION.

The thesis does not prioritize 3D visualization as its ultimate objective, as illustrated in Figure 1.1. In contrast, visualization is situated within a more comprehensive data-readiness pathway that encompasses evaluation, object reconstruction, database structuring, and future interoperability.

1.2 From Digital Model to Digital Twin

The term "Digital Twin" is used interchangeably, however not all digital representations qualify. It is advantageous to differentiate between a digital model, a digital shadow, and a digital twin. A digital model is a digital depiction of a physical thing or system that does not facilitate automatic data interchange. The digital model will not automatically update in the event that the physical system undergoes any changes. Many traditional GIS maps and static 3D city models fall under this category because they show the city but do not continuously interact with it (Kritzinger et al., 2018; Singh et al., 2021).

A digital shadow signifies a more sophisticated relationship. In this instance, data can transfer autonomously from the physical system to its digital representation. Sensors may refresh a monitoring platform or dashboard. Nonetheless, the interaction is predominantly unidirectional: the digital system acquires information from the physical world, yet it does not inherently affect or regulate the physical system (Kritzinger et al., 2018; Singh et al., 2021).

A Digital twin requires a deeper level of integration between the physical and digital worlds. A digital representation from which it is possible to gather data from a physical system, conduct an analysis or simulation, and influence decisions or actions affecting the physical system is broadly accepted. The formal modeling of this relationship is often more straightforward in industrial or formal environments where the focus of the research may be a regulated process, product, or apparatus. The urban framework consists of buildings, infrastructure, environmental systems, social activities, governance frameworks, and a variety of data owners which introduce complications within urban systems (Batty, 2018; Ketzler et al., 2020).

Consequently, urban digital twins are incapable of being reduced to 3D city models that are visually realistic. A 3D city model might provide the spatial and semantic basis of an Urban Digital Twin, but a UDT requires additional capabilities: the integration of heterogeneous datasets, dynamic context information, interoperability between systems, simulation or analytical functions, and decision-support processes. This distinction is crucial as it explains why the present thesis focuses on data preparation before full Digital Twin deployment (Ketzler et al., 2020; Lei et al., 2023).

This conceptual difference is illustrated in Figure 1.2, which compares digital twins, digital shadows, and digital models based on the direction and intensity of data transmission.

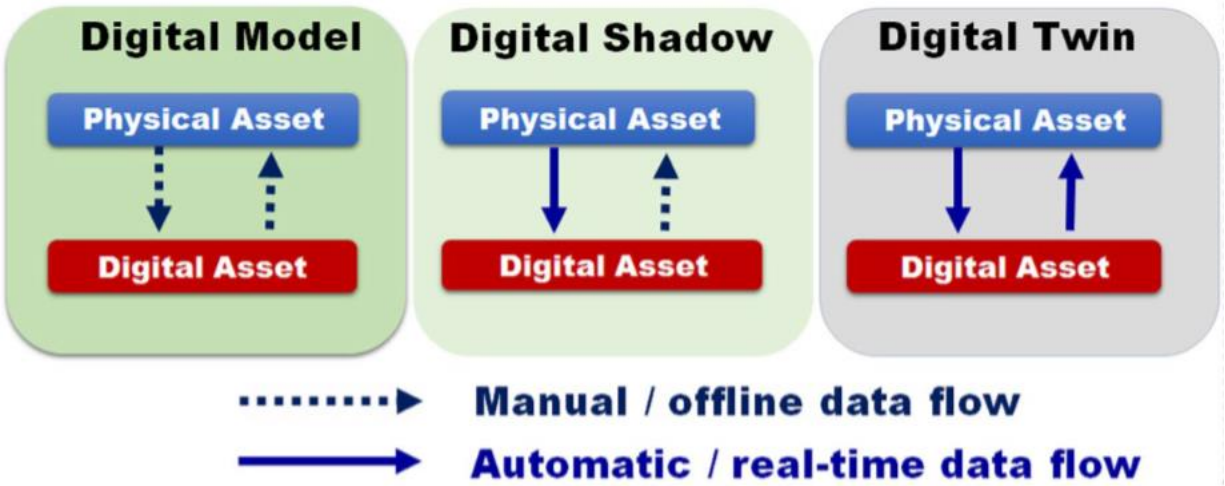


FIGURE 1.2 CONCEPTUAL DISTINCTION BETWEEN DIGITAL MODEL, DIGITAL SHADOW, AND DIGITAL TWIN ACCORDING TO THE LEVEL OF DATA EXCHANGE. SOURCE: ADAPTED FROM KRITZINGER ET AL. (2018) AND SINGH ET AL. (2021).

This distinction is significant for the thesis since the ultimate product is a readiness-oriented prototype rather than a fully functional Digital Twin.

1.3 Urban Digital Twins and the Role of Urban Data

Urban Digital Twins have been developed in response to the increasing demand for urban management that is data-driven, simulation-oriented, and integrated. They are being increasingly discussed in the context of smart cities, climate neutrality, infrastructure monitoring, mobility planning, environmental simulation, and energy transition. They have the capacity to combine disparate data sources and analytical tools in a common digital environment, to help analyze, anticipate and make decisions. (Dembski et al., 2020; Ketzler et al., 2020; Lei et al., 2023).

On the other hand, the quality and structure of urban data are critical to the development of Urban Digital Twins. A UDT cannot work properly if its underlying data is incomplete, fragmented, out of date, semantically weak, or difficult to integrate. For example, a building dataset may include footprints but no height values; height values may exist but be incomplete or inconsistent; building components may be stored as separate polygons without a common object identifier; or attributes may be distributed across layers without explicit relationships. These restrictions immediately limit the potential for the production of reliable 3D models and interoperable Digital Twin architectures (Biljecki et al., 2014; Noardo et al., 2020).

For this reason, it is imperative to evaluate the significance of urban data prior to discussing dashboards or platforms. The mere fact that a dataset can be visualized in 3D doesn't mean it's ready to be used in an UDT – technically or otherwise. A model may be visually understandable but not semantically coherent, standard-aligned, or scalable. So, the thesis is not only about whether data can be shown but if they can be used for organized 3D city modeling and future interoperable reuse.

Buildings are among the most central objects in 3D city models and UDT which is why urban building data are particularly significant. They are relevant for estimating energy consumption, solar analysis, urban morphology, emergency planning, infrastructure management, environmental modelling and

public-service planning. Additionally, buildings are hard to describe because they can be shown in different ways in different datasets, such as as footprints, cadastral units, volumetric units, addressable objects, building complexes, or building parts. This presents a structural and semantic problem for reuse (Biljecki et al., 2014; Kolbe et al., 2005).

The current thesis solves this issue by using multi-scale logic to an existing municipal building dataset. The analysis starts with large-scale urban data structures and proceeds to a fine-grained, object-level reading. This is significant because dataset preparedness cannot be fully comprehended using generic statistics or map visualization. While a dataset may appear to be comprehensive on a broad scale, it may still contain object-level issues, such as fragmentation, absent relationships, or weak semantic coherence. Figure 1.3 summarizes the practical gap between municipal GIS data and UDT-ready data.

The data-readiness gap

Between existing municipal GIS data and the requirements of 3D city modelling and future Urban Digital Twin reuse

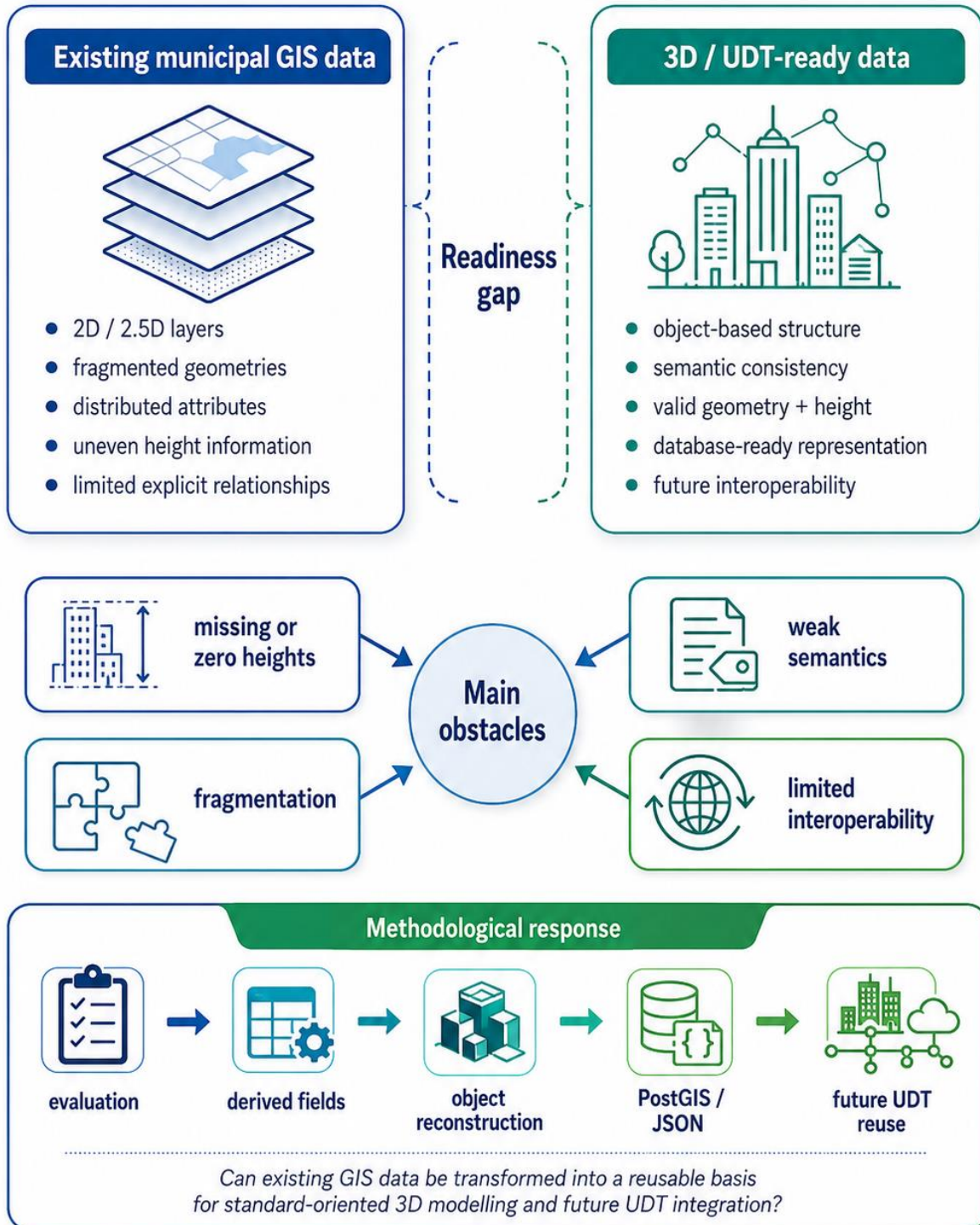


FIGURE 1.3 THE DATA-READINESS GAP BETWEEN EXISTING MUNICIPAL GIS DATA AND THE REQUIREMENTS OF 3D CITY MODELLING AND URBAN DIGITAL TWIN REUSE. SOURCE: AUTHOR'S ELABORATION.

Figure 1.3 demonstrates that the primary difficulty is not just data availability, but also the transformation of fragmented, incomplete, and weakly connected GIS elements into organized, semantic, and reusable urban objects.

1.4 Level of Detail in 3D City Modelling

The Level of Detail (LoD) is an important concept in 3D city modelling since it dictates the amount of geometric and semantic information represented in a model. A variety of applications necessitate varying levels of detail. A regional or city scale visualization may require simplified building volumes, whereas energy analysis, architectural interpretation, evacuation modelling or facade level simulation may require more precise geometry, roof structures, apertures, semantic surfaces or internal information. (Biljecki et al., 2014; Kolbe et al., 2005).

CityGML is one of the most important references for understanding LoD. It was developed as a semantic and multi-scale model for virtual 3D city models including geometric, topological and semantic features of urban objects such as buildings, transportation objects, vegetation, water bodies and terrain (Kolbe et al., 2005; Open Geospatial Consortium, 2023).

The historical importance of CityGML is that it overcame a significant weakness of earlier 3D models: numerous models were able to show urban geometry, but they did not offer a shared semantic structure. CityGML is designed to facilitate semantic and syntactic interoperability by defining common object classes, characteristics and relations for 3D city models. In simple words CityGML enables software and users to grasp not just that a shape exists, but what the form stands for: a structure, a building portion, a wall surface, a roof surface, topography, road space, vegetation or any other city object (Gröger & Plümer, 2012; Kolbe et al., 2005).

CityGML arranges city items in multiple LoD. LoD0 is a rough regional- or terrain-level model. LoD1 models are simple block models of buildings. LoD2 comprises distinct roof structures and more elaborate exterior features. Walls, rooftops, balconies, doors, and windows comprise complex architectural exterior components in LoD3. LoD4 extends the model to inside building structures. Depending on the use case, this hierarchy permits varying degrees of abstraction while representing the same city or building (Biljecki et al., 2014; Kolbe et al., 2005).

LoD is not just employed as a visual category for this thesis. It is used as an evaluative idea. A dataset with building footprints and usable heights allows for volumetric depiction, similar to LoD1. LoD2 support requires roof geometry to be present and reliable. LoD3 cannot be directly supported without facade elements, apertures, texturing or detailed architectural components. LoD thus provides a means to operationalize the vague concept of “3D readiness”, by translating it into an actual question: to what extent can the dataset at hand assist 3D city modelling?

Figure 1.4 depicts the Level of Detail hierarchy utilized in this thesis to determine what kind of 3D representations are actually supported by the available data.

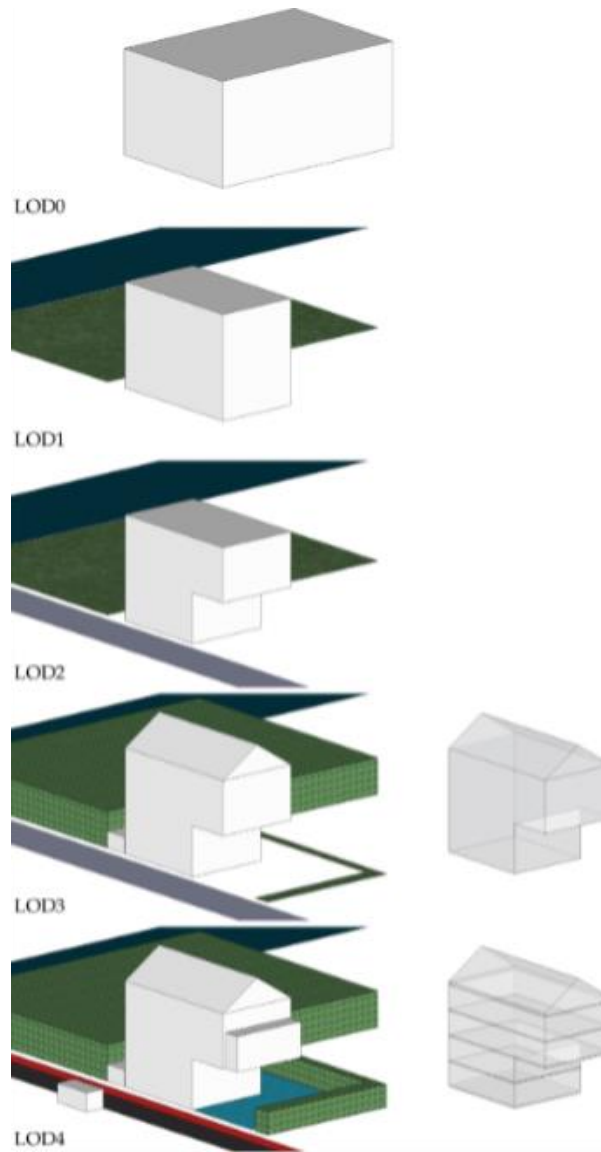


FIGURE 1.4 LEVELS OF DETAIL IN CITYGML, FROM REGIONAL OR BLOCK-LEVEL REPRESENTATION TO DETAILED EXTERIOR AND INTERIOR BUILDING MODELLING. SOURCE: ADAPTED FROM KOLBE ET AL. (2005) AND BILJECKI ET AL. (2014).

This means that with the dataset available, LoD1-like modelling can be performed if footprint and height information is available, but higher LoDs need extra roof, façade, texture, opening or interior information.

1.5 Interoperability and FIWARE

Interoperability is required for both 3D city modeling and urban digital twin development. Urban data are frequently created by multiple institutions, departments, platforms and technical systems. These data can vary in format, scale, update frequency, accuracy, meaning and purpose. Consequently, the obstacle is not only to obtain data, but also to render it comprehensible and reusable across systems (Ketzler et al., 2020; Lei et al., 2023).

In the scope of this thesis, interoperability is considered a multi-layered criterion and not a simple file exchange. CityGML and CityJSON are relevant as they are reference models for representing urban objects via geometry, semantics, LoD and object relationships. FIWARE/NGSI-LD is pertinent at a later stage due to its implementation of an entity–property–relationship structure that facilitates context-data interoperability, making it appropriate for future UDT-oriented workflows. PostGIS is complimentary, because it allows the reconstructed object logic to be saved, searched, related and exported in a spatial relational database. Thus, these references are not seen as competing standards but as complementary components of the same transformation pathway: CityGML/CityJSON are supporting the readiness of the 3D city modelling, FIWARE/NGSI-LD are fostering the future interoperability and PostGIS are providing the database structure needed to operationalize and validate the reconstructed data model (Conde, Munoz-Arcentales, Alonso, et al., 2022; Kolbe et al., 2005; Ledoux et al., 2019).

The CityGML data model can be more easily integrated with developer-oriented, more practical digital processes with the help of CityJSON. CityGML is an essential open standard for the representation of 3D city objects by means of geometry, semantics, relationships and LoD. Its XML/GML encoding, however, might be difficult and unclear for direct implementation in application-oriented or web-based settings. CityJSON tries to overcome this by providing a compact JSON encoding of the CityGML data model, allowing 3D city information to be more easily parsed, exchanged and integrated in digital systems. The significance of this approach is that it respects the object-oriented logic of CityGML, while also allowing for a more lightweight and interoperable data exchange. In particular, the identifiers and parent-child relationships allow for complex urban objects to be represented as organized entities made of connected elements. This logic is effective in transforming fragmented geographic data into a more cohesive object-based form and preparing such data for subsequent database, web and UDT-oriented operations (Ledoux et al., 2019).

FIWARE serves a distinct purpose than CityGML and CityJSON. It is not used in this thesis as the major standard for creation or modelling of 3D geometry. Instead, it is envisioned as a future interoperability layer that will enable the reuse of organized urban objects in UDT-oriented contexts. FIWARE was born as a set of European Future Internet initiatives, and has grown into an open-source ecosystem to develop smart applications. Its significance for this research is derived from context information management, which involves the representation of real-world or logical objects as entities, the description of their properties, and the connection of these objects to other objects through relationships.(Bauer, 2021a; Conde, Munoz-Arcentales, Romero, et al., 2022).

The Context Broker is the core component of the FIWARE architecture. Applications can generate, query, update and subscribe for context information of entities. In an urban context, an entity can represent different types of things or occurrences, such as a building, a district, a road segment, a sensor, an environmental observation or an infrastructure component. NGSI-LD expands this logic with linked-data principles whereby context information is described as an entity–property–relationship model. UDT are notably affected by this, as urban systems are comprised of numerous interconnected objects that span various domains and scales. With this architecture FIWARE/NGSI-LD can contribute to making urban information more interoperable, queryable and re-usable across platforms and applications (Bauer, 2021a; Conde et al., 2024; FIWARE Foundation, 2026).

In this thesis, FIWARE/NGSI-LD is consequently positioned subsequent to the logic of object-reconstruction and 3D city modeling. First, the dataset is assessed to check whether it is able to enable

structured 3D city modelling, object interpretation and Building/BuildingPart interactions. After this step the reconstructed items can be viewed as potential entity-based structures for future usage in the Urban Digital Twin. Accordingly, CityGML and CityJSON enable the assessment of 3D city modelling readiness, whereas FIWARE/NGSI-LD supports the latter question of how rebuilt urban objects could be represented, linked, queried and reused in an interoperable Digital Twin oriented environment. Figure 1.5 illustrates the role of FIWARE/NGSI-LD as this interoperability layer. As demonstrated in Figure 1.5, FIWARE is structured around the handling of context information. IoT Agents are in charge of translating data coming from different devices or urban systems and then are handled by the Context Broker using NGSI-based communication. This architecture is significant for Urban Digital Twins because it enables representation of heterogeneous urban objects and observations as entities, attributes and relationships. In this thesis context, the figure explains why FIWARE is considered an interoperability layer, and not a 3D modelling standard: it enables the future connection, querying and updating of structured urban objects, after their geometric and semantic reconstruction has been defined by 3D city modelling logic.

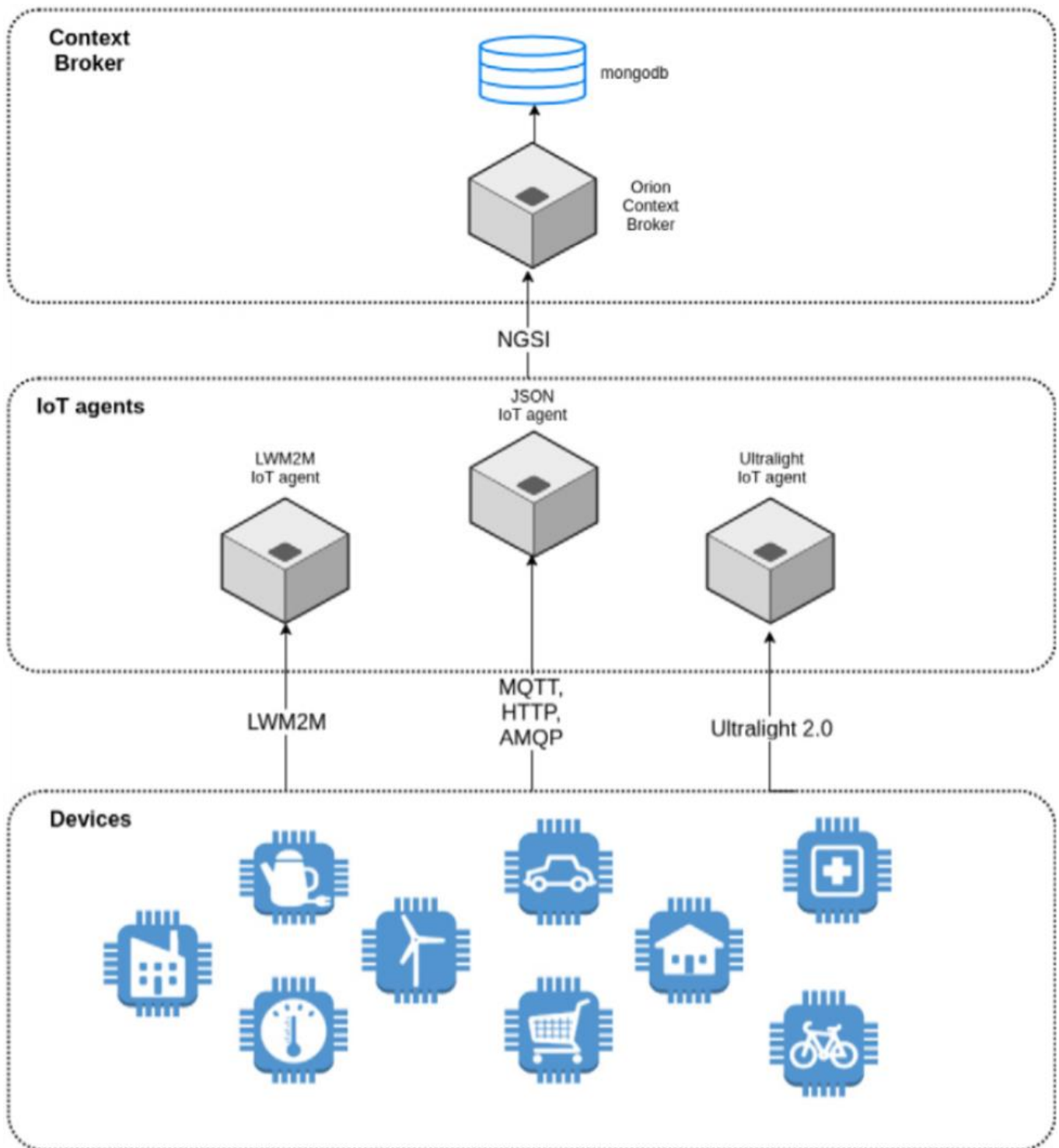


FIGURE 1.5 FIWARE CONTEXT-INFORMATION ARCHITECTURE SHOWING THE ROLE OF THE CONTEXT BROKER IN MANAGING ENTITY-BASED URBAN INFORMATION. SOURCE: FIWARE FOUNDATION, ADAPTED BY THE AUTHOR.

1.6 Scalability as a Dataset and Methodological Requirement

Scalability is key to this thesis, because preparedness of the datasets cannot be judged at one spatial level only. Urban datasets are frequently employed at several scales: at the regional or institutional level, at the city scale, at the district level and for granular object-level interpretation. A dataset may appear complete on a large scale while revealing substantial deficiencies at the level of individual items or components (Lei et al., 2023; Noardo et al., 2020).

In this thesis, scalability is conceived as a methodological necessity with three interrelated dimensions. First, geographical scalability is the ability of the workflow to shift between different levels of analysis, from broad territorial or institutional contexts to the interpretation of city, district, building and component levels. This is significant because, on a broad scale, urban data may appear comprehensive, but more thorough examination can show missing features, fragmented objects, or weak links. Second, data-structure scalability is about applying the same transformation logic to multiple objects, not treating each scenario as a separate manual task. Such a scalable system needs to provide reproducible rules for detecting things, keeping their components, producing identifiers, and displaying relationships. Third, database scalability is the ability to store, query, relate and export the reconstructed information in a structured environment that can be supported by future automation and integration. This framework introduces the PostGIS, because it allows to describe the reconstructed object logic as a spatial relational structure. The Building/BuildingPart logic might go beyond a visual process in GIS and be saved in related tables, run queries using SQL, exported in GeoJSON/JSON, and perhaps re-utilized for other objects and larger datasets. Therefore, the scalability concept in this thesis is not only about working at a bigger geographical extent, but is also about building a repeatable and database backed procedure to get from GIS characteristics to organized urban objects.

CityGML is scalable as it has been developed as a multi-scale 3D city model. It can depict urban objects at various levels of complexity and supports both large-area models and specific building representations. This makes it appropriate for study ranging from broad metropolitan environment to object-level interpretation. CityJSON promotes practical scalability by simplifying the CityGML data model into a more compact JSON-based structure, making it easier to process, exchange, and potentially employ in web-based processes (Kolbe et al., 2005; Ledoux et al., 2019).

Scalability is also determined by the generalizability of reconstruction principles. A workflow that works for only one manually interpreted object is constrained. If the process establishes a repeatable rule, for example understanding one real world item as a parent object and its geometric components as related parts, then the logic can possibly be applied to numerous objects. But this requires accurate grouping criteria, durable identities or automated spatial techniques. Scalability is therefore not simply a concern of software performance, but also of data structure, object logic and methodological transferability (Lei et al., 2023; Noardo et al., 2020). The multi-scale meaning of scalability is summarized in Figure 1.6.

General logic of dataset and methodological scalability

From broad geodata context to database/output representation

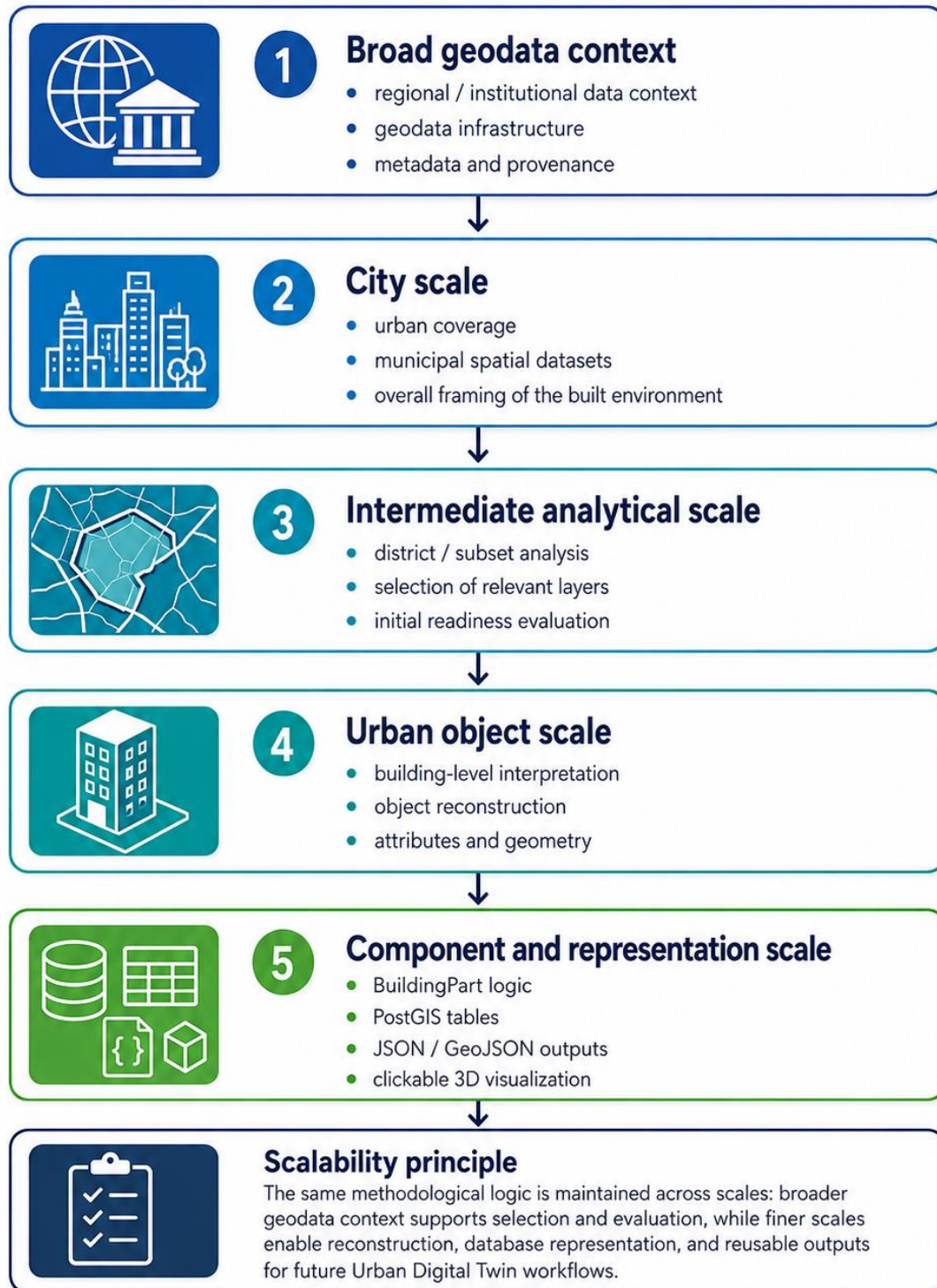


FIGURE 1.6 GENERAL LOGIC OF DATASET AND METHODOLOGICAL SCALABILITY, FROM BROAD GEODATA CONTEXT TO DATABASE/OUTPUT REPRESENTATION. SOURCE: AUTHOR'S ELABORATION.

From what can be seen in Figure 1.6, scalability is understood to be a methodological condition. This means that the same logic should be able to transition from a broad geodata context to object reconstruction and database/output representation.

1.7 State of the Art and Research Positioning

1.7.1 From 3D City Models to Urban Digital Twins

According to the literature, 3D city models serve as a solid foundation for UDT, but they are not interchangeable. A 3D city model provides the geographical and semantic representation of urban objects. A UDT requires extra layers of interoperability, dynamic context, simulation and decision support (Ketzler et al., 2020; Lei et al., 2023).

In the realm of 3D city models, CityGML is one of the most widely recognized standards. Kolbe et al. characterize CityGML as a multi-purpose and multi-scale model that encompasses the geometric, topological, and semantic features of 3D city models. They also mention the fact that CityGML differentiates between several classes of urban items such as buildings, transportation objects, vegetation, water bodies and topography. This makes it useful for big area city models as well as building level depiction (Kolbe et al., 2005).

Evaluations of dataset readiness are particularly pertinent to the building model. In CityGML a building is represented by a Building object and may contain BuildingPart members. This is significant due to the fact that municipal GIS data does not usually depict real-world buildings as singular, simple objects. They could be separated in volume units, footprints, or other components. Therefore, the CityGML Building/BuildingPart logic offers a valuable reference for a more structured interpretation of disintegrated building geometries (Kolbe et al., 2005; Ledoux et al., 2019).

CityJSON strengthens this topic by making the CityGML data model more useful to developers and web-based operations. Ledoux et al. believe that CityJSON respects the logic of the CityGML data model while eliminating some of the XML/GML encoding's complexity. They also show that CityJSON can describe a Building and its BuildingPart objects using identifiers and parent-child connections, which is directly relevant to object reconstruction from fragmented GIS data (Ledoux et al., 2019).

Nevertheless, a structured 3D city model is only one component of the UDTs system. UDTs also need to be able to link data from different domains, and to update or query information on urban objects. This is the reason why interoperability frameworks like FIWARE/NGSI-LD play an important role when the 3D object structure is clarified. FIWARE is an entity-based logic for organizing context information. CityGML/CityJSON provides the geometric and semantic object logic for 3D city modelling (Bauer, 2021a; Conde, Munoz-Arcenales, Alonso, et al., 2022).

1.7.2 Interoperability and FIWARE for Urban Digital Twins

Interoperability remains one of the major obstacles in UDTs development, since urban information is seldom created within one system or according to one data model. Cities are usually locations where heterogeneous datasets are hosted including GIS layers, BIM models, sensor observations, environmental measurements, administrative records, simulation outputs and operational data streams. These sources are often produced by different institutions, for different objectives, at different spatial scales, and with

distinct update cycles. The key challenge is thus not only data collection, but the ability to make heterogeneous datasets comprehensible, interrelated and reusable across platforms, domains and decision-making processes (Ketzler et al., 2020; Lei et al., 2023).

In this sense, FIWARE is relevant since it provides an open-source ecosystem for smart applications and context information management. Its logic is based on the representation of real or logical things as entities, which can be specified by properties and related to other entities by relationships. An entity might be a building, a district, a road segment, a sensor, an environmental observation, an infrastructure part or another urban object in an urban context. Each entity can contain descriptive or dynamic information like: height, use, status, location, measurements or references to related objects. This entity–property–relationship structure provides FIWARE/NGSI-LD with the ability to express urban information in a way that can be searched, modified, connected and reused in future DT-oriented workflows (Bauer, 2021a; Conde et al., 2024).

In this thesis, FIWARE is not considered as a replacement of CityGML or CityJSON. This divergence is significant since the standards have different aims. 3D city modeling readiness assessments refer to CityGML and CityJSON as they cover directly urban objects, geometry, semantics, LoD and object structures. Instead, FIWARE/NGSI-LD is adopted as a second interoperability layer, because it allows to represent organized urban objects as entities and connections in a wider context-information environment. FIWARE is not used for the generation of 3D geometry, but for the description of how rebuilt or structured urban objects could be linked, subsequently, to other datasets, services, sensors, dashboards or applications in a UDT-oriented system.

When working with urban data that is fragmented or layer-based, this duty is of particular importance. Once the spatial features have been interpreted, and transformed into sound urban objects, the same structure can be translated into FIWARE/NGSI-LD style logic: a main object can be considered as a parent entity, its components as related entities, and their connections can be expressed through relationships such as *hasPart* or *partOf*. In this way, the item is not only comprehensible as a geometric shape, but also as a structured information entity, which can possibly be in interaction with various streams of urban data. FIWARE/NGSI-LD thus enables future interoperability of reconstructed urban data through clear and reusable objects, properties and relationships across multiple DT-oriented workflows (Bauer, 2021a; Conde et al., 2024; FIWARE Foundation, 2022).

1.7.3 Challenges in Urban Digital Twin Implementation

Despite increased interest in UDTs, their implementation is challenging due to the heterogeneity of urban data settings. Many forms of information are used to describe cities such as GIS layers, BIM models, sensor observations, environmental measurements, administrative records, infrastructure databases and simulation results. These datasets are often produced by multiple institutions, for different objectives, at different spatial and temporal scales. Integration is therefore not merely a technical issue of changing file formats but rather a semantic and methodological issue of making heterogeneous datasets intelligible, comparable and reusable inside the same digital context (Biljecki et al., 2014; Noardo et al., 2020).

A second significant difficulty is data quality and completeness. UDTs need trustworthy data concerning geometry, properties, relationships, and, in increasingly complex situations, temporal change. This is particularly crucial for 3D city modelling, since the achievable LoD is directly dependent on accessible

information. Building footprints could serve as a simple spatial representation, but height values are needed for LoD1-like volumetric modelling, roof structures for LoD2 interpretation and façade elements, openings, textures or interior information for higher levels of complexity. Missing heights, inaccurate or fragmented geometries, confusing characteristics and weak object relationships can thus reduce the reliability of 3D outputs as well as their reusability in UDT-oriented operations (Biljecki et al., 2014; Kolbe et al., 2005).

Scalability is the third obstacle to overcome. A workflow might function in a small pilot region or for one object, but this does not immediately guarantee its scalability to a district, a city or a larger territorial dataset. Repeatable rules, stable identifiers, consistent attributes, object relationships and standard-oriented structures are the key to scalability. That's fine if each object is interpreted by hand. It's not a very generalizable procedure, though. Therefore, an assessment of dataset-readiness should include not just what can be done in one particular scenario, but also if the same logic can be transferred, automated and applied across bigger datasets (Ledoux et al., 2019; Lei et al., 2023).

A further obstacle is the discrepancy between formal standards and actual municipal data. There are sophisticated reference models to organize urban information such as CityGML, CityJSON and FIWARE/NGSI-LD, although existing public data do not automatically match their geometric, semantic or relational requirements. In practice, standard-oriented implementation may encounter problems of incomplete geometry, inconsistent semantics, georeferencing, software interoperability, lost attributes or missing object relationships. This emphasizes the importance of testing standards readiness on real datasets and not presuming that data can be directly utilized in 3D city modelling or UDT systems just because standards exist (Noardo et al., 2020).

1.7.4 Synthesis of the Literature and Research Gap

The literature reviewed in this chapter reveals that the shift from municipal GIS data to UDT-oriented systems is not an automatic one. Different standards and frameworks facilitate this shift at different levels. INSPIRE and Spatial Data Infrastructure principles assist institutional organization, documenting, discovery, access and interchange of public geodata. CityGML specifies urban objects, LoD and relationships among components as a conceptual reference for semantic multi-scale 3D city modeling. CityJSON goes farther and provides a more compact and practical JSON-based encoding of CityGML that makes the CityGML data model more usable in digital workflows, on the web and for structured data interchange. FIWARE/NGSI-LD adds an additional layer of interoperability by modeling urban information as entities, characteristics and relationships that can be accessed, updated and linked in future context-data and Digital-Twin oriented applications. Thus, these frameworks shall not be considered as independent or competing solutions, but complementing references in a continuous transformation route from institutional geodata to structured 3D city objects and eventual interoperable urban digital systems (Bauer, 2021a; Conde et al., 2024; Kolbe et al., 2005; Ledoux et al., 2019).

This thesis addresses the research gap between data availability and standard-oriented reuse, the intermediary stage. Public administrations may already have authoritative and geographically detailed building datasets, but the existence of such data does not inevitably suggest that they are ready for 3D city modelling or UDT integration. Many municipal GIS datasets have been intended for mapping, administrative management or territorial reference rather than for semantic 3D representation, object-based modelling or interoperable digital workflows. And so, a crucial missing step is the systematic

assessment of whether existing data can support the geometric information, semantic attributes, object structures, LoD, interoperability requirements and scalability conditions required for future 3D city modelling and UDT-oriented applications (Biljecki et al., 2014; Ketzler et al., 2020; Lei et al., 2023).

This thesis bridges this gap by proposing and using a multi-scale dataset-readiness evaluation. The investigation does not accept municipal geodata as ready-made for sophisticated digital urban systems. Instead, it investigates how such data may be examined, processed and restructured through a structured workflow. The technique starts from the wider institutional and territorial geodata framework, followed by the data evaluation at the district level and ends with the interpretation at the object and component level. In this way, the project analyzes whether a municipal building dataset existing in a traditional GIS-layer structure may be turned into a more standard-oriented and reusable data format. The contribution is twofold: first, it assesses the dataset's usability for 3D city modelling in terms of CityGML/CityJSON-oriented concepts like Building, BuildingPart, and LoD; second, it investigates how the reconstructed structure could facilitate future UDT interoperability through FIWARE/NGSI-LD-style entities, properties, and relationships.

1.8 Research Problem, Aim and Thesis Structure

The research issue might be described as follows: The available municipal building data today are not automatically ready to be used in 3D city modelling or UDTs. They may be authoritative, available and usable for traditional GIS but still lack the geometry, height information, semantic structure, item hierarchy or linkages needed by standard-oriented digital urban systems.

The main research question is:

Considering geometric completeness, semantic richness, interoperability, and scalability, to what extent can an existing municipal building dataset facilitate the transition from GIS-based representation to CityGML/CityJSON-oriented 3D city modeling and FIWARE/NGSI-LD-oriented UDT interoperability?

The purpose of this thesis is to assess the readiness of a state-of-the-art municipal building dataset for 3D city modeling and for future reuse directed to UDT. The thesis specifically seeks to evaluate whether the available data can support a CityGML-oriented Building/BuildingPart interpretation, ascertain what LoD is realistically achievable, identify the primary geometric and semantic limitations, test reconstruction logic through in-depth object-level analysis, and discuss how FIWARE/NGSI-LD entities and relationships could be used to represent the reconstructed output in the future. A prototype using PostGIS shows that the rebuilt Building/BuildingPart structure may be kept as a queryable spatial relational model, linked by database relationships and exported to GeoJSON and NGSI-LD style outputs.

This thesis does not intend to develop a complete UDT platform, nor does it intend to produce a complete CityGML/CityJSON translation or to deploy a working FIWARE Context Broker. It concentrates on the preliminary but critical stage of assessing the readiness of the dataset. This distinction is crucial, because the transfer from municipal GIS data to UDT-oriented workflows requires a methodical review of the data before advanced implementation can be considered. The thesis consequently contributes a methodological and technical workflow, which integrates institutional geodata, standards for 3D city modelling, object level reconstruction, representation in a spatial database and future interoperability logic.

The thesis consists of five key chapters. Chapter 1 explains the theoretical basis of 3D city modelling, UDTs, LoD, interoperability, FIWARE/NGSI-LD, scalability and the research gap. Chapter 2 presents the multi-scale dataset-readiness framework and describes the technique. Chapter 3 The case-study context, data sources, spatial dimensions, and building-scale focus Chapter 4 presents the application of the methodology in terms of QGIS processing, PostGIS relational modelling, GeoJSON and NGSI-LD-style outputs and interactive 3D visualization. Chapter 5 ends with a discussion of findings, answer to the research question, contribution and limitations of the study and future work.

02

CHAPTER

Methodology

Defining the analytical workflow used to assess data quality, interoperability, and reuse potential.

2.1 Methodological Approach and Conceptual Framework

The methodology is developed to assess dataset preparedness. It does not presume the available geospatial data is ready for advanced digital urban applications. In contrast, it assesses if the data have the geometric, semantic, structural and interoperable features required for 3D city modelling and future UDT-oriented reuse.

The methodological perspective of the thesis is founded on the concept that the transfer from ordinary GIS data to 3D city modelling and Urban Digital Twin settings is not automatic. Municipal datasets are typically created for mapping, administration or planning purposes. 3D city modelling and DT frameworks have additional requirements, including height information, object coherence, semantic attributes, explicit relationships and compatibility with standard-oriented structures. The methodology thus not only assesses the availability of spatial data but also their potential for interpretation, transformation and reuse within increasingly complex digital urban workflows (Biljecki et al., 2014; Ketzler et al., 2020; Lei et al., 2023).

The methodology is also standards-aware, which means that the evaluation is not restricted to the dataset's internal quality but is explicitly linked to well-established reference models for 3D city modelling, interoperability, and spatial data management. CityGML and CityJSON serve as conceptual reference points for determining whether the data supports semantic 3D city objects, LoD, and Building/BuildingPart structures. FIWARE/NGSI-LD is utilized as reference for future UDT interoperability, in particular by modelling information as entities, properties and relationships. The implementation environment of PostgreSQL/PostGIS is introduced to evaluate if the reconstructed object structure could be stored, associated, searched and exported in a spatial relational database. We do not consider these standards and tools as complete implementation targets in this thesis. The dataset is not fully translated to CityGML or CityJSON and a FIWARE Context Broker is not deployed. Conversely, the standards are utilized as analytical and methodological benchmarks to assess what the dataset can presently support, what information is lacking and what changes are needed for future usage. In this way CityGML/CityJSON are the guide for the assessment of the 3D modeling preparedness, FIWARE/NGSI-LD are the guide for the interpretation of the future interoperability and PostGIS is the technique to practically evaluate the rebuilt object logic through a queryable database structure (Bauer, 2021a; Conde et al., 2024; Kolbe et al., 2005; Ledoux et al., 2019).

The framework is constructed in four primary areas of evaluation: geometric completeness, semantic richness, interoperability and scalability. These dimensions were chosen because they represent the essential characteristics that an urban dataset should satisfy before it can enable standard-oriented 3D city modelling and future UDT-oriented reuse. Geometric completeness refers to the validity of spatial features and the usability of vertical information like height or elevation values inside the dataset that could support 3D representation. Semantic richness Availability and clarity of non-geometric information, including object type, function, characteristics, or component meaning. Interoperability is the possibility to interpret, trade, link and reuse the dataset by means of standard-oriented structures, such as object identifiers, relationships and entity-based representations. Scalability means that the same reasoning can be translated over several spatial levels and reproduced for multiple objects, rather than a single manual example.

These four dimensions are required since dataset preparedness cannot be determined using a single metric. A dataset could have geometrically acceptable features but no useful semantic properties. It may contain useful information, but it does not define explicit relationships between objects and their components. It

may also be applicable for visualization at a scale but not for precise object-level reconstruction or wider applicability across a district or city. The technique assesses the dataset readiness by combining geometric, semantic, relational and methodological constraints. This technique allows understanding not only if data exist, but if they are structured enough to support 3D modelling, standard alignment, database representation and future UDT-oriented operations (Biljecki et al., 2014; Lei et al., 2023; Noardo et al., 2020).

A key characteristic of the technique is its multi-scale logic. The assessment is not limited to the broad territorial level and is not focused on only one object. It is rather aimed at going from coarse spatial context to more precise object and component level analysis. More broadly the dataset can be analysed by institutional provenance, territorial coverage, coordinate reference system, general completeness and layer structure. At intermediate scales the analysis can look at patterns in the availability of data for example the distribution of usable height information, or the consistency of building related features. The methodology can be applied at detailed scales to determine, whether individual urban objects are coherently represented, whether their components can be identified and whether relationships between parent objects and parts can be made explicit.

This multi-scale structure is significant because different data restrictions are obvious at different levels of investigation. At the city-wide or district-wide layer, a dataset can look comprehensive but deeper investigation may reveal missing heights, fractured geometries, confusing semantics or weak object associations. On the one hand, it is not very useful to thoroughly reconstruct one thing without a larger methodological logic that might perhaps be repeated. The approach, thus, takes the broader spatial context, intermediate analytical scale, object scale and component scale as interconnected stages of the same dataset-readiness evaluation. This allows the research to assess both the overall quality of the dataset and its potential for standard-based reconstruction at a more granular level.

In this respect, scalability is not just considered as a technical attribute of software, platforms or computing performance. As a methodological condition, it is assumed that the proposed procedure can be replicated beyond a single case. A dataset and method are more scalable when the same interpretation and transformation logic can be applied to various objects, spatial units, or levels of analysis. If a procedure is simply demonstrated using a single manual example, then it is a demonstration. But where the workflow involves clear and repeatable rules for object identification, preservation of components, assignment of standardized attributes, creation of unique identifiers and representation of relationships, the same logic may be extended to wider datasets if suitable grouping criteria, spatial rules or stable identifiers can be found (Ledoux et al., 2019; Lei et al., 2023).

This methodological position is summarized in Figure 2.1 that shows the link between four elements of the dataset-readiness framework: the assessment dimensions, the reference standards, the GIS-based processing steps and the database/output representation. The figure describes that the methodology is not only based on data visualization in 3D but also on assessment if data can flow through a coherent transformation path: from municipal GIS layers, to standard-oriented object interpretation, to PostGIS-based relational representation, and finally to future interoperable outputs. Figure 2.1 is thus the conceptual linkage between the theoretical framework in Chapter 1 and the operational process which is used later in Chapter 4.

Conceptual framework of the dataset-readiness methodology

Linking evaluation dimensions, standards, GIS processing, PostGIS representation, and future interoperability

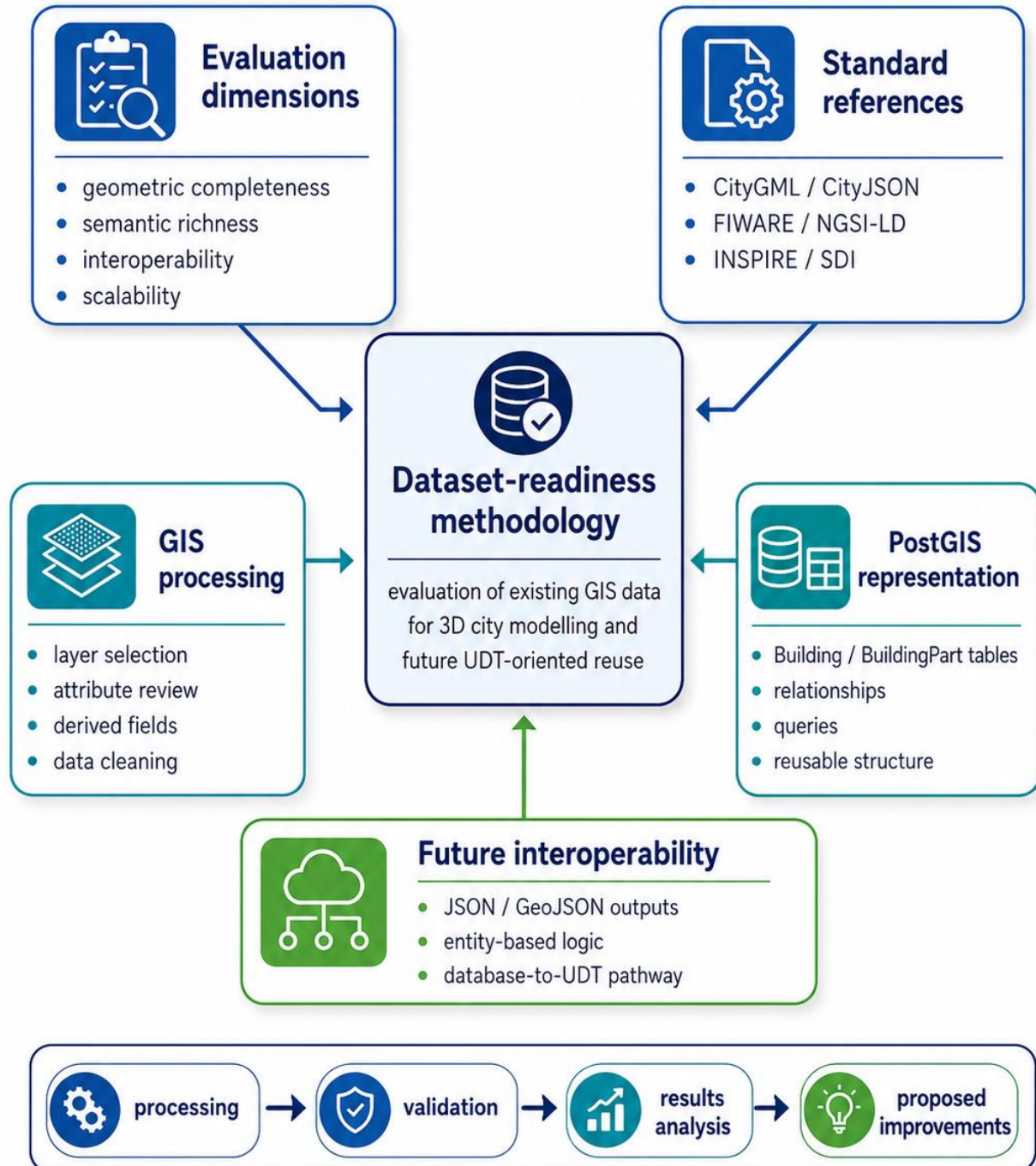


FIGURE 2.1 CONCEPTUAL FRAMEWORK OF THE DATASET-READINESS METHODOLOGY LINKING EVALUATION DIMENSIONS, STANDARDS, GIS PROCESSING, POSTGIS REPRESENTATION, AND FUTURE INTEROPERABILITY. SOURCE: AUTHOR'S ELABORATION.

2.2 Multi-scale Dataset-Readiness Logic

The multi-scale logic of the methodology is founded on the premise that urban datasets cannot be assessed from a single level of analysis. The same dataset can be useful for a wide geographical overview, district level assessment, an object level reconstruction or a component level interpretation but each scale asks for different level of detail and focuses on different types of limits. For example, a dataset may seem to be comprehensive and helpful when seen as a city- or district-wide map, but a more detailed object-level examination may show missing height values, fragmented geometries, ambiguous semantic features, or poor inter-part linkages. On the other hand, a detailed reconstruction of one thing can be a matter of technological feasibility but cannot be deemed methodologically scalable unless it is related to repeatable rules that can be possibly applied to other objects or locations. The methodology is thus constructed as a continuous succession of scales, not as a collection of discrete analyses.

The initial level revolves around the comprehensive institutional and spatial framework. At this level, the dataset is analysed in terms of territorial coverage, provenance, coordinate reference system, source structure, documentation and institutional role. The objective is not yet to recreate precise objects but to understand where the data come from, what spatial area they cover, how they are organised and if they are traceable, reusable. This level is closely related to Spatial Data Infrastructure logic, because metadata, access conditions, documentation and institutional reliability are fundamental features of dataset ready. In this respect, preparedness is not only a matter of geometry or properties, but also whether the dataset is appropriately documented and embedded into a credible geodata framework.

Level two pertains to the intermediate analytical scale. At this level, the dataset is treated as a set of spatial features within a given research area. The goal is to evaluate overall trends of completeness, consistency and usability before proceeding to detailed interpretation of objects. This includes identifying important layers, validating geometries, selecting usable attributes, analyzing missing or null values, determining height availability, and understanding the distribution of building-related information across the dataset. This level offers evidence on the general state of the data and supports the assessment of whether the dataset can sustain basic 3D modelling operations, such as LoD1-like extrusion, at a more extensive analytical scale.

The urban object scale is the subject of the third phase. At this level the technique investigates whether a real-world urban entity may be understood as a coherent digital object. This is related to the fact that many municipal GIS datasets are structured in terms of layers and features, rather than full object-based models. A real-world object might be represented by one polygon, numerous polygons, volumetric units or related elements scattered over different levels. The object-scale analysis consequently examines if these GIS data can be understood with standard-oriented categories such as urban objects, buildings and building pieces. This level is crucial as it ties the overall dataset evaluation to the question of whether the data can support effective 3D city modelling.

At the fourth level, the component scale is addressed. At this stage, the analysis is directed at the parts which comprise an urban object. This is particularly true for 3D city modelling, since standards such as CityGML and CityJSON allow representation of complex objects through components, parts, semantic surfaces and relationships. In a typical GIS data set, these pieces may exist as independent geometries or properties that do not necessarily have an explicit parent-object relationship. The methodological question is whether these components can be retained, identified and related to a coherent parent entity. This is a

significant step towards the organized reconstruction of objects and not just visualization.

Overall, this multi-scale structure enables the thesis to assess the preparedness of the dataset from both a broad and detailed perspective. The wide and intermediate levels show data provenance, coverage, layer structure and overall usability. The object and component levels test if the dataset is able to allow standard-oriented reconstruction. This prohibits the evaluation to be based exclusively on aggregate indicators that can disguise flaws at the object level. At the same time, it avoids the comprehensive study of objects becoming an isolated example, because the object-level test remains linked to the wider data collection and analytical framework. This multi-scale analytical logic is illustrated in Figure 2.2, where the transition from wide spatial context to intermediate analysis, interpretation of urban objects and re-construction at component level.

Multi-scale analytical logic of the methodology

Moving from broad spatial context to intermediate analytical scale, urban object scale, and component scale

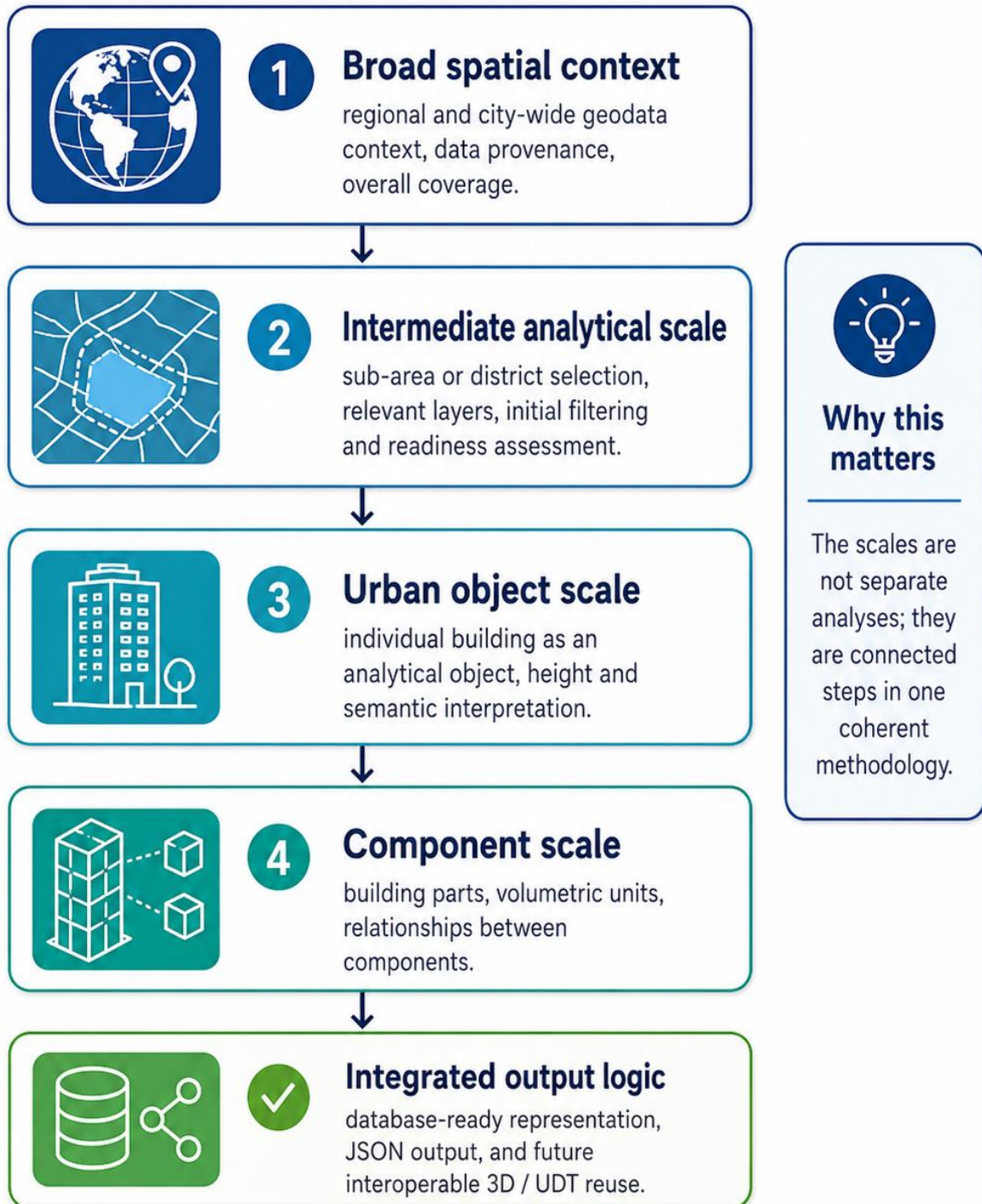


FIGURE 2.2 MULTI-SCALE ANALYTICAL LOGIC OF THE METHODOLOGY, MOVING FROM BROAD SPATIAL CONTEXT TO INTERMEDIATE ANALYTICAL SCALE, URBAN OBJECT SCALE, AND COMPONENT SCALE. SOURCE: AUTHOR'S ELABORATION.

2.3 Analytical Workflow

The analytical workflow is subdivided into four sequential steps to transform the conceptual framework into a pragmatic and traceable research activity. The necessity of this structure is that dataset-readiness evaluation cannot be reduced to a single technical operation, such as database export, extrusion, or mapping. Alternatively, the process needs to know the source data, confirm its applicability, analyze the results and lastly suggest changes for future usage. Therefore, the technique is arranged as a sequence of interrelated phases: data processing and model setup; methodological validation and consistency testing; analysis of results and identified issues; and synthesis of findings and proposed improvements.

These phase titles are utilized again in Chapter 4 where the approach is applied to the case study. This allows for a direct linking of the methodological design and the empirical implementation. Thus, Chapter 2 describes the framework of the dataset-readiness evaluation, while Chapter 4 illustrates the application of this same structure through QGIS processing, derived field construction, PostGIS representation, SQL validation, export to GeoJSON/NGSI-LD style, and interactive 3D visualization. In this way, the methodological theory and the empirical application are always in line with each other. This chapter presents the technical operations performed in the case study as a practical application of the analytical process outlined in Chapter 2, rather than as a series of separate procedural procedures.

Figure 2.3 illustrates the operational sequence of the technique. The workflow is shown to commence with the preparation and understanding of the dataset, followed by validation and consistency checks, then interpretation of results and limitations, and lastly a synthesis of findings and improvement recommendations. It also helps to link the conceptual framework to the case-study application, elucidating how each of the phases contributes to the subsequent overarching goal of assessing the potential for existing municipal building data to facilitate 3D city modelling and future UDT-oriented reuse.

Four-phase analytical workflow for dataset-readiness evaluation

General workflow applicable to municipal geospatial datasets

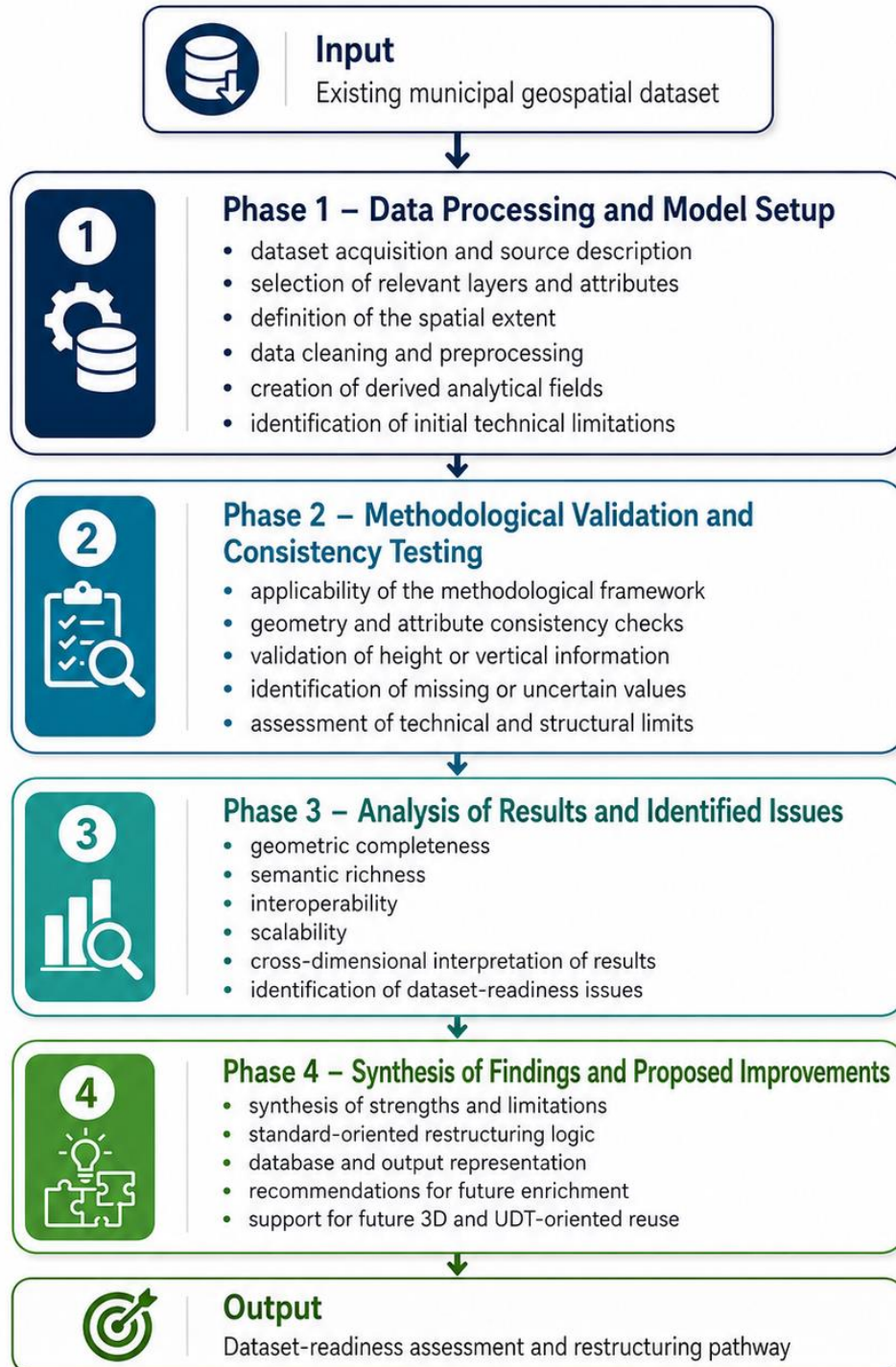


FIGURE 2.3 FOUR-PHASE ANALYTICAL WORKFLOW USED FOR DATASET-READINESS EVALUATION. SOURCE: AUTHOR'S ELABORATION.

2.3.1 Phase 1 – Data Processing and Model Setup

The first phase involves comprehending and preparing the source dataset before any readiness evaluation is performed. At this stage, the dataset is analyzed for its basic structure, available layers, types of geometry, coordinate reference system, attribute fields, metadata and documentation. The intention is to get a clear understanding of what the dataset consists of, how it is structured and which sections of it are relevant to the study objective. This phase is significant since a municipal dataset may include many layers and attributes, but not all of them are directly relevant for 3D city modelling or for future reuse directed to UDT. Therefore, in Phase 1, key analytical layers are separated from contextual or supporting layers that serve to contextualize the analysis, but are not the overarching basis for reconstruction.

Phase 1 also includes beginning data preparation in a GIS context. This may include loading the dataset, validating geometry validity, examining field names and data types, finding missing or zero values, selecting important layers, and setting the spatial area of the study. These activities are required since the raw municipal datasets are rarely directly usable in 3D city modelling or UDT-oriented workflows. They are generally developed for administrative, cartographic or planning objectives and therefore need to be inspected and prepared before their potential for geometric modelling, semantic interpretation, interoperability and scalability can be evaluated.

The Phase 1 result is a structured and documented dataset. It should be evident after this phase which levels are employed and why, which qualities are relevant, what the function of each layer is in the technique and what first constraints are already visible. At this point, the final readiness assessment has not yet been produced and evaluation scores have not yet been assigned. But instead, it lays the groundwork for the next steps by making sure the dataset is understood, organized, and available for verification, analysis, and possibly reconfiguration.

2.3.2 Phase 2 – Methodological Validation and Consistency Testing

The second phase is dedicated to determining whether the dataset's information can be interpreted in accordance with the needs of 3D city modeling and future interoperability frameworks. This phase is not intended to push the source data into a complete standard format and does not presume that the dataset is already compliant with CityGML, CityJSON or FIWARE/NGSI-LD. It does not specify which existing attributes may be used for standard-based interpretation, but which new analytical fields must be added to enable such interpretation. For example, height-related attributes may help volumetric modelling, floor or use-related information may contribute to semantic interpretation and identifiers may support the construction of links between objects and their components.

The distinction between original attributes and derived analytical fields is a critical component of this phase. Original characteristics are fields that are already present in the source data collection such as geometry, value(s) linked to height, elevation information, or existing classification fields. Analytical fields derived from the data are produced as part of research to normalize, elucidate or extend the interpretation of the data. These can comprise a standardized height field, a binary indicator for height availability, object identifiers, component identifiers, quality flags, semantic categorization fields, or relationship fields. This is a significant distinction for openness and repeatability, since it helps the reader to understand which information comes straight from the municipal dataset, and which information is developed by the research methodology.

So phase 2 is a bridge from raw GIS data to standard focused interpretation. It discusses whether the dataset can be understood in terms of urban objects, building parts, geometry, semantics and LoD in the context of CityGML and CityJSON. In relation to FIWARE/NGSI-LD it discusses whether the same features subsequently can be represented as entities with attributes and relationships or not. The goal is not to convert completely to these standards, but to develop a structured mapping between the available data and the concepts required for future 3D modelling and UDT-oriented reuse.

The outcome of this phase is a validated and interpretable data structure. By the end of Phase 2 it should be obvious which attributes can directly support the approach, which attributes need to be cleaned or reinterpreted, and what new fields are necessary to assist object reconstruction, interoperability and database representation. This phase is consequently mandatory since it changes the dataset from a set of GIS features into an analytical framework that can be analyzed, restructured and tested in the subsequent phases.

2.3.3 Phase 3 – Analysis of Results and Identified Issues

The third phase assesses the dataset based on the four characteristics of preparedness, including geometric completeness, semantic richness, interoperability, and scalability. Each dimension is evaluated by criteria that represent the objectives of 3D city modelling and UDT-oriented reuse.

The assessment is based on a qualitative scoring logic: Low, Medium and High. This method is justified, as dataset readiness is not always reducible to a single number. Some dimensions can be measured numerically, such as determining the ratio of features having valid height values. Other aspects are of qualitative nature, including whether characteristics are semantically significant or whether object relations are explicit. A qualitative grading system allows the two sorts of evidence to be merged in a visible manner.

If the score is low, the condition is to a considerable extent not met and restricts reuse considerably. A Medium score indicates that the condition is partially met but requires further processing, interpretation or transformation. A High score implies that the criterion is mostly met and may directly feed into standard-based modelling or integration. The scoring is not meant to be an absolute universal metric, it is an interpretive tool to help compare across aspects.

2.3.4 Phase 4 – Synthesis of Findings and Proposed Improvements

The third phase is devoted to the real evaluation of the dataset according to the four aspects of preparation outlined in the methodological framework: geometric completeness, semantic richness, interoperability and scalability. At this point the dataset is not only assessed regarding content or structure but also what it can realistically support in terms of 3D city modelling and future UDT-oriented reuse. Every dimension is measured against certain criteria. Geometric completeness assesses the correctness of spatial characteristics and the availability of relevant height or elevation information. Semantic richness quantifies the presence of meaningful qualities in the dataset which allows interpreting features as urban objects or components. Interoperability assesses if the dataset can be linked to standard-oriented structures with identifiers, relationships and exportable formats. Scalability is about repeating the same logic at several spatial levels, and across multiple objects.

The evaluation is based on a qualitative scoring rationale with three levels: Low, Medium and High. This approach is suitable since the readiness of a dataset cannot always be expressed by a single number. Some elements can be measured quantitatively, for example the number or percentage of features having accurate height values. Other characteristics require a qualitative interpretation, especially if the attributes are semantically relevant, whether object relationships are explicit or whether the workflow can be extended to other domains. In this way the qualitative scoring system permits the integration of quantitative facts and interpretive assessment in a visible and comparable manner.

A Low score means that the criterion is not well satisfied and strongly limits the usage of the dataset for 3D city modelling or future UDT-oriented interoperability. A Medium score means the criterion is partially met and the data collection will need some cleaning, interpretation, restructuring or enrichment before it can be effectively reused. A High score means that the criterion is mostly met and can be used immediately for standard-oriented modelling, database representation or interoperable reuse. The scoring is not meant to be an absolute or universal measuring method. In contrast, it is used as a tool of interpretation to compare the strengths and weaknesses of the dataset on the four dimensions and where change is needed.

Hence, the output of Phase 3 is a structured diagnosis of dataset ready. In this phase we identify what parts of the data set already support 3D city modelling and where parts are still constrained. It also clarifies the primary concerns to be tackled in the next phase such as missing height values, fractured geometries, weak semantic structure, absence of explicit object relationships or limited scalability. In this approach, Phase 3 relates the technical evidence obtained from the dataset to the methodological purpose of determining if existing municipal building data can enable a transition towards 3D city modelling and future UDT-oriented procedures.

2.4 Evaluation Dimensions and Criteria

The evaluation framework is structured on four dimensions: geometric completeness, semantic richness, interoperability, and scalability. The dimensions were chosen as they are the major characteristics that an existing dataset has to meet in order to allow for standard-oriented 3D city modelling and future reuse in UDTs.

2.4.1 Geometric Completeness

Geometric completeness relates to the presence and utility of spatial and vertical information. In 3D city modeling geometry is not only the footprints. The data set must be either available or be able to be derived for height, volume, or elevation. It is possible to have a dataset that supports 2D mapping but not meaningful 3D modelling without useable vertical information.

The dimension measures if geometries are legitimate, if they are full enough for the intended usage, if height relevant characteristics are present and if the data can allow extrusion or further LoD interpretation. From a CityGML point of view, geometric completeness helps to define the level of 3D representation which the dataset can actually support. As described in Chapter 1 and shown in Figure 1.4, different LoD require different geometric and semantic information. Therefore, correct footprints and height values

can enable modelling similar to LoD1, whereas higher degrees of representation require additional information such roof geometry, façade components, apertures, texturing or inner structures.

A dataset containing complete footprints and valid height values could support a LoD1-like block model. If the roof structures are present and dependable, the dataset may partially support LoD2. LoD3 cannot be supported directly if there is a lack of facade elements, apertures, textures or architectural details. So, the measure of geometric completeness is not just the presence of geometry, but the ability of that geometry to support a specific level of 3D representation.

2.4.2 Semantic Richness

Semantic richness is the availability and clarity of non-geometric information. Geometry alone is not enough in a 3D city model. The model should also explain what the objects are representing. For instance, A polygon might be a building, part of a building, a roof element, a minor construction or any other urban element. The dataset may be visually usable but analytically weak without semantic information.

This dimension assesses the presence of meaningful attributes in the dataset, the intelligibility of the attributes, the clarity of the object types and the distribution of information in the layers. Semantic richness also concerns the distinction made by the dataset between different categories of urban items and the possibility of mapping the categories to standard-oriented concepts.

Semantic richness related to CityGML and CityJSON makes it possible to interpret GIS features as city objects. Regarding FIWARE/NGSI-LD, the semantic richness allows features to be transformed into entities with properties. semantic richness is therefore a must for 3D modelling and for future interoperability.

2.4.3 Interoperability

Interoperability is the ability to interchange, interpret, link and reuse a dataset across different systems, tools and data models. Interoperability in this thesis is tackled on two related levels. The first level is about compatibility with 3D city modelling references like CityGML and CityJSON, where urban elements should be interpretable as structured objects with geometry, semantics, LoD and relationships. The second level refers to future-proof compliance with entity-based UDT frameworks, such as FIWARE/NGSI-LD, where urban information is modelled by entities, properties and relationships.

Interoperability involves more than the ability to export data to a common GIS file format. The dataset may be exportable as a shapefile, GeoPackage or GeoJSON but if the semantic or structural interoperability is not there, it will be hard to use the dataset in a different context. This means that if in the real world one building is represented by numerous independent parts that have no common identity, another system may not be able to identify those parts as belonging to the same item. Similarly, qualities that are imprecise, inconsistent or undocumented may be challenging to translate to standard oriented data models. By definition, interoperability is based on the existence of stable identifiers, clearly defined attribute names, unambiguous relationships between objects and a structure that can be converted into known modelling or information-management frameworks.

In this thesis, the interoperability is tested by investigating if the dataset can be transferred from a GIS layer-based structure to a more object-based and relationship-aware structure. From the CityGML/CityJSON point of view, this involves investigating if features may be understood as urban objects, which include buildings and building pieces. From the FIWARE/NGSI-LD-oriented perspective, this implies considering whether the same features could later be represented as things, characterized through attributes and related through relationships. This dimension is thus a key to the thesis as it ties 3D city modelling readiness to future UDT-oriented reuse.

Spatial relational databases are a crucial bridge between desktop GIS processing and scalable UDT-oriented operations. QGIS allows you to inspect, clean, update, map and visualize geographic data, including 3D extrusion. However, a spatial database allows to store, query, relate, validate and export the reconstructed data structure in a more systematic way. This becomes especially essential when the workflow is moving from individual GIS features to object-based structures like Building and BuildingPart, where relationships between parent objects and components can be explicitly expressed in database tables.

PostgreSQL is a free and open-source relational database management system (RDBMS) Its official documentation calls it a descendant of the POSTGRES system from the University of California, Berkeley and points out features such as complex queries, foreign keys, triggers, transactional integrity, multiversion concurrency control and extensibility through additional data types, functions, operators and index methods. The properties of PostgreSQL make it suited for managing the structured relations between urban objects and their components. PostGIS is the spatial extension of PostgreSQL including spatial data storage, spatial indexes, spatial queries, coordinate translation, and spatial export operations. In this thesis, PostGIS is not utilized to replace QGIS but to examine if the reconstructed object logic can be stored as a queryable spatial relational model (PostgreSQL: Documentation; PostgreSQL Global Development Group, 2026).

Therefore, the PostGIS step is presented after the reconstruction in QGIS. The parent urban object is maintained in a building database and each volumetric component in a building_part table. These tables are linked by the common field building_id and are formalized via a foreign-key relationship. This structure allows to query all components belonging to one parent object, to validate the Building/BuildingPart relationship, to export the data as GeoJSON and to generate NGSI-LD style JSON outputs. PostGIS offers both interoperability and scalability here. It transforms the rebuilt object from a visual GIS grouping into a structured, queryable, and exportable data model.

2.4.4 Scalability

Scalability refers to the capacity of the dataset and methodological procedure to enable reuse beyond a single, isolated operation. A method that works for a small area, or a manually interpreted object, does not necessarily follow that it can be extended to a larger dataset, a broader spatial extent, or many urban objects. Therefore, the scalability evaluation is carried out as a methodological criterion, not merely as a technical one. A scalable workflow should be repeatable, consistent, and follow standard-oriented structures so that the same logic can possibly be applied to numerous spatial levels and objects.

In this thesis, scalability is examined in three related approaches. The spatial scalability is the capacity of the method to scale up and down from institutional and city-scale context to district, building and

component level interpretation. Scalability of data structures means the same transformation rules can be applied to multiple objects, like consistent IDs, component classification, and relationship logic. Standard-oriented scalability deals with the question whether the rebuilt output can be read by reference models such as CityGML/CityJSON and FIWARE/NGSI-LD, so that the result is not restricted to one software environment or one visual representation.

A dataset is more scalable if it includes uniform IDs, repeatable properties, clear object logic and relationships that can be used systematically. However, scalability is worse if each object needs individual manual interpretation, if relations have to be inferred case-by-case or if attributes are too inconsistent to allow for automated or semi-automated processing. Hence, scalability is tightly coupled with semantic richness and interoperability: it is difficult to expand the workflow to a second test case without meaningful qualities and explicit linkages.

Table 2.1 Operationalizes the four evaluation categories into questions, criteria and expected evidences. The table puts in perspective that the thesis does not only evaluate if one object can be reconstructed, but if the logic of reconstruction, database storage and standard oriented interpretation may be theoretically repeated through broader datasets, with respect to scalability. Scalability is the main requirement for testing if municipal GIS data can go from isolated visualization to reusable 3D city modelling and future UDT-oriented operations.

Dimension	Main question	Criteria	Evidence / output
Geometric completeness	Can the data support 3D form?	valid geometry, usable height, extrusion potential	height_m, has_height, 3D extrusion
Semantic richness	Do features have meaningful attributes?	use, floors, type, component meaning	part_type, attributes, layer interpretation
Interoperability	Can objects be exchanged and linked?	identifiers, relationships, standard mapping	building_id, part_id, ngsi_entity, SQL/JSON
Scalability	Can the logic be repeated?	multi-scale structure, repeatable rules, database storage	PostGIS tables, foreign key, transferability rules

TABLE 2-1 EVALUATION DIMENSIONS AND CRITERIA USED FOR DATASET-READINESS ASSESSMENT. SOURCE: AUTHOR'S ELABORATION BASED ON BILJECKI ET AL. (2014), KOLBE ET AL. (2005), LEDOUX ET AL. (2019), KETZLER ET AL. (2020), AND LEI ET AL. (2023).

2.5 Qualitative Scoring Logic

To facilitate evaluation in a systematic way and to make it comparable across the four preparedness dimensions, each dimension is interpreted through a three-level qualitative scoring system: Low, Medium and High. This grading system is not intended to give a hard number ranking or an absolute evaluation of data quality. Conversely, it offers a straightforward approach to understand how much the dataset can support 3D city modelling and future reuse directed to UDT. This is suitable since dataset preparedness has both quantifiable and interpretive dimensions. For example, availability of height can be measured as counts or percentages, whereas semantic clarity, linkages between objects, and possibility for interoperability need qualitative assessment.

A Low score implies that the dataset does not satisfy the requirement sufficiently, and that this shortcoming greatly constrains reuse. The Medium score means that the criterion is partially fulfilled but needs further cleaning, interpretation, restructuring or enrichment before the dataset can be used successfully. The higher the score the more the requirement is met, and the more directly the dataset can serve the intended modelling, database or interoperability function. In this way, the scoring logic helps not only to identify the strengths of the dataset but also the specific adjustments needed to increase its readiness.

Table 2.2 provides the qualitative scoring reasoning to understand the level of preparedness. The table serves as a common ground for the evaluation later in Chapter 4, in which the same Low–Medium–High logic is used to geometric completeness, semantic richness, interoperability and scalability. This increases the transparency of the evaluation and guarantees that the interpretation of the results is tied to the scientific framework and not to individual observations.

Score	Interpretation
Low	The criterion is largely unmet and significantly limits the dataset’s use for 3D city modelling or Urban Digital Twin-oriented interoperability.
Medium	The criterion is partially satisfied, but additional cleaning, interpretation, restructuring, or enrichment is required.
High	The criterion is largely satisfied and can directly support standard-oriented modelling or future interoperable reuse.

TABLE 2-2 QUALITATIVE SCORING LOGIC USED FOR DATASET-READINESS EVALUATION. SOURCE: AUTHOR’S ELABORATION.

2.6 Standard-Alignment Logic

The methodology uses standards and reference frameworks as analytical guides, as opposed to as end targets for implementation. This distinction is crucial, as the thesis does not presume that the selected dataset can be directly transformed into CityGML, CityJSON or FIWARE/NGSI-LD. On the contrary, these standards provide a basis to assess the level of support presently offered by the dataset, the remaining gaps and the types of transformation required for future 3D city modeling and UDT-oriented reuse. In this sense, the standards give a structured manner of interpreting the potential and constraints of the dataset rather than being complete conversion outputs.

The CityGML is used as the basic conceptual reference for 3D city modeling and LoD. It provides a foundation for understanding geographical elements, such as semantic urban objects including buildings, portions of a building and other city components. A practical extension of this is the usage of CityJSON, which retains the CityGML data model, but in a more compact JSON-based structure. With CityGML and CityJSON together we may evaluate the possibility to re-organize GIS features from simple layer-based geometries into structured 3D city models with identifiable components, properties and relations.

FIWARE/NGSI-LD is used as reference for future interoperability of UDT. Its entity–property–relationship model is used to evaluate whether reconstructed urban objects can be modeled as interoperable information entities. In this logic, an urban object can be an entity, its measured or descriptive features can be attributes and its connections to other objects can be relationships. This is important because UDT-oriented procedures need more than just 3D geometry; they need data structures that can be searched, connected, updated and reused across systems.

Table 2.3 shows the contribution of each standard, tool, or reference framework to the methodology. The institutional geodata context is framed by INSPIRE and SDI principles, the interpretation of 3D city modelling readiness is guided by CityGML and CityJSON, the future interoperability logic is supported by FIWARE/NGSI-LD, the operational data processing and visualization is enabled by QGIS and the spatial relational environment needed to store, query, validate, and export the reconstructed data structure is provided by PostgreSQL/PostGIS. This alignment indicates that the technique is not based on one single standard, but on a cohesive set of references and tools supporting the many stages of the transformation process.

Reference / tool	Role in methodology	Main relevance
INSPIRE / SDI	Institutional data context	metadata, provenance, access
CityGML	3D city modelling reference	LoD, semantic objects, Building/BuildingPart logic
CityJSON	Practical JSON-based bridge	compact object representation and web-oriented workflows
FIWARE / NGSI-LD	Future interoperability reference	entities, properties, relationships
QGIS	Operational processing and visualization	data cleaning, maps, 3D extrusion
PostgreSQL / PostGIS	Spatial relational representation	queryable database, spatial export, scalability proof

TABLE 2-3 STANDARD AND TOOL ALIGNMENT WITHIN THE METHODOLOGY. SOURCE: AUTHOR'S ELABORATION.

2.7 Summary of the Methodology

In this chapter the methodological framework to assess the capability of an existing municipal building dataset to facilitate 3D city modelling and future reuse directed to UDT was established. The methodology is founded on the main premise that data availability is not the same as data ready. A dataset can be official, detailed and usable in GIS but still need cleaning, interpretation, restructuring or enrichment before it can support standard-oriented digital urban workflows.

The chapter specified four evaluation dimensions, namely, geometric completeness, semantic richness, interoperability and scalability. These factors enable us to examine whether or not the dataset has acceptable geometry and height information, relevant qualities, explicit linkages, and a logic that may potentially be duplicated for multiple items and scales.

Also, the methodology is multiscale and standards-aware. It moves from general spatial and institutional framework to object and component level interpretation. CityGML and CityJSON are referenced for the 3D city modelling preparedness. FIWARE/NGSI-LD is referenced for the future UDT compatibility. The data processing and visualization is done in QGIS, the relational storage, querying, validation and export in PostgreSQL/PostGIS.

Finally, the chapter used this framework for a four-phase workflow: data processing and model setup, methodological validation and consistency testing, analysis of results and identified issues, and synthesis

of findings and proposed improvements. The next chapter presents the case-study setting and data sources. Chapter 4 implements this methodology in the real QGIS, PostGIS, JSON and interactive 3D process.

03

CHAPTER

Case Study

Introducing the urban context, available datasets, and the selected building-scale focus.

The empirical context of the thesis is introduced in Chapter 3, which also delineates the spatial, institutional, and data-related background of the case study. Following the broad discussion on dataset preparation, 3D city modelling, interoperability and scalability in Chapters 1 and 2, this chapter contextualizes the research in a specific urban case. At this stage, the aim is not to give the findings of the analysis, but to clarify the origin of the data, the logic of the chosen geographical scales and the reasons for the choice of the detailed building-scale focus. This is similar to the role of the case-study chapter in the structure of the thesis where data sources and reference models serve as a link between the theoretical framework and the practical execution.

The case study is designed using a multi-scale logic. The analysis is organized following a multi-scale logic. It starts from the broader urban and institutional setting of Turin city and Piedmont Region, then passes to the official geodata framework and finally to a district scale analytical region inside the Circonscrizione 7. The last level concentrates on one selected building of this district, which is utilized for the evaluation of detailed object-level reconstruction. This structure follows the process described in Chapter 2, where the assessment of dataset preparation is not based on a single map or item, but on a progressive movement from broader spatial context to precise object-level interpretation.

3.1 Urban and Institutional Context: Turin

Turin is a major urban centre in north-western Italy and one of the principal cities of the Piedmont region. The city has always been a vital player in the development of Italian industry, especially in manufacturing and the automotive sector, and then a key setting for post-industrial transformation, regeneration, cultural reuse and innovation-focused urban policy. This historical path makes Turin a useful framework for analyzing the reuse of existing urban data, since the city mixes dense historical fabrics, previous producing regions, regenerated spaces, infrastructural systems and modern planning difficulties (Città di Torino, 2024; Torino Social Impact, 2018).

The importance of Turin for this thesis is not just historical or morphological, but also institutional. In recent years, the city has been engaged in policies on climate neutrality, transition to smart-city and urban innovation. The City of Turin presented their Climate City Contract to the European Commission in March 2024, within the framework of the EU Mission “100 Climate-Neutral and Smart Cities by 2030”. According to the official municipal message, the paper was developed by the local administration, in partnership with the Politecnico di Torino, and sent to Brussels for approval as part of the Mission Label procedure (Città di Torino, 2024).

This policy environment is crucial because climate-neutral and smart-city plans increasingly rely on the ability to deploy urban data in integrated and operational manners. Buildings, infrastructure, public spaces, mobility systems, environmental conditions and energy demand all need spatially structured datasets if they are to be examined using 3D city models or future UDT settings. This makes Turin a useful case-study scenario, given that the subject of data preparedness is particularly pertinent in light of the city’s institutional objectives for climate neutrality and digital transformation (Città di Torino, 2024; Ketzler et al., 2020; Lei et al., 2023).

At the same time, the existence of urban innovation initiatives does not indicate the available data are ready for sophisticated digital application. A city can have official datasets, geoportals and planning papers but still have limits with regard to geometric completeness, semantic consistency, interoperability or

scalability. This is the reason why the thesis does not analyze the whole UDT of Turin, instead merely uses the city as an institutional and spatial environment in which to test if existing building-related data might support future 3D city modelling and UDT-oriented procedures (Ferré-Bigorra et al., 2022; Lei et al., 2023).



FIGURE 3.1 URBAN AND INSTITUTIONAL CONTEXT OF TURIN WITHIN THE PIEDMONT REGION. SOURCE: AUTHOR'S ELABORATION BASED ON REGIONAL AND MUNICIPAL GEODATA, PROCESSED IN QGIS.

This historical trajectory is essential for the thesis, since Turin is not just a city with a significant industrial heritage, but also a city which has actively reinvented itself through urban reconstruction, sustainability regulations and smart-city projects. Following the fall and decentralization of parts of its industrial sector, many former industrial and infrastructural regions provided key potential for physical transformation, cultural reuse, innovation activities, and new urban roles. In this respect, Turin represents a useful environment for the study of the interaction between the existing urban data, the spatial transformation and the future digital urban systems.

The city's transformation has been accompanied by institutional measures relating to sustainability and smart-city development. In 2009, Turin became a member of the Covenant of Mayors and produced the Turin Action Plan for Energy, aiming to reduce urban carbon emissions. Later, the city's smart-city focus was reinforced by projects linked to innovation, mobility, energy, inclusivity and environmental transformation. These ideas demonstrate that Turin has considered urban transformation not just as a spatial-planning issue but as a more comprehensive process encompassing governance, data, technology, sustainability and stakeholder participation (Aderisci al Climate City Contract | Torino Vivibile, 2026; Città di Torino, 2024).

This path was made clearer by experimental efforts such as the Torino City Lab, which positioned the city as an open laboratory for testing urban innovation and frontier technologies in real environments. The program promoted experimentation in the fields of autonomous mobility, drones, IoT, 5G, artificial intelligence, robotics and novel communication, aiming to improve the quality of life and support

environmental and social sustainability at the urban scale. This way of working is aligned with the more general living-lab paradigm where public institutions, private actors, researchers, companies and citizens can be involved in real world experimentation and co-creation. This history is essential, because it indicates that Turin has a tradition, institutional and experimental, to use the urban environment as a laboratory for developing digital and sustainability focused solutions (European Network of Living Labs, 2026; Torino Social Impact, 2018).

In more recent years, Turin has aligned itself with the European climate-neutral city plan. The city is one of the European cities' parts of the EU Mission "100 Climate-Neutral and Smart Cities by 2030", which aids cities in establishing pathways to climate neutrality. It is in this context that Turin produced its Climate City Contract, a strategy document that specifies objectives, activities and investments for the transition towards climate neutrality. The City of Turin in an official message writes that the Climate City Contract was drawn up by the local administration together with Politecnico di Torino and presented to the European Commission for the process in view of the European Mission Label (Città di Torino, 2024). In addition, the Climate City Contract is described on the Torino Vivibile portal as a collaborative method that involves involvement from both the municipality and local stakeholders in the process of achieving climate neutrality (Aderisci al Climate City Contract | Torino Vivibile, 2026).



FIGURE 3.2 TURIN'S CLIMATE CITY CONTRACT WITHIN THE EU MISSION FOR CLIMATE-NEUTRAL AND SMART CITIES. SOURCE: COMUNE DI TORINO / TORINO VIVIBILE, ACCESSED 2026.

The design of climate-neutral and smart-city plans depends not only on political goals, but also on the ability to use urban data in a reliable and integrated way. Urban datasets are required to capture buildings, infrastructure, land use, energy demand, environmental conditions, and geographical inequities. Therefore, the quality, organization and interoperability of municipal datasets are crucial prerequisites for future digital planning tools including 3D city models and UDT. This research is contextualized in the broader city scale of Turin, chosen for its post-industrial transformation, sustainability strategies and smart-city orientation that make it a suitable context to investigate if existing institutional datasets can enable more sophisticated urban-digital applications.

3.2 Data and Institutional Geodata Context: BDTRE and CSI Piemonte

The data context of this thesis is the institutional geodata infrastructure of the Piedmont Region. GeoPortale Piemonte is the access point for the regional geographical data sets, metadata, cartographic services and web services provided by public entities in the region. Its purpose is not limited to publishing data but also to facilitate the organization, documentation, harmonization and dissemination of territorial information within an official public-sector geodata framework.

This institutional structure is related to the European INSPIRE Directive which aims at improving the availability, accessibility and interoperability of geographical information among public authorities in Europe. INSPIRE does not act as a 3D city modelling standard in the same form as CityGML, nor does it work as a UDT interoperability framework in the same way as FIWARE/NGSI-LD. Its key role is in the management of spatial data: metadata, data exchange, standardised access, documentation, harmonised public geodata infrastructures. In this context, INSPIRE promotes the wider institutional circumstances for the discoverability, traceability and reusability of geospatial resources.

This thesis is fundamental to INSPIRE because it indicates that the case-study data are not informal, isolated or manually acquired datasets. They are embedded in an official regional geodata infrastructure with data provenance, institutional responsibility, metadata and public access as part of the data context. However, availability through an INSPIRE-oriented infrastructure does not mean that the dataset is ready for 3D city modelling or UDT-oriented reuse. INSPIRE promotes data access and institutional harmonization, but the detailed readiness of the collection is still dependent on geometric completeness, semantic richness, object linkages, interoperability and scalability.

The institutional starting point of the research is therefore set by GeoPortale Piemonte and the INSPIRE framework, while the methodology of the thesis assesses whether the available building data may advance beyond the availability of public geodata towards standard-oriented 3D modelling and future UDT interoperability. This distinction is an imperative one: INSPIRE is about the official data architecture, while CityGML/CityJSON, FIWARE/NGSI-LD and PostGIS are used later on to check the object structure, interoperability and database supported reuse(Regione Piemonte, 2026).

The geospatial data utilized in this thesis are linked to the institutional data infrastructure of the Piedmont Region and the City of Turin, both technically supported by CSI Piemonte. In this context CSI Piemonte is considered as the technical and institutional player involved in the generation, administration and publication of regional and municipal geospatial datasets. Therefore, the thesis does not regard CSI as a single dataset, but as the framework in which different geodata sources are made available.

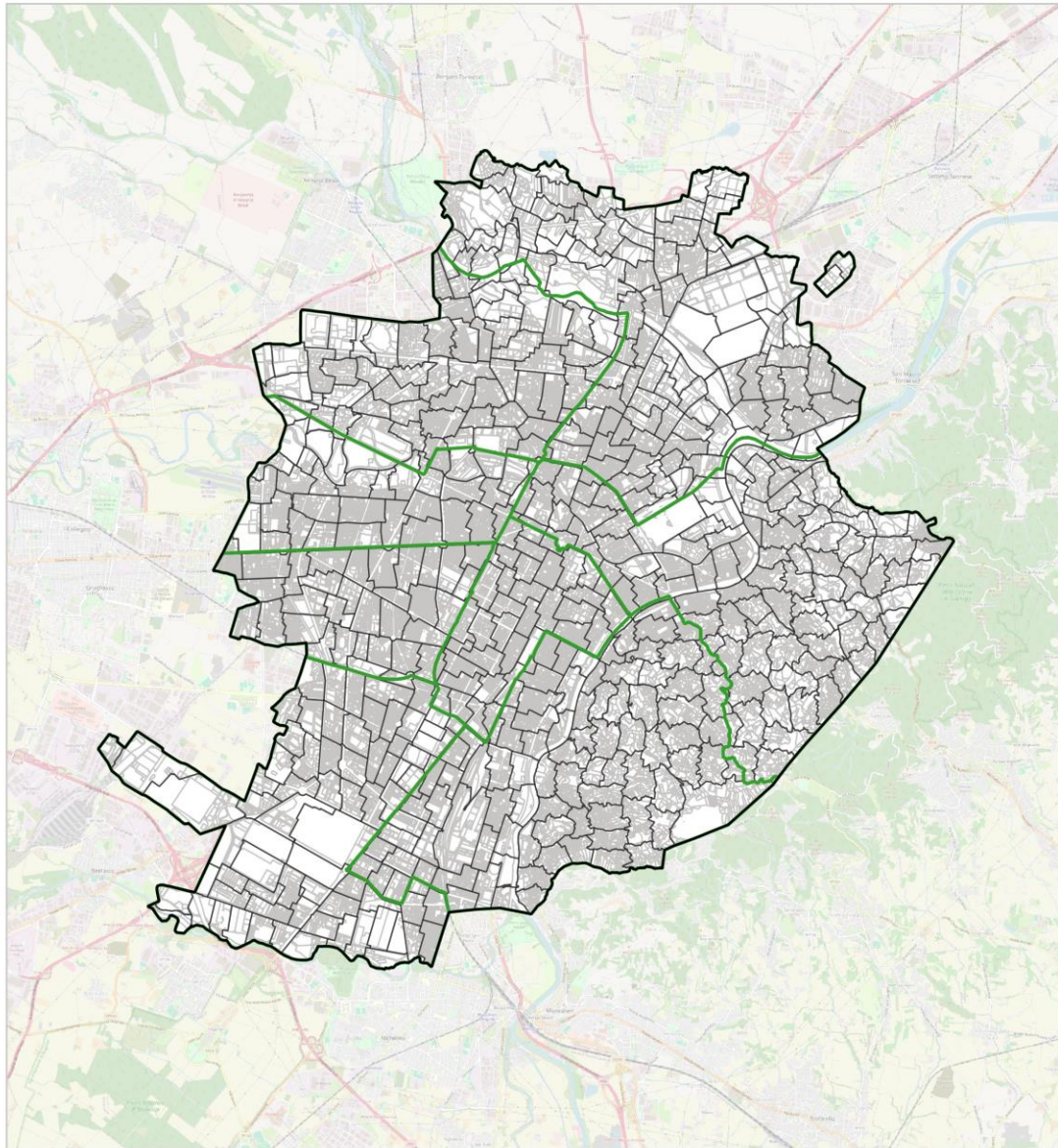
Within this institutional geodata infrastructure there is the regional territorial reference database for Piedmont BDTRE (Base Dati Territoriale di Riferimento degli Enti). It aims to provide an official and structured geographic base of the territory, to help public administration, territorial governance, planning activities, environmental protection and cartographic production. BDTRE, according to GeoPortale Piemonte, is structured in line with national technical specifications for geotopographic databases, and constitutes a reference framework for the derivation and publication of official regional cartographic products. Accordingly, BDTRE is not only a source of maps but also part of a bigger institutional structure to organize and disseminate authentic geospatial information (Regione Piemonte, 2026a, 2026b).

BDTRE, in this regard, offers the regional territorial reference database and is employed in the present thesis to support the wider territorial and institutional background. The empirical material for the district-scale and building-scale preparation evaluation is derived from the City of Turin building-related dataset, linked to the geodata infrastructure CSI Piemonte. The larger geographical and institutional scale is provided by BDTRE. The complete assessment of the building geometry, height information, semantic features, object structure and reconstruction potential is performed with CSI dataset. The thorough analysis is based on the major empirical dataset, the CSI dataset, which is made available through Centro Est / Energy Center for the purposes of this thesis work. The dataset is considered the main source connected to the building as it comprises the geometry and attribute data essential for the evaluation of the height availability, layer structure, semantic richness, and object-reconstruction potential. The BDTRE is consistent with the broader geographical and institutional framing, but the CSI dataset offers the detailed material utilized for the district-scale and building-scale preparedness evaluation.

This division of roles helps clarify the methodological rationale of the case study. BDTRE provide the official background information necessary for understanding the geographical and institutional environment, and CSI offers the more detailed building-related information necessary for district-scale evaluation and building-scale reconstruction. This means that the thesis does not assume a uniformity of function across all datasets. In contrast, each dataset is employed according to its magnitude, substance and usefulness to the research workflow.

Map 3.1 reflects the city-scale background based on BDTRE utilized to locate the case-study area within the wider municipal organization of Turin. The graphic indicates the location of the selected district and building-scale emphasis inside the official territorial reference framework, before the study continues towards the more comprehensive CSI-based preparedness assessment.

BDTRE-Based City-Scale Context Map of Turin



Legend

Administrative areas

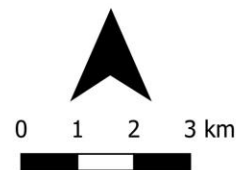
Turin municipal boundary 

Turin districts 

Cadastral map sheets 

Cadastral parcels 

OpenStreetMap



MAP 3-1 BDTRE-BASED CITY-SCALE CONTEXT MAP OF TURIN, USED AS A REFERENCE FRAMEWORK TO SITUATE THE CASE-STUDY AREA WITHIN THE BROADER MUNICIPAL AND CADASTRAL STRUCTURE OF THE CITY. SOURCE: BDTRE PIEMONTE / REGIONE PIEMONTE GEOPORTAL.

The map is a territorial reference layer in which BDTRE is involved; detailed analytical work is based on the CSI edificato dataset. This dataset includes multiple building-related layers describing built environment through various geometric and semantic components which includes volumetric units, building entities, minor buildings, roof or covering elements, architectural details and sub-municipal boundaries. Its richness is a benefit for 3D-readiness evaluation, but its organization by layers is a methodological difficulty. The building information is indeed scattered over numerous levels, instead of being structured as a single object model.

Volumetric geometries and height-related attributes are present in 020101_UNITA_VOLUMETRICA, which is the primary analytical layer among these layers. These attributes allow for fundamental 3D interpretation. Fields such as ground elevation, eaves or roof elevation, calculated height and number of storeys are fundamental to evaluate the feasibility of moving the dataset from 2D representation towards LoD1-like volumetric modelling. But the existence of these traits doesn't always ensure readiness. The values must be complete, interpretable and consistently used across the dataset, for successful 3D modelling (Biljecki et al., 2014; Kolbe et al., 2005).

The other building-related layers contribute complementary information to the readiness evaluation. 020102_EDIFICIO layer corresponds to interpretation at building level and 020106_EDIFICIO_MINORE for minor buildings. 020104_ELEMENTO_DI_COPERTURA can support interpretation linked to roofs. 020105_PARTICOLARE_ARCHITETTONICO gives information connected to architectural features. The sub-municipal analytical boundary is defined by the layer 090111_SUDDIVISIONE_SUB-COMUNALE. The layers together provide a rich but fragmented base to assess whether conventional GIS data may be interpreted in terms of CityGML/CityJSON and FIWARE/NGSI-LD related logic.

Table 3.1 presents an overview of the key data sources used in the thesis and explains the significance of each source in the research workflow. It further differentiates datasets for territorial context, databases for specific building study, and implementation of outputs such as PostGIS.

Data source	Main role	Scale	Use in research
BDTRE / CSI Piemonte regional geodata	Territorial reference and institutional context	regional / city	case-study framing
City of Turin building-related dataset / CSI Piemonte	Main analytical building dataset	district / building	geometry, height, semantics, reconstruction
Orthophoto / basemap	Visual interpretation	local / building	contextual validation and map production
External documentation	Supporting interpretation	building / object	context and validation of selected building
PostGIS database	Implementation output, not source data	building / database	queryable relational representation

TABLE 3-1 MAIN DATA SOURCES AND THEIR ROLE IN THE THESIS. SOURCE: AUTHOR'S ELABORATION.

The building-related layers used in this thesis are those from the City of Turin geospatial dataset released through the CSI Piemonte data infrastructure. These layers do not depict a single cohesive building model, although quite different components of the built environment, such as volumetric units, building entities, minor structures, roof or covering elements, architectural details, and sub-municipal boundaries. Therefore, each layer is analyzed in terms of its contribution to the dataset-readiness assessment summarized in Table 3.2.

The 020101_UNITA_VOLUMETRICA layer is the main analytical layer, as it includes the volumetric units and the properties connected to the height for the assessment of the extrusion and 3D-readiness. The 020102_EDIFICIO layer helps to interpret the building identity. The roof, minor-building and architectural-detail layers give additional information for understanding the limits of higher-LoD modelling. The analytical area is defined by the sub-municipal boundary layer. Consequently, Table 3.2 disambiguates the potential and limitation of the source data. The dataset is rich in building related information, but this information fragments across layers and needs to be interpreted before it can support standard-oriented 3D modelling or future UDT-oriented reuse.

Layer	General content	Relevance for the thesis
020101_UNITA_VOLUMETRICA	Volumetric building units	Main layer for height and 3D extrusion potential
020102_EDIFICIO	Building-level entities	Supports interpretation of building identity and use
020106_EDIFICIO_MINORE	Minor buildings	Complements the built-environment representation
020104_ELEMENTO_DI_COPERTURA	Roof / covering elements	Relevant for possible higher-LoD interpretation
020105_PARTICOLARE_ARCHITETTONICO	Architectural details	Relevant for semantic richness and detail assessment
090111_SUDDIVISIONE_SUB-COMUNALE	Sub-municipal boundary	Defines the analytical area

TABLE 3-2 MAIN LAYERS USED IN THE DATASET. SOURCE: AUTHOR'S ELABORATION.

3.3 Territorial Focus: Circoscrizione 7 and Vanchiglia/Vanchiglietta

The thesis is focused on the district-scale, known as the Circoscrizione 7, an administrative district of Turin that comprises neighborhoods like Aurora, Vanchiglia, Vanchiglietta, Sassi, and Madonna del Pilone. This district is a good intermediary scale between the larger city environment and the more specific building scale examination. It is large enough to accommodate a variety of urban forms, building kinds and territorial conditions but small enough to allow a concentrated evaluation of data quality concerning buildings, height availability, layer structure and object interpretation.

The choice of Circoscrizione 7 is a response to the multi-scale logic of the thesis. Turin provides an institutional and territorial framework at the magnitude of the city. At the district scale, the Circoscrizione 7 offers a defined analytical area in which the dataset of CSI buildings may be thoroughly evaluated. One can next select a complicated object at the building size to verify whether the dataset supports a cohesive

object-level reconstruction. This cycle permits the research to advance from general data context to specific interpretation, rather than considering the building-scale analysis as an isolated case.

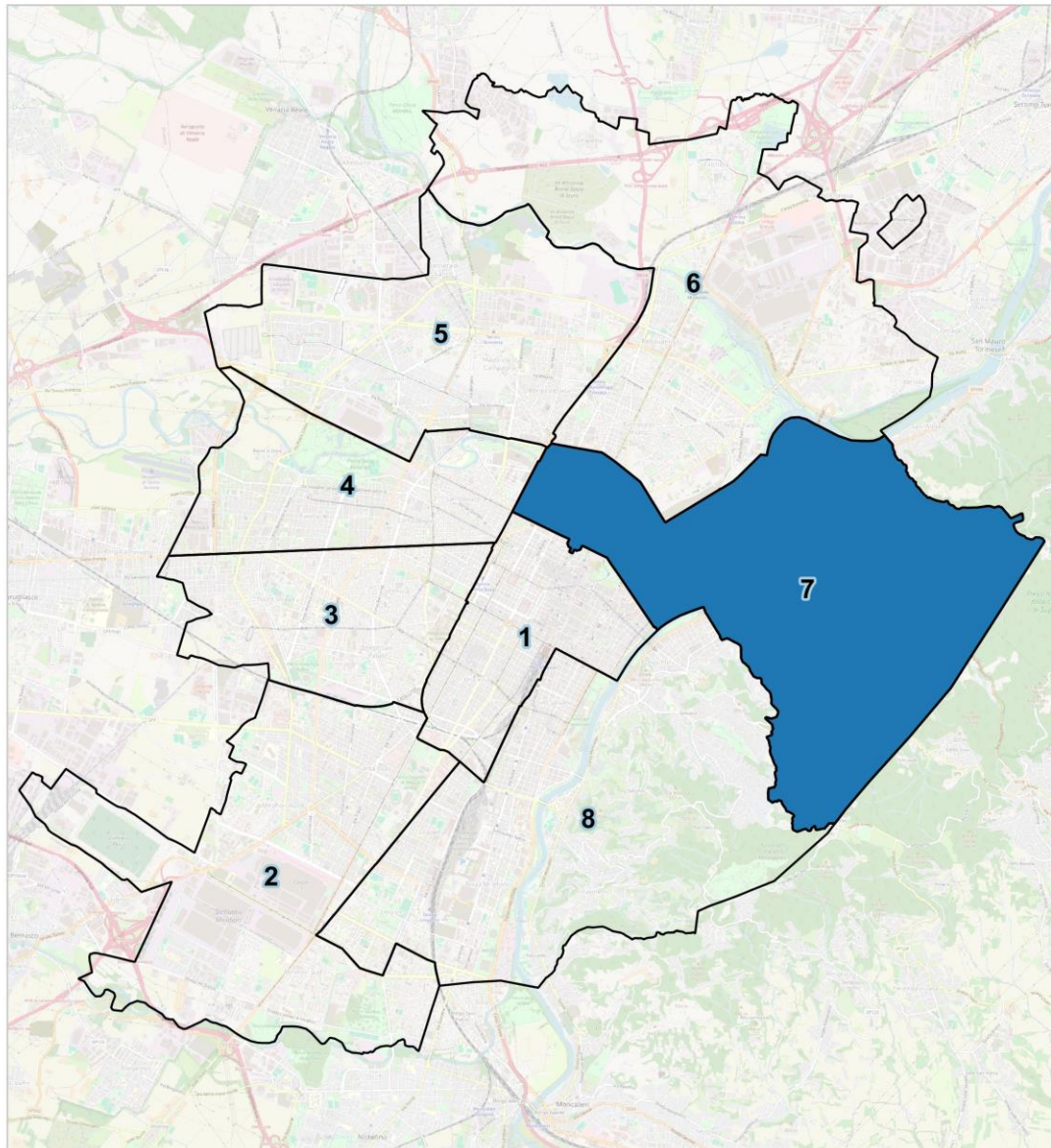
Circoscrizione 7, territoriality is another reason why it has been chosen. The district is composed of dense urban fabrics, parts next to rivers, hillside parts, historically layered neighborhoods, regenerated spaces and various building types. This variation is useful to evaluate dataset-readiness because it tests data in a non-uniform urban setting. A homogeneous location may mask some problems and a more diversified neighborhood can disclose how the dataset reacts under different construction conditions and spatial design.

Within this district, Vanchiglia and Vanchiglietta are particularly pertinent due to their representation of the multifaceted evolution of Turin's urban fabric. MuseoTorino characterizes Vanchiglietta as a simple location between the Po and Dora rivers, historically a swamp and agricultural area, later modified by productive and residential development. The same source recalls the ancient industrial identity of the area with the term Borg dal fum, linked to the existence of factories and production activities (MuseoTorino, 2026).

This territorial context is relevant since the data to be built in such an area must represent varied urban situations, including older residential fabrics, regenerated industrial districts, huge complexes, smaller buildings and heterogeneous volumetric patterns. Circoscrizione 7 acts as not just an administrative border but an intermediate analytical scale for testing the dataset before going to the comprehensive reconstruction of the objects.

Map 3.2 highlights the district scale, outlining Circoscrizione 7 within the municipal border of Turin, and clarifying its function as the intermediate level between the city-scale framework and the building-scale analysis.

Circoscrizione 7 in the Municipal Context of Turin



Legend

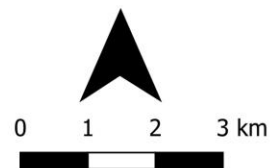
Turin Districts



District 7 - Circoscrizione 7 Torino



OpenStreetMap



MAP 3-2 LOCATION OF CIRCOSCRIZIONE 7 WITHIN THE MUNICIPAL BOUNDARY OF TURIN, PROVIDING THE SPATIAL CONTEXT FOR THE SELECTED CASE-STUDY AREA.
SOURCE: BDTRE PIEMONTE, REGIONE PIEMONTE GEOPORTAL.

3.4 Building-Scale Focus: The Lavazza Building

The thesis focuses on the building scale of the Lavazza complex in Turin. This building is relevant as a contemporary urban regeneration initiative in a historically complex region of the city. According to the official documentation, Lavazza was opened on 8 June 2018, has a footprint of almost 30,000 square metres and redefines the area between Via Bologna, Largo Brescia, Corso Palermo and Via Ancona, while retaining parts of the old industrial fabric. The complex, which houses the corporate headquarters, the Lavazza Museum, public and cultural spaces and event facilities, is an important urban object and not just a single isolated building (Lavazza, 2026a).

The relevance of the complex is also related to its architectural and sustainability profile. "The headquarters, designed by architect Cino Zucchi and developed through an investment of more than €120 million, is part of an urban regeneration process related to the Aurora neighbourhood, Lavazza explains." The project also achieved LEED Platinum certification, further tying it to sustainable architecture and the current wave of urban change. In this sense the building chosen is not only conceived as a physical infrastructure, but also as a complex urban object linked to regeneration, adaptive reuse, public space, sustainability and innovative forms of workplace organization (Lavazza, 2026b).

The methodological basis for the choice of this building is its complexity in the dataset. In the GIS data source, the building is not represented as one instantaneously united object but through numerous volumetric components. This makes it a suitable test case for the thesis at the building scale, where the research can explore whether fragmented GIS features might be perceived as components of a coherent digital object. In this sense, the building is used to evaluate the transition from a layer-based representation to an object-based structure, where one parent Building can be associated with numerous BuildingPart components.

This building-scale focus supports the assessment at the district-scale. At broader scales the data collection can be analyzed using layer structure, height availability, feature distribution and general completeness indices. But these broader indications do not fully disclose if an actual urban object can be recreated coherently from the given data. The analysis on the building scale allows the identification of issues that can be hidden in aggregate statistics, including geometric fragmentation, variation of height values between components, lack of explicit parent-child relationships, limited information for higher LoD.

It is worth noting that the building-scale focus is not directed at delivering a complete functioning UDT of the Nuvola Lavazza complex. Instead, it assesses the extent to which accessible GIS data can support a reconstruction logic based on a standard. In this interpretation CityGML and CityJSON give the conceptual reference for Building, BuildingPart and LoD, whereas FIWARE/NGSI-LD provides the future interoperability logic through entities, properties and relationships. The building therefore acts as a stress test for dataset readiness: if a complex and fragmented object can be re-organized into a coherent Building/BuildingPart structure the same logic can potentially be transferred to other buildings as long as suitable geometric features, attributes and grouping criteria are available (Bauer, 2021b; Conde et al., 2024; Kolbe et al., 2005; Ledoux et al., 2019).



FIGURE 3.3 NUVOLO LAVAZZA COMPLEX, SELECTED AS THE BUILDING-SCALE FOCUS OF THE THESIS. SOURCE: LAVAZZA OFFICIAL DOCUMENTATION.

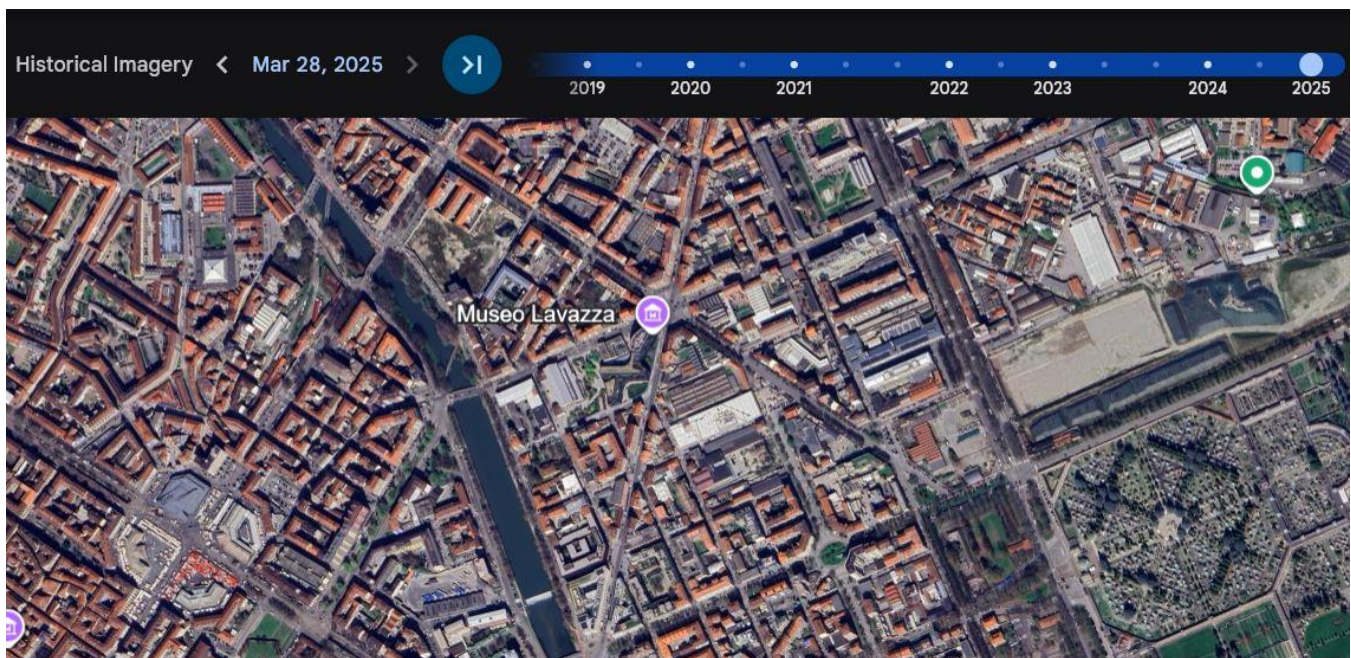


FIGURE 3.4 HISTORICAL SATELLITE VIEW OF THE LAVAZZA COMPLEX AND ITS SURROUNDING URBAN CONTEXT IN TURIN. SOURCE: GOOGLE EARTH, 28 MARCH 2025.



FIGURE 3.5 GOOGLE EARTH 3D VIEW OF THE LAVAZZA COMPLEX, SHOWING ITS BUILDING VOLUMES, ROOF FORMS, AND COURTYARD CONFIGURATION.

Map 3.3 depicts the Lavazza building in the Vanchiglia/Vanchiglietta urban environment, demonstrating the transition from the district-scale analytical region to the specific building-scale object required for reconstruction.

Lavazza Building within the Vanchiglia–Vanchiglietta Urban Context

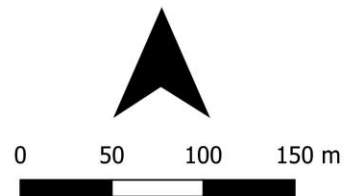


Legend

Lavazza volumetric units

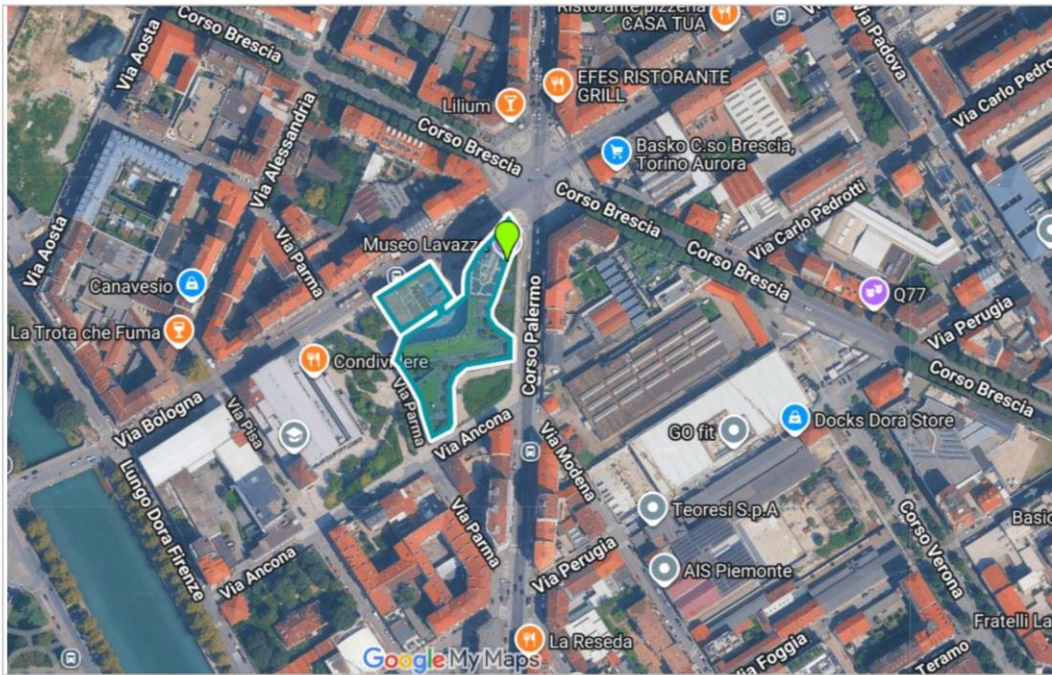
Volumetric units

OpenStreetMap



MAP 3-3 LOCATION OF THE LAVAZZA BUILDING WITHIN THE VANCHIGLIA/VANCHIGLIETTA URBAN CONTEXT. SOURCE: AUTHOR'S ELABORATION BASED ON CSI DATA AND ORTHOPHOTO/BASEMAP LAYERS.

Comparison between the CSI-Based Lavazza Footprint and Google Maps Aerial View



MAP 3-4 GIS-BASED FOOTPRINT AND GOOGLE MAPS AERIAL REFERENCE VIEW OF THE LAVAZZA BUILDING CASE STUDY. SOURCE: AUTHOR'S ELABORATION BASED ON CSI DATA, OPENSTREETMAP BASEMAP, AND GOOGLE MAPS/MY MAPS IMAGERY.

Map 3.3 shows the Lavazza building case study from two perspectives. The upper image illustrates the GIS-based visualization of Lavazza volumetric units obtained from the CSI dataset, superposed on a basemap based on OpenStreetMap. This perspective underlines the geometry and geographical location of the chosen building in relation to the surrounding urban fabric. The lower image is an aerial reference view from Google Maps/My Maps of the same building complex, which enables a visual contrast between the authorized dataset representation and the actual architectural form as viewed from satellite photography.

3.5 Multi-scale Territorial Framework of the Case Study

The case study is organized around a multi-scale territorial framework that integrates the larger institutional geodata backdrop, the city scale, the district-scale analytical region, and the building-scale focus. This structure is crucial since a detailed investigation of a building should not be seen as an isolated case. In contrast, it is the last and most detailed phase in a larger dataset readiness assessment. The case study therefore follows the same logic outlined in the methodology, from general spatial and institutional framework towards object-level and component-level interpretation.

The case study is inserted in the official geodata architecture of GeoPortale Piemonte and BDTRE at the regional level and institutional level. At city level, Turin provides the urban, policy and planning context where 3D city modelling and future UDT-oriented reuse can be significant. The Circoscrizione 7 at the district level gives a well-defined analytical region for the CSI building dataset to be analysed based on the layer structure, the availability of height, completeness of data and semantic interpretation. The Lavazza complex offers a complete test case at the building level for object reconstruction, Building/BuildingPart interpretation and standard-oriented reorganization.

This multi-scale structure is significant as each scale captures a distinct component of dataset ready . The larger scale of the institution clarifies data provenance, official geodata infrastructure and territorial framing. The city and district scales allow to estimate the spatial context and the general state of the building dataset on a feasible area for analysis. The building and component sizes indicate if the fragmented GIS characteristics may be used to recreate the individual urban objects consistently. So the scales are not independent or disconnected analyses but rather a continuous methodological pathway from the data environment to thorough reconstruction.

This structure is also reflected in the interaction between standards and scales. INSPIRE and the regional geodata infrastructure describe the institutional environment of data access, documentation and public geodata organization. CityGML and CityJSON provide the major conceptual references for 3D city modelling, especially LoD, Building/BuildingPart logic and semantic object interpretation. Entities, attributes and relationships offer FIWARE/NGSI-LD interoperability logic for the future UDT. PostGIS then supports the database/output scale by allowing the reconstructed structure to be saved, queried, validated and exported as a spatial relational model.

Table 3.3 summarizes the relationship between spatial scale, data source, and standard-oriented role. It illustrates how each stage of the case study contributes to the overall workflow: BDTRE supports the institutional and geographical context, the CSI dataset enables the readiness evaluation at the district and building size and PostGIS supports the database representation and future interoperability logic. Therefore, the table makes plain that the case study is multi-scale in space and methodologically connected from data provenance to object reconstruction and UDT-oriented reuse.

Scale	Data/support	Main purpose	Standard-oriented role
Regional / institutional	BDTRE, regional geodata	data provenance and territorial reference	INSPIRE / SDI context
City	municipal boundaries, contextual layers	urban framing	City model context
District	CSI building dataset	readiness evaluation	CityGML/CityJSON object-readiness logic
Building	extracted CSI components	object reconstruction	Building/BuildingPart and LoD interpretation
Database/output	PostGIS, GeoJSON, NGSI-LD JSON	query/export/interoperability	spatial database and future UDT logic

TABLE 3-3 RELATIONSHIP BETWEEN SCALE, DATA SOURCE, AND STANDARD-ORIENTED ROLE. SOURCE: AUTHOR'S ELABORATION.

The table is at the core of the multi-scale argument of the thesis, because it shows how institutional geodata, CSI building data, PostGIS and interoperability standards are related to each other in a single methodical path.

This chapter provides the spatial and data related context for the empirical application. The approach is applied to the selected datasets in the following chapter, starting with data preparation and layer interpretation followed by validation, results, building scale reconstruction and standard oriented output. In the implementation chapter QGIS is used for the spatial reconstruction and PostgreSQL/PostGIS for storing the reconstructed Building/BuildingPart output as a queryable spatial relational structure.

04

CHAPTER

Model Validation and Application Results

Testing the dataset against real modelling requirements and evaluating its readiness for 3D/UDT workflows.

This chapter applies the dataset-readiness methodology developed in Chapter 2 on the case-study data introduced in Chapter 3. The chapter is structured according to the four analytical processes outlined in the methodology: data processing and model setup, methodological validation and consistency testing, analysis of results and issues, synthesis of findings and proposed improvements. This structure provides a direct equivalence between the methodological framework and its empirical implementation. The technical activities are therefore shown in a defined analytical workflow, and not as separate procedural phases.

The application is in the multi-scaled logic of the thesis. The workflow starts from the institutional geodata context, which means to identify the regional and municipal data sources and to locate them in their official data architecture. Then it comes to the analytical area on district scale where the building-related layers are prepared and evaluated. Finally, the analysis reaches the building and component scale, through GIS processing, database representation, structured export and visualization are applied to test the reconstructed object structure. This sequence permits to progressively apply the methodology, from the data context and preparation to the precise object-level reconstruction.

This chapter deals with the practical execution of the technique. QGIS is used for spatial inspection, pre-processing, field construction and mapping and 3D visualization. The reconstructed object structure is stored in PostgreSQL/PostGIS as spatial relational model and SQL queries are used to check the relation between the parent object and its components. Finally, the rebuilt data are exported in structured formats by generating GeoJSON and NGSI-LD-style JSON outputs. The reconstructed model and its properties are finally communicated using an interactive 3D representation.

Chapter 4 describes the empirical implementation of the workflow from data preparation, readiness assessment, object reconstruction, storage in PostGIS, validation in SQL, structured export, and interactive visualization. The purpose is to demonstrate how the basic technique may be concretized with a specific case-study application while preserving the same analytical setting established in Chapter 2.

4.1 Phase 1 - Data Processing and Model Setup

Phase 1 prepares the data for analysis and provides the technical and methodological foundation for the subsequent phases. The goal is to comprehend the origin, structure, scale and constraints of the given data before the application of the evaluation dimensions. This step comprises data collecting, layer selection, spatial delimitation, data cleaning, pre-processing and alignment with the conceptual framework.

4.1.1 Dataset Acquisition and Source Description

As described in Chapter 3, the empirical study is based on two complementing levels of data. BDTRE and regional geodata provided through the Piedmont geodata infrastructure provide support for the broader territorial and institutional contexts. The detailed district and building scale analysis is based on the CSI edificato dataset, through Centro Est / Energy Center, which contains several building related layers like volumetric units, building entities, minor buildings, roof or covering elements, architectural details and sub-municipal boundaries.

The multi-scale technique relies on this differentiation. BDTRE is not the key layer for the comprehensive Lavazza reconstruction, but it is significant for placing the work in a wider institutional geodata context. The major analytical dataset is the CSI dataset, since it contains the building scale information needed to assess height availability, layer structure, semantic richness, item fragmentation and reconstruction

potential. This way the two data sources play diverse but interconnected roles, with BDTRE supporting the regional and city-scale framework, and CSI supporting the district and building-scale implementation.

4.1.2 BDTRE as the multi-scale institutional reference database

In this thesis BDTRE is treated as the wider institutional and regional geodata reference. It is not meant to be a substitution of the CSI edificato dataset, but to clean the data context in which the case study is located. This is vital from a multi-scale point of view, as a UDT-oriented workflow cannot be assessed based on a single building or district dataset alone. It also needs to be understood in the context of the wider geodata infrastructure supporting territorial administration, public-sector data dissemination and possible city-scale extension.

At the regional scale, BDTRE helps to understand how public territorial information is organized and made available. It is a reference framework for administrative boundaries, base cartography and territorial features and is used to place the comprehensive case study in a broader spatial context. At the city scale BDTRE can help contextual mapping and the relation between the analytical area and the surrounding urban fabric. It helps to define the link between wider geodata coverage and the more comprehensive CSI building layers at the district scale. However, on the building scale, the CSI dataset is still ideal for detailed height and component analysis since it contains the building-related layers used in the empirical evaluation. BDTRE is the largest scale discussed in the thesis. It gives the regional and institutional geodata background to frame the case study in a broader territorial structure. Without this level the study would proceed immediately from a municipal or district dataset to a single building which would limit the scalability standpoint of the process.

Furthermore, in the process, BDTRE is applied to support the regional and city size framing and the thorough readiness assessment is conducted using the building-related dataset at the district and building scale. Consequently, a continuous multi-scale sequence is established, consisting of regional geodata context, district-scale evaluation, and building/component-level reconstruction. In this way, BDTRE contributes to the development of the wider spatial reference from which the more detailed analytical scales are drawn.

BDTRE also aids interoperability. Regional geodata infrastructures are part of the larger Spatial Data Infrastructure concept involving metadata, data dissemination, access and standards. This does not indicate that BDTRE is ready for UDT implementation automatically. Instead, it offers the official geodata framework for the interpretation and possible linking of more detailed datasets. In the thesis workflow, BDTRE contributes to the initial level of preparedness by understanding provenance, institutional reliability, and territorial framing before moving on to comprehensive QGIS, PostGIS, and FIWARE/NGSI-LD-oriented outputs.

In practical terms, this chapter should present BDTRE in the form of a short contextual map or table, rather than a comprehensive technical explanation. The proposed output is a map at a regional/city size, depicting the relationship between the regional setting, Turin, Circoscrizione 7 and the Lavazza building. The methodology is multi-scale, as illustrated in Map 4-1, while the CSI data is subject to specific technical implementation. Given this, the thesis may clearly assert that BDTRE sets the multi-scale environment while CSI supplies the detailed building-scale material for the readiness evaluation and output prototype.

The levels of these data are given in Table 4.1 along with their corresponding functions in the implementation workflow. Source or reference datasets are BDTRE and CSI edificato dataset. The QGIS working layers are the analytical derivatives developed for evaluation and reconstruction. PostgreSQL/PostGIS is not considered as a source dataset, it is an implementation output to check whether the reconstructed Building/BuildingPart logic can be saved as a relational spatial structure. The pipeline progresses from regional and city-scale reference data to district-scale evaluation, then to building/component-level modeling, and lastly to database representation for queryability, structured export, and future scaling.

Data level	Dataset / source	Role in Chapter 4	Use in the methodology
Regional / institutional scale	BDTRE / CSI Piemonte regional geodata	Frames the official regional geodata context	Supports provenance, institutional context, and multi-scale logic
City / boundary scale	BDTRE / municipal boundaries / contextual layers	Situates Turin, Circoscrizione 7, and the selected building within the wider territory	Supports city-scale orientation and scalability perspective
District scale	City of Turin building-related dataset / CSI <i>edificato</i>	Main analytical dataset for readiness evaluation	Supports height availability analysis, layer interpretation, and district-scale assessment
Building scale	Extracted components from CSI <i>edificato</i>	Detailed reconstruction test	Supports Building/BuildingPart interpretation and object-level validation
Database / output scale	PostgreSQL/PostGIS	Stores the reconstructed structure	Supports queryability, structured export, and future scalability

TABLE 4-1 MULTI-SCALE ROLE OF BDTRE, CSI EDIFICATO, AND POSTGIS IN THE IMPLEMENTATION WORKFLOW. SOURCE: AUTHOR'S ELABORATION.

4.1.3 Selection of Layers and Attributes

Layer and attribute selection was based on the evaluation dimensions defined in Chapter 2; geometric completeness, semantic richness, interoperability and scalability. The intention was not to include all possible layers but to identify the layers that directly contribute to the assessment of 3D readiness and object reconstruction.

The implementation is based on the same building related layers as discussed in Chapter 3, but here they are understood in the context of their operational role in the workflow. The 020101_UNITA_VOLUMETRICA layer is employed as the main analytical layer while the other levels are used to assist the building identification, the roof interpretation, the architectural-detail assessment, the minor-building context or the spatial delimitation.

The main analytical layer was chosen as 020101_UNITA_VOLUMETRICA since it reflects the volumetric units of the buildings. In the dataset these units mean sections of the built volume, which can

have their own properties relating to height, elevation or floor. This layer is accordingly the most relevant for LoD1-like extrusion. The main features are ALTEZZA_VO, QT_GRONDA, QT_SUOLO and NUM_PIANI (if accessible) These fields offer the opportunity to assess whether the data can be moved from a 2D or 2.5D representation to a simple volumetric model.

The additional layers represent distinct characteristics of the built environment and explain why the dataset is arranged in separate thematic components rather than one unified building model. The layer 020102_EDIFICIO represents entities at the building level and helps in the interpretation of larger building items. The layer 020106_EDIFICIO_MINORE represents minor buildings or secondary built structures, such as garages, small service buildings, sheds or other auxiliary constructions that are not always depicted in the same way as main buildings. This differentiation is necessary due to the fact that not all constructed structures possess the same function, scale, or modeling relevance.

The layer 020104_ELEMENTO_DI_COPERTURA refers to roof or covering elements. This layer is of interest to debate probable LoD2 interpretation, even if it does not automatically result in a complete roof model. The layer 020105_PARTICOLARE_ARCHITETTONICO contains architectural features or specific built aspects that can help the debate of higher-LoD potential, but are not adequate on their own for a complete LoD3 modelling. Finally, the layer 090111_SUDDIVISIONE_SUB-COMUNALE is used to represent the sub-municipal boundaries and to establish the district-scale analytical region.

These layers demonstrate how the dataset separates the built environment into distinct geometric and semantic classes: volumetric units, buildings, minor buildings, roof elements, architectural details and administrative boundaries. This structure is useful as it gives different sorts of information, but it also requires interpretation before the data can be reassembled into a standard-oriented Building/BuildingPart logic. Table 4.2 specifies the datasets and layers used in the implementation workflow and their relation to the aspects of preparedness.

Layer	Role in workflow	Main attributes / information	Relation to readiness dimensions
020101_UNITA_VOLUMETRICA	Primary analytical layer	Geometry, ALTEZZA_VO, QT_GRONDA, QT_SUOLO, NUM_PIANI	Geometric completeness, LoD1 extrusion potential
020102_EDIFICIO	Building-level support	Building identity, use/type information where available	Semantic richness, object identity
020106_EDIFICIO_MINORE	Complementary built-environment layer	Minor building geometries and attributes	Completeness of built environment
020104_ELEMENTO_DI_COPERTURA	Roof / covering support	Covering and roof-related elements	Possible LoD2 discussion
020105_PARTICOLARE_ARCHITETTONICO	Architectural-detail support	Architectural details where available	Semantic richness and higher-LoD discussion
090111_SUDDIVISIONE_SUB-COMUNALE	Boundary layer	Sub-municipal administrative boundaries	Spatial delimitation and scalability
BDTRE / regional context layers	Regional and city-scale context	Territorial reference and contextual features	Multi-scale framing and institutional provenance

TABLE 4-2 MAIN DATASETS AND LAYERS USED IN THE IMPLEMENTATION WORKFLOW. SOURCE: AUTHOR'S ELABORATION.

This selection shows how the 020101_UNITA_VOLUMETRICA layer is the main analytical layer for LoD1-like extrusion, while the other layers are used to assist the semantic interpretation and the contextual validation.

4.1.4 Spatial Delimitation of the Case Study

The geographical boundaries of the case study were set in QGIS. The sub-municipal boundary layer was utilized to extract Circoscrizione 7 from the larger municipal dataset. This step was needed to establish a consistent district-scale analytical region and to avoid mixing features outside the chosen boundary. The district scale subset was then used to evaluate height availability, layer distribution, and overall 3D-readiness indicators.

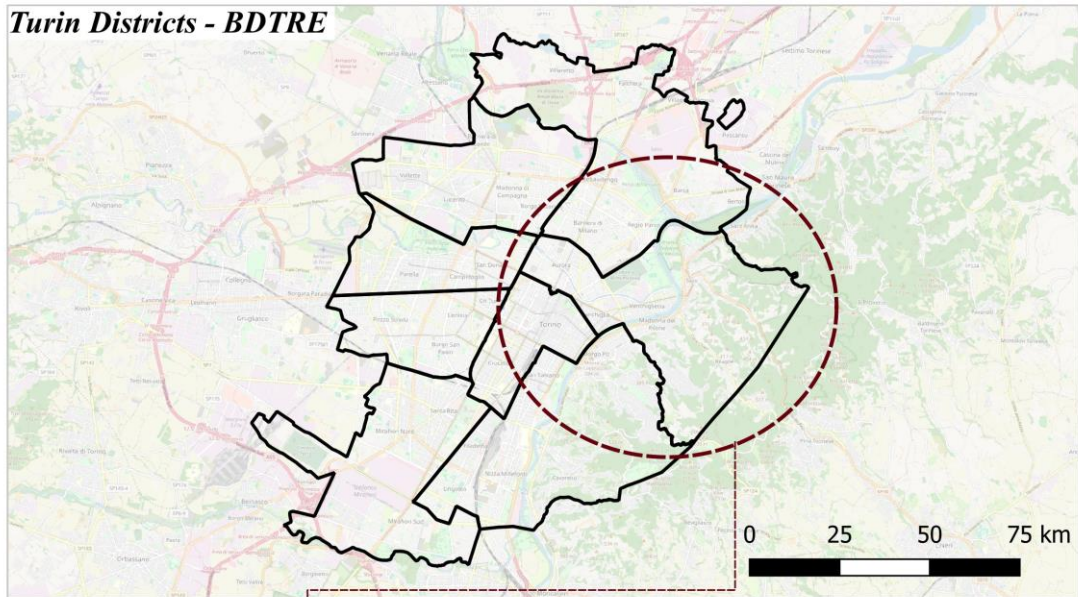
The building elements of the Lavazza were recognized within the district subset at building scale. The corresponding volumetric units were isolated and exported as a separate layer for analysis. This extraction produced a working layer at the building scale restricted to only those elements needed for the detailed rebuilding. The layer served as the basis for the subsequent implementation processes including derived

field development, 2D mapping, 3D extrusion, PostGIS import, SQL validation and interactive visualization.

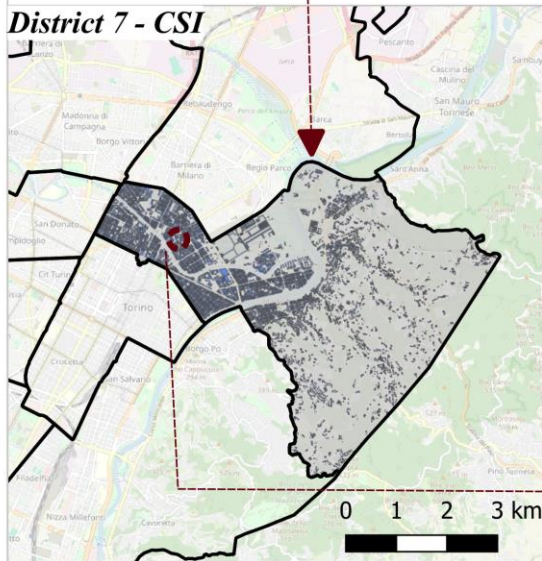
Therefore, spatial delimitation has an analytical and methodological aim. It creates analytically manageable working layers. Methodologically it demonstrates the step from the city and district size to the building and component scale in the workflow. This supports directly the scalability argument of the thesis. Map 4.1 displays the spatial delimitation applied in the empirical workflow, demonstrating the progression from the city and district scales to the specific building-scale focus, which supports the idea of methodological scalability.

Multi-Scale Delimitation of the Case Study

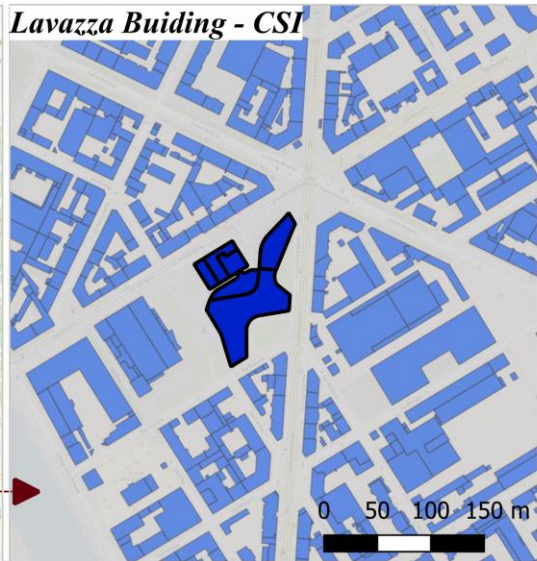
Turin Districts - BDTRE



District 7 - CSI



Lavazza Building - CSI



Legend

- Turin Districts 
- Lavazza volumetric units 
- Volumetric units 
- District 7 - Circoscrizione 7 Torino 
- OpenStreetMap 



MAP 4-1 SPATIAL DELIMITATION OF THE CASE STUDY, SHOWING THE RELATIONSHIP BETWEEN TURIN, CIRCOSCRIZIONE 7, AND THE LAVAZZA BUILDING-SCALE FOCUS. SOURCE: AUTHOR'S ELABORATION BASED ON BDTRE/CSI AND MUNICIPAL GEODATA.

4.1.5 Data Cleaning and Preprocessing

Following spatial delimitation, the dataset was examined and preprocessed. The pre-processing phase involved geometry checks, attribute completeness checks, null and zero values checks, and creation of derived analytical fields. The idea was not to permanently change the source data but to obtain an analytical version that would be suitable for review and reconstruction.

Prior to the construction of derived fields, the coordinate reference system of the working layers was confirmed in QGIS. This step guarantees that all layers utilized in the study were spatially aligned and could be clipped, compared, imported into PostGIS and viewed accurately. The source layers were left in their original projected reference system throughout the GIS and PostGIS processing steps. The transformation to WGS84/EPSSG:4326 was only performed during GeoJSON export, since web-based outputs of GeoJSON generally require geographic coordinates.

In QGIS a uniform height field called `height_m` was established. This variable is required because the original dataset can have many height related qualities and the analysis needs one consistent field for district scale statistics and 3D extrusion. The field uses `ALTEZZA_VO` when this value is positive and valid. In the absence of `ALTEZZA_VO`, the difference of `QT_GRONDA` and `QT_SUOLO` can be utilized as a check or derivation logic, provided that both values are legitimate and the difference is positive.

QGIS expression for `height_m`:

```
CASE
  WHEN "ALTEZZA_VO" IS NOT NULL AND "ALTEZZA_VO" > 0
  THEN "ALTEZZA_VO"
  WHEN "QT_GRONDA" IS NOT NULL
  AND "QT_SUOLO" IS NOT NULL
  AND ("QT_GRONDA" - "QT_SUOLO") > 0
  THEN ("QT_GRONDA" - "QT_SUOLO")
  ELSE NULL
END
```

A binary height-availability variable was also constructed to discriminate between features supporting LoD1-like extrusion and features with missing or unusable height values

QGIS expression for `has_height`:

```
CASE
  WHEN "height_m" IS NOT NULL AND "height_m" > 0
  THEN 1
  ELSE 0
END
```

The field `height_m` supports geometric completeness, while `has_height` supports the calculation and visualization of height readiness indications. These derived fields are analytical outputs and should be documented as author-created fields, not original CSI attributes.

4.1.6 Alignment with the Methodological Framework

The individual steps of preprocessing were meant to support one or more of the evaluation dimensions outlined in the approach. The aim of preprocessing was not only to technically prepare the data but also to transform the source GIS layers into an analytical structure that could be assessed in terms of geometric completeness, semantic richness, interoperability and scalability. In this respect, the preprocessing stage is the link between the raw municipal dataset and the subsequent readiness assessment.

The height normalization directly supports the geometrical completeness. The addition of the `height_m` variable gives a single consistent height value for analysis, mapping and 3D extrusion. This is significant since the original dataset might include varied height related properties and these values need to be interpreted in a consistent format before the data can be analyzed for LoD1-like modelling. This dimension is also supported by the `has_height` field which separates features with useful height information from features with missing, zero or useless data. Together these elements allow to assess which features can support direct 3D representation and which need to be further enriched.

The richness of the semantics is in the choice of the layers and interpretation of attributes. The analysis does not treat all layers equally. More specifically, it identifies which layers have geometric information, which layers support building-level interpretation, and which layers may contain roof, minor-building, architectural-detail or border information. This is important because the collection is not produced as a common semantic object model. Semantic interpretation is consequently required to understand what each feature stands for and how it might contribute to 3D-readiness evaluation.

Derived identifiers (e.g., `building_id` and `part_id`) promote interoperability where split geometries can be read as related parts of a parent object. Without such IDs, distinct polygons may represent individual GIS features even when they are part of the same real-world item. By assigning common `building_id` and unique `part_id` values, the workflow establishes the foundation for a Building/BuildingPart structure that may be linked to CityGML/CityJSON-based interpretation.

The fields `ngsi_entity`, `relationship` and `partOf` are intended for future FIWARE/NGSI-LD type interoperability. These fields convert the reconstructed object logic into an entity-property-relationship structure, where each component can be represented as an entity and related to a parent object. This does not mean that a complete FIWARE Context Broker is developed in the thesis, but it shows how the reconstructed data could be readied for future reuse orientated to UDT.

Finally, the import of the reconstructed layer in PostGIS is scalable and ready to use in the database. PostGIS allows to save, query, validate and export the logic of Building/BuildingPart as a spatial relational structure, rather than merely as a visual action in QGIS. The PostGIS stage makes it possible to manipulate the reconstructed structure, not only for visual examination but also for structured queries, relational validation, export to GeoJSON and potentially further automation.

Table 4.3 relates each preprocessing operation to its methodological characteristic. In the table it is shown that the derived fields and database processes are not arbitrary technical additions but merely

methodological instruments to connect the original GIS data to 3D modelling ready, semantic interpretation, interoperability and future scale reuse.

Processing step	Purpose	Methodological dimension
Spatial clipping / filtering	Define the district-scale analytical subset	Scalability and reproducibility
Creation of height_m	Standardize height for analysis and extrusion	Geometric completeness
Creation of has_height	Identify features usable for LoD1-like modelling	Geometric completeness
Selection of Lavazza components	Extract building-scale stress test	Object-level validation
Creation of building_id and part_id	Represent parent object and components	Interoperability
Creation of ngsi_entity and partOf	Prepare FIWARE/NGSI-LD-style interpretation	Interoperability
Import into PostGIS	Store the reconstructed output relationally	Scalability and database-readiness

TABLE 4-3 ALIGNMENT BETWEEN PREPROCESSING OPERATIONS AND THE METHODOLOGICAL FRAMEWORK. SOURCE: AUTHOR'S ELABORATION.

The implementation workflow created in this chapter is summarized in Figure 4.1. It illustrates the development of the study from QGIS based data preparation and object reconstruction to relational storage in PostGIS, structured JSON export and interactive 3D display. From the graphic, it is seen that the workflow is not only to generate a visual 3D model. In contrast, it adopts a pipeline where the source GIS data is first cleaned and interpreted, then restructured into a Building/BuildingPart structure, stored into a spatial database, validated through queries, exported as GeoJSON and NGSI-LD-style JSON, and eventually visualized through static and interactive outputs. Therefore, Figure 4.1 connects the implementation phases to the core methodological elements of the thesis, which include geometric completeness, semantic richness, interoperability and scalability.

Implementation workflow from QGIS reconstruction to interactive 3D output

From QGIS reconstruction to PostGIS relational storage, GeoJSON/NGSI-LD export, and interactive 3D visualization

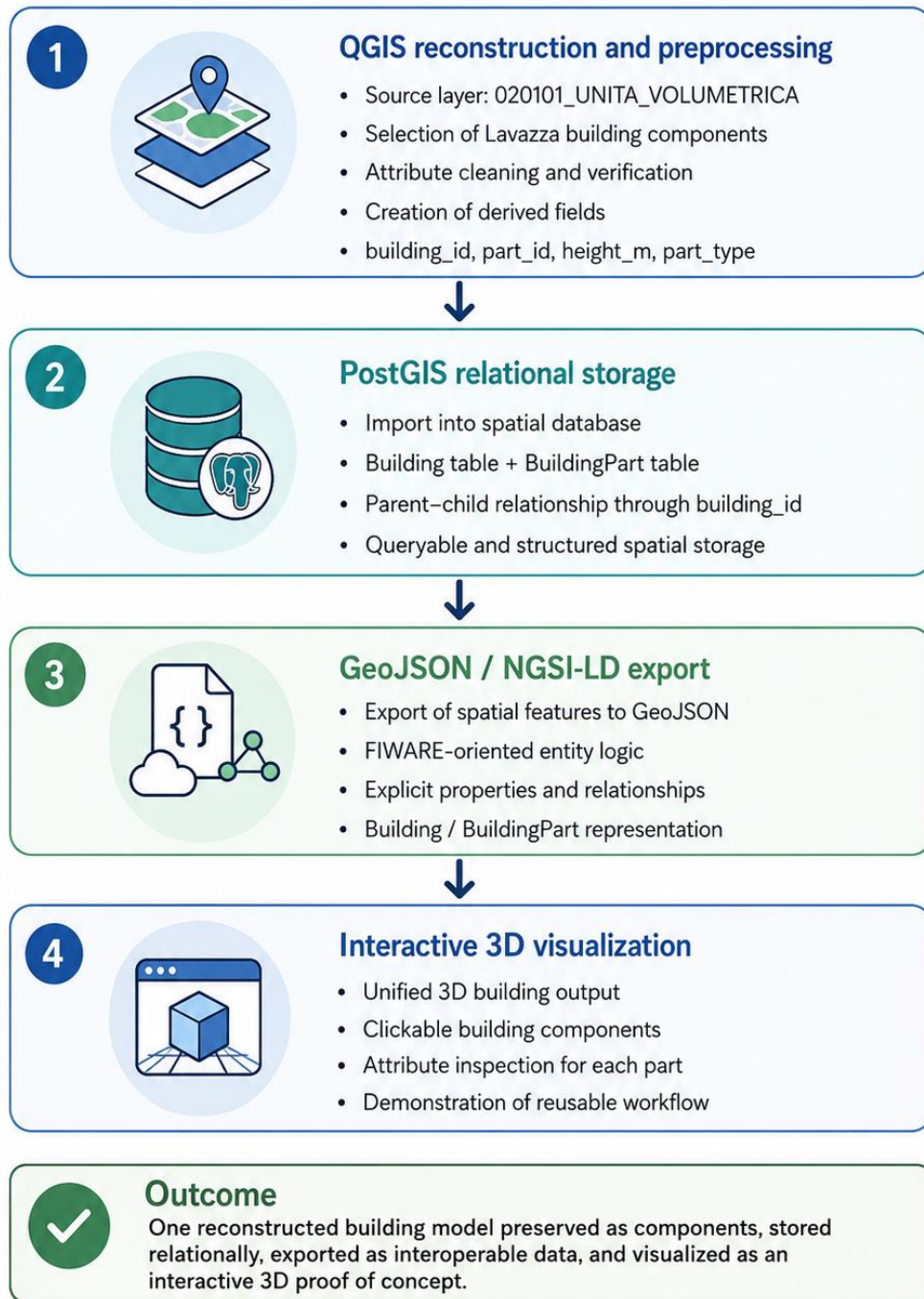


FIGURE 4.1 IMPLEMENTATION WORKFLOW FROM QGIS RECONSTRUCTION TO POSTGIS RELATIONAL STORAGE, GEOJSON/NGSI-LD EXPORT, AND INTERACTIVE 3D VISUALIZATION. SOURCE: AUTHOR'S ELABORATION.

4.1.7 Initial Technical Limitations

During the setup process, certain technical constraints were discovered. The first limitation is the layer-wise structure of the dataset. Information about buildings exists in different layers, rather than being modelled as a finished object-based model. Therefore, the association between a real-world building and its potential components is not always apparent. This is a difficulty for the standard-oriented interpretation as 3D city modelling and UDT-oriented workflows demand unambiguous definitions of objects, parts, identifiers and connections.

Completeness of height is the subject of the second restriction. The dataset has certain height properties; however, the values are not comprehensive and suitable for all aspects. In certain records height is missing, null, zero, or indeterminate, which prevents a direct LoD1-like extrusion. This means that the dataset cannot be automatically turned into a reliable 3D model without a check and standardisation of the given height information.

Thirdly, the statistics only provide a limited amount of detail. Basic volumetric interpretation can be more easily supported by the dataset than higher-LoD modelling. LoD1-like block models could be realized using footprints and height values, but richer models need roof geometry, information on facades, openings, texturing and interior data. Since these elements are not consistently available, the dataset can't immediately enable complete LoD2 or LoD3 models without further enrichment.

The fourth barrier is the absence of a database ready object schema. The source dataset does not contain a structured Building/BuildingPart model with explicit parent-child relationships. More fields and steps of restructuring are needed to represent the data as a relational and queryable structure in PostGIS.

The constraints do not diminish the usefulness of the dataset. However, they set out the conditions for reuse. They also justify the key methodological phases of the thesis: creation of derived fields; reconstruction of Building/BuildingPart relationships; storing the output into PostGIS; and creation of GeoJSON and NGSI-LD style outputs. In this respect, the limits are not simply technological impediments but they are part of the research findings, as they reveal precisely where municipal GIS data need to be interpreted, restructured or supplemented to be able to support 3D city modelling and future UDT-oriented workflows.

4.2 Phase 2 - Methodological Validation and Consistency Testing

4.2.1 Applicability of the Methodological Framework

The methodological framework was appropriate since it allowed the dataset to be assessed at various interconnected scales. On the district scale, it made it possible to assess layer structure, height availability and overall readiness indicators. At the building scale it enabled the rebuilding of fragmented geometries in a coherent Building/BuildingPart interpretation. At the database/output scale, it allowed testing if the reconstructed object structure could be saved and searched in PostGIS.

The usefulness of the framework is shown not only in the descriptive analysis but also in the implementation. The same derived fields developed in QGIS are utilized for 3D visualization, PostGIS storage, SQL queries, GeoJSON export and NGSI-LD style JSON. This continuity demonstrates that the technique is not a theoretical framework apart from the technological result.

4.2.2 Control Parameters and Consistency Checks

The validation phase tests the internal consistency of the dataset, derived fields and final outputs with a set of control parameters. These settings allow the workflow to not only build maps or visualizations, but also to add new analytical fields, reconstruct relationships between objects, import data into PostGIS, generate SQL outputs, and prepare GeoJSON/NGSI-LD-style representations. This means that the validation must check that each step is consistent with the prior one.

The control parameters are determined according to the four-evaluation dimension defined in the methodology. The workflow ensures geometric completeness by checking geometry correctness, height availability, and whether the standardized height_m field contains positive and useable values. It also tests for semantic richness, meaning, if the chosen characteristics and generated classifications provide meaningful information for the objects and their components. For interoperability it checks that identifier such as building_id, part_id, ngsi_entity and partOf are consistent and support object relationships. For scalability, it verifies if the reconstructed logic can be saved, queried, exported and perhaps re-executed through PostGIS relational structure.

Table 4.4 demonstrates the control parameters used to validate the internal consistency of the workflow. The table illustrates that validation requires more than visual inspection. Instead, the outputs are validated using geometry controls, height controls, identifier consistency, relationship consistency, SQL query validation, exportability, and 3D inspectability. This means that the final output is not just a visually rebuilt model but also a structured and testable data collection serving the methodological aims of the thesis.

Control parameter	Purpose	Scale / output level
Geometry validity	Check whether spatial features can be processed reliably	Dataset / district / building
Height availability	Assess LoD1-like extrusion potential	District / building
Height consistency	Check whether standardized height values are positive and usable	District / building
Object coherence	Test whether multiple polygons can represent one real-world building	Building
Identifier consistency	Ensure building_id and part_id are clear and non-ambiguous	Building / database
Relationship consistency	Verify parent-child logic through partOf and foreign key	PostGIS
Exportability	Test whether the output can be generated as GeoJSON and NGSI-LD-style JSON	Web / UDT-oriented output
3D inspectability	Test whether the components remain clickable and interpretable	Interactive 3D output

TABLE 4-4 CONTROL PARAMETERS USED DURING METHODOLOGICAL VALIDATION. SOURCE: AUTHOR'S ELABORATION.

4.2.3 Limits Encountered During Validation

During the validation phase it was shown that the restrictions found in the setup phase also apply to the subsequent phases of the workflow. Height incompleteness is still a limitation since features without valid positive height values cannot be directly used to allow LoD1-like extrusion. The fragmentation of layers is expressed in the need to understand building-related information in different theme layers rather than in one cohesive object schema. Object fragmentation is noticeable on the architectural scale, where a building in the actual world can be represented by multiple polygons or volumetric units as a substitute of a ready-made object. Finally, the absence of systematic roof, façade, opening, texturing and inside information confirms inadequate higher-LoD support. Accordingly, these boundaries arise in multiple ways throughout the workflow: as data-preparation concerns, as validation constraints and as requirements for subsequent restructuring or enrichment.

4.2.4 Synthesis of the Validation Phase

The validation process thus verifies the thesis' primary argument: the dataset is not unsuitable, but it is not always ready. When reviewed, cleansed, restructured and stored in a way that makes objects and relationships apparent, it becomes more suitable for 3D city modelling and UDT-oriented workflows. The validation further demonstrates that the proposed methodology is usable outside the selected building as the workflow relies on repeatable operations: height standardization, object/component identification, creation of derived identifiers, restructuring of Building/BuildingPart, PostGIS relational storage and structured export. In this case, the same analytical rationale can be extended to other buildings, even if the comprehensive test is conducted on the Lavazza building, as long as equivalent geometrical features, height attributes and grouping criteria are present.

4.3 Phase 3 - Analysis of Results and Identified Issues

4.3.1 Geometric Completeness

Geometric completeness was assessed based on the availability of correct geometry and suitable height data. The volumetric-unit layer forms the basic basis for geometric interpretation since it contains the features that can be extruded into LoD1-like volumes. If height_m is valid and positive, the feature can allow basic volumetric 3D representation. where height_m is null, zero or indeterminate, straight extrusion is impossible and the feature needs to be enriched or interpreted.

At district scale, height availability can be illustrated using maps and charts illustrating the proportion and spatial distribution of features with usable height values. At the scale of the building, geometric completeness is measured component-wise. This is significant because a building can look complete when seen as an overall footprint, but the individual pieces can have varying height values or data-quality conditions. Figure 4.2. Height of availability results for the district-scale volumetric-unit layer. The chart offers quantitative evidence of geometric completeness by separating features that can support LoD1-like extrusion and features that require further enrichment.

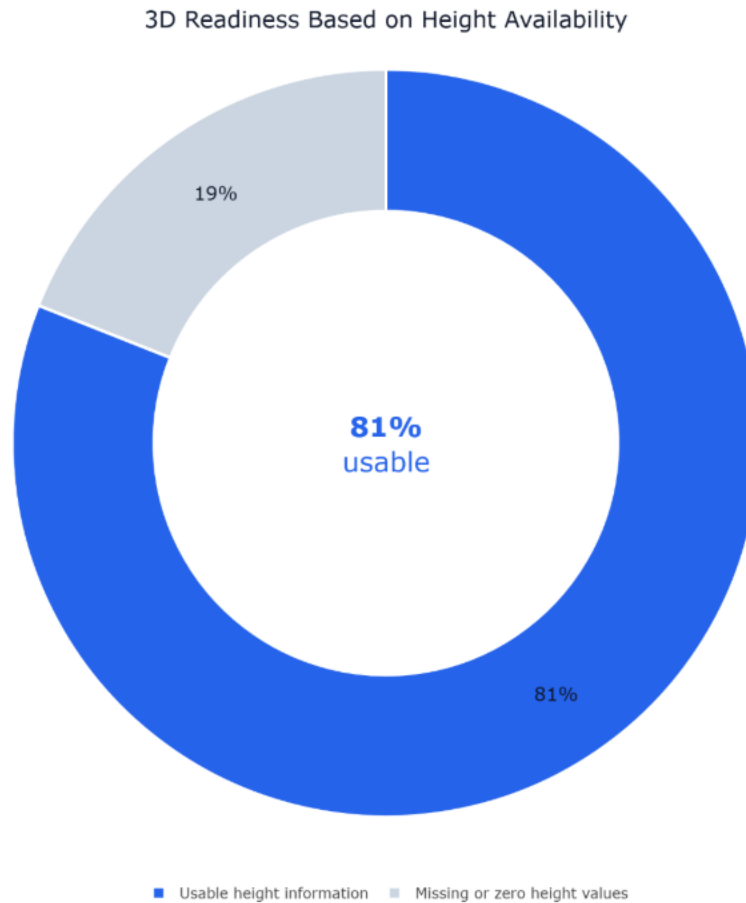
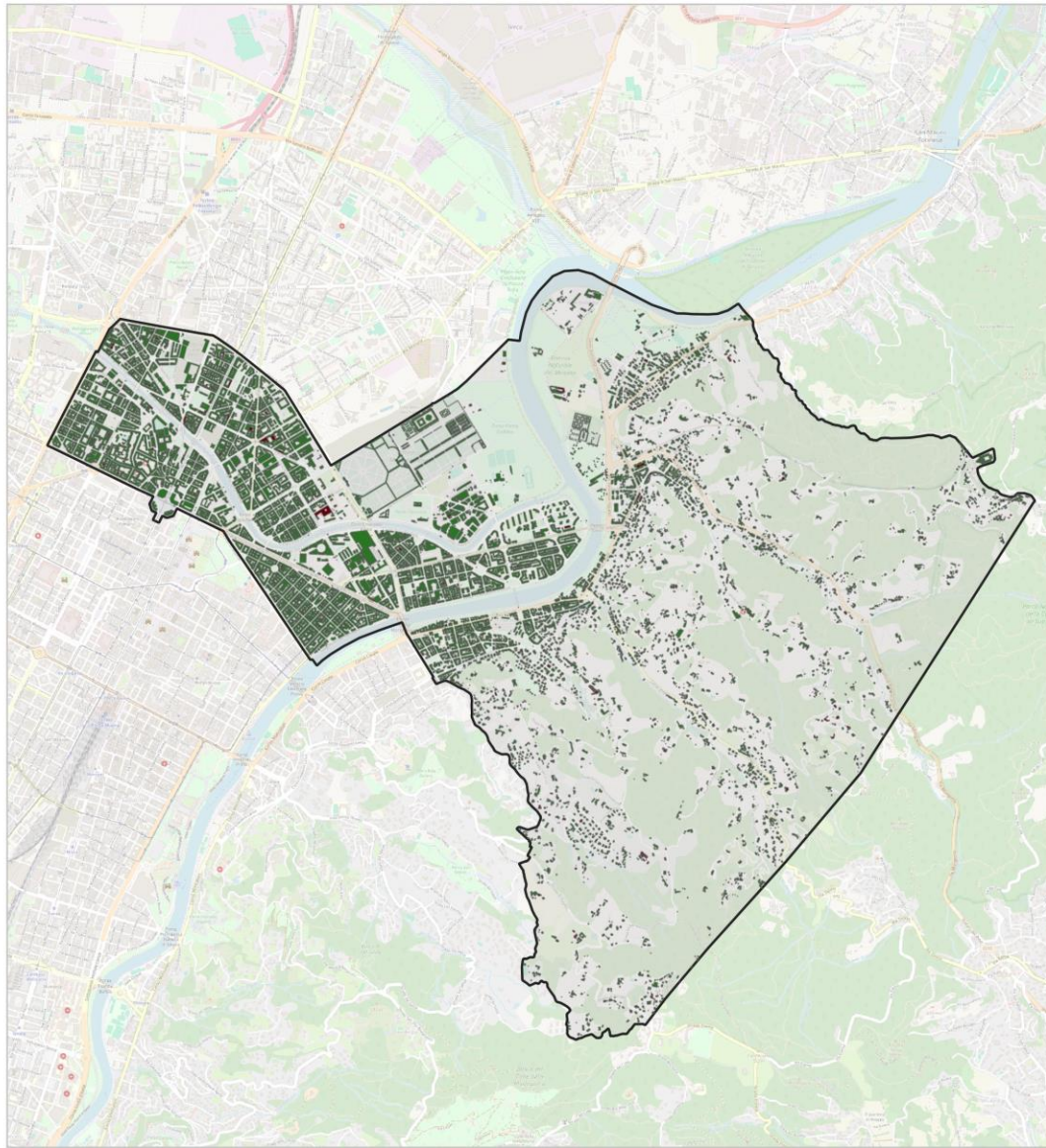


FIGURE 4.2 HEIGHT AVAILABILITY CHART FOR THE DISTRICT-SCALE VOLUMETRIC-UNIT LAYER. SOURCE: AUTHOR'S ELABORATION BASED ON CSI DATA.

Map 4.2 spatializes the identical height-availability data over the district-scale analytical area. Because height incompleteness is both a numerical and a spatial distribution issue, this map is crucial for determining where 3D modeling is directly applicable and where further data is needed.

District-scale height availability in the volumetric-unit layer



Legend

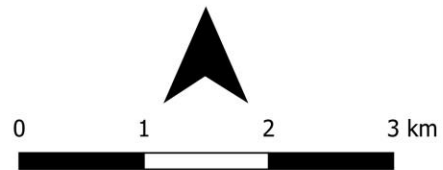
Volumetric units

MISSING

OK

District 7 - Circoscrizione 7 Torino

OpenStreetMap



MAP 4-2 DISTRICT-SCALE HEIGHT AVAILABILITY IN THE VOLUMETRIC-UNIT LAYER. FEATURES WITH VALID HEIGHT VALUES CAN SUPPORT LOD1-LIKE EXTRUSION, WHILE FEATURES WITH MISSING OR ZERO VALUES LIMIT DIRECT 3D MODELLING. SOURCE: AUTHOR'S ELABORATION BASED ON CSI DATA.

The combined reading of Figure 4.2 and Map 4.2 indicates that geometric preparedness varies across the district-scale dataset. Out of total 17,565 volumetric units, 14229 units have reliable height values (81% of the dataset). Features with valid positive height values can be directly used to produce LoD1-like extrusion. However, features with missing or zero height values cannot be converted to reliable 3D volumes without further information. This demonstrates that the dataset has some potential for partial 3D modelling, but also that the completeness of height must be examined before any attempt at automatic city scale extrusion.

4.3.2 Semantic Richness

Semantic richness was operationalized as the presence of non-geometric meaningful information in the dataset. The CSI dataset contains valuable features and layers, among them information relating to buildings, minor buildings, covering elements, architectural details and sub-municipal boundaries. But the information is dispersed over layers instead of being contained in one object structure.

It is therefore somewhat semantically ready. The dataset is more complex than a simple footprint record, yet needs interpretation to facilitate object-based modelling. The derived field `part_type` was created at building size, to make explicit the semantic role of each component. This field is not a replacement of the original data but rather an analytical classification that will be useful for display and explanation.

Semantic richness is important for both CityGML/CityJSON and FIWARE/NGSI-LD. In the CityGML/CityJSON logic, a feature should be interpretable as a city object, for instance `Building` or `BuildingPart`. In FIWARE/NGSI-LD logic the same feature should be representable as an entity with properties. Semantic richness consequently contributes to both 3D city modelling and future UDT-oriented interoperability.

4.3.3 Interoperability

Interoperability was examined by determining if the dataset may be restructured according to standard-oriented structures. The dataset can be used in QGIS as it is, however technical usability is not the same as semantic interoperability. Object-level interoperability requires solid IDs, meaningful characteristics and explicit relationships.

This limitation is solved by the derived fields `building_id`, `part_id`, `ngsi_entity`, `relationship` and `partOf`. The field `building_id` points to the parent building. Each component is identified by its `part_id` field. The `ngsi_entity` field contains the NGSI-LD style identification for each component. The fields `relationship` and `partOf` describe the relationship between a component and the parent building.

The PostGIS implementation improves the compatibility as it stores the relationship in the database form. The `building` table contains the parent object and the `building_part` table contains the components. The foreign key on `building_id` formally links the two tables. This implies that the relationship is not merely expressed in text or shown, but realized as a relational structure that can be queried.

4.3.4 Scalability

Scalability was tested by asking if the workflow can be transferred between scales and if the same reasoning can be reproduced. The methodology is spatially scalable from a regional and city setting to district evaluation and building-scale rebuilding. It is architecturally scalable as it defines a repeated object rule: one real-world building can be represented as one parent object building and its volumetric components can be represented as BuildingPart records.

Additional parameters must be met for operational scalability. The dataset must have valid grouping identifiers or rules for automatic spatial grouping, if the procedure is to be applied to the whole district or city. Without such principles complicated buildings still require manual interpretation. The PostGIS prototype is future-proof on scalability, as it has a database structure that is repeatable, queryable and exportable. The prototype itself does not automate the grouping of all buildings.

4.3.5 Cross-dimensional Interpretation of the Results

The four evaluation dimensions are interconnected. 3D modeling feasibility depends on geometric completeness. The semantic richness determines whether the model may be interpreted in a meaningful way. Interoperability relies on identifiers and relations. Scalability depends on the repeatability of the transformation logic and its ability to be stored in a structured context.

Results illustrate the dataset potential for basic 3D visualization, and LoD1-like modeling where height information is provided. But stronger readiness needs object reconstruction and database representation. The reorganization of the Building/BuildingPart and the prototype of PostGIS are therefore not decorative supplementary outputs, they are a direct response to the difficulties found in the evaluation.

4.3.6 Identified Issues

Table 4.5 summarizes the major issues raised during the investigation and links each to its methodological response. The table demonstrates that the proposed procedure immediately addresses the shortcomings of the observed data, specifically height incompleteness, object fragmentation, weak linkages and no database-ready structure.

Issue	Explanation	Impact	Response in the thesis
Height incompleteness	Some features have missing, null, or zero height values.	Limits LoD1-like extrusion.	height_m, has_height, quality_flag.
Layer fragmentation	Building information is distributed across several layers.	Requires interpretation and layer comparison.	Layer selection and semantic mapping.
Object fragmentation	One real-world building may be represented by multiple polygons.	Limits direct object interpretation.	Building/BuildingPart reconstruction.
Distributed semantics	Attributes are not unified in one schema.	Limits direct standard mapping.	part_type and derived semantic fields.
Weak relationship structure	Parent-child object relationships are not directly encoded.	Limits interoperability.	building_id, part_id, partOf, PostGIS foreign key.
No ready database schema	Source data are not structured for database-driven UDT use.	Limits queryability and automation.	PostGIS building and building_part tables.
Limited higher-LoD support	Roof, facade, opening, texture, and interior data are insufficient.	Prevents direct LoD2/LoD3/LoD4 modelling.	lod_potential classification and future enrichment.

TABLE 4-5 MAIN ISSUES IDENTIFIED DURING THE ANALYSIS AND THEIR METHODOLOGICAL RESPONSES. SOURCE: AUTHOR'S ELABORATION.

4.4 Phase 4 - Synthesis of Findings and Proposed Improvements

4.4.1 FIWARE-oriented Restructuring of the Dataset

The fundamental enhancement proposed by this thesis is the re-structuring of the building-scale output, according to a CityGML/CityJSON oriented Building/BuildingPart logic and an interoperability logic in the style of FIWARE/NGSI-LD. This reorganization is not only to make the geometry look cleaner in QGIS, but also to convert fragmentary GIS characteristics to a more explicit object-based structure. The initial GIS representation can show different polygons as different features, whether they are part of the same real-world object or not. However, for 3D city modelling and future UDT-oriented reuse, these components need to be read as connected pieces of a consistent object.

That is why the original geometries are not dissolved into a single polygon. While visually merging the geometries would result in a single, unified item, it would also result in the loss of critical information at the component level, such as the specific geometry, height, type, and quality condition of each part. Instead of the Building with a polygon, a BuildingPart is created for each polygon and referenced to a parent Building with derived identifiers. This technique addresses fragmentation as a limitation of the source material, but also as a chance to save and organize information at the component level. This way the reconstructed result is visually consistent and analytically detailed.

The derived fields were generated in QGIS using the Field calculator and where necessary manual classification based on the geometry and role of each component. These are analytical fields introduced by authors. They are not original attributes of the CSI dataset. This distinction matters for transparency and reproducibility. The source dataset contains geometry and height related information. The derived fields make the reconstruction logic explicit. For example, `building_id` identifies the parent object, `part_id` identifies each component, `height_m` normalizes the height number needed for extrusion, and `part_type` provides semantic interpretation. Other fields, such as `lod_potential` and `quality_flag`, contain the modelling potential and data condition of each component.

The fields `ngsi_entity`, `relationship` and `partOf` prime the reconstructed structure for future FIWARE/NGSI-LD-style interpretation. They permit each component to be interpreted as a potential entity, characterized by properties and related to a parent object by a relationship. This means that the thesis does not implement a comprehensive FIWARE Context Broker. Conversely, it shows how the reconstructed data could be represented in an entity–property–relationship logic, which is suited for future UDT-oriented processes.

The reconstructed fields, tables and outputs were given basic naming conventions. The parent `building_id` was `Lavazza_B1`, where `Lavazza` is the building-scale focus and `B1` is the first Building object that was recreated. Component identities such as `LAV_1081` and `LAV_7341` were used as `part_id` values. The prefix `LAV` indicates the belonging to the `Lavazza` subset and the numeric value identifies each component. For the reconstruction, a parent-component structure was adopted. Therefore, the database tables were designated `building` and `building_part`. This convention exposes the connection between source geometries, reconstructed objects, PostGIS tables and JSON outputs to the reader.

Table 4.6 Derived fields created for the Building/BuildingPart reconstruction It is important to have the table since it indicates exactly what fields were added, how they were produced and why they were needed. It also explains the distinction between original CSI attributes and the fields generated by the author for reconstruction, interoperability, PostGIS storage and display. This way, the table promotes the reproducibility of the workflow and demonstrates that the restructuring process is not arbitrary but closely related to the methodological aims of geometric completeness, semantic richness, interoperability and scalability.

Field	Type	Creation logic	Purpose	Interpretation
building_id	Text	The same value assigned to all components of the selected building.	Identifies the parent building.	Common parent object.
part_id	Text	Unique value assigned to each volumetric component.	Identifies each component.	BuildingPart / component.
height_m	Decimal	Derived from ALTEZZA_VO or QT_GRONDA - QT_SUOLO were valid.	Stores standardized height.	LoD1-like extrusion.
part_type	Text	Analytical classification based on component form and role.	Adds semantic meaning.	main_body, tower, block, connector, etc.
lod_potential	Text	Assigned according to available geometry and height.	Records possible LoD support.	LoD1-like / insufficient.
quality_flag	Text	Assigned according to completeness and uncertainty.	Records data quality.	complete_for_LoD1 / height_missing / uncertain.
ngsi_entity	Text	Concatenation of NGSI-LD prefix and part_id.	Stores NGSI-LD-style component ID.	Future entity identifier.
relationship	Text	Constant value such as partOfBuilding.	Defines relationship type.	Relationship property.
partOf	Text	Parent NGSI-LD-style Building identifier.	Links component to parent.	partOfBuilding relationship.

TABLE 4-6 DERIVED FIELDS CREATED FOR BUILDING/BUILDINGPART RECONSTRUCTION. SOURCE: AUTHOR'S ELABORATION.

In QGIS, the FIWARE-compatible fields can be created as follows:

```

building_id = 'Lavazza_B1'

ngsi_building = 'urn:ngsi-ld:Building:Lavazza_B1'

ngsi_entity = concat('urn:ngsi-ld:BuildingPart:', "part_id")

relationship = 'partOfBuilding'

partOf = 'urn:ngsi-ld:Building:Lavazza_B1'

```

4.4.2 PostGIS Representation of the Reconstructed Structure

Following QGIS-based reconstruction, the reconstructed layer was imported into PostgreSQL/PostGIS to assess database suitability and scalability. This stage has been implemented because the aim of the thesis is not only to produce a visual 3D representation, but also to check if the reconstructed object logic can be stored, searched, related and exported in a structured database environment. The reason PostgreSQL is important is because it can handle relational database architectures, complicated queries, and formal links between tables through primary and foreign keys. PostgreSQL is an open-source object-relational database management system originally developed from the POSTGRES project at the University of California, Berkeley. It supports complex queries, foreign keys, triggers, transactional integrity, multiversion concurrency control, and extensibility, according to the official documentation (PostGIS Project, 2026a).

PostGIS adds geographic data, spatial indexing, spatial functions, coordinate transformation and spatial export to PostgreSQL. PostGIS is not used as a replacement of QGIS in this thesis. QGIS is the main spatial inspection, editing, mapping and 3D visualization environment. PostGIS is utilized as a supplemental implementation layer to verify whether the reconstructed Building/BuildingPart structure may be a queryable spatial relational model. This distinction matters because while a dataset can be seen in GIS, it may still lack the relational structure necessary for scalable and interoperable reuse.

The parent building was maintained in a building database. Every reconstructed component was saved in a `building_part` table. The two tables were related by the common `building_id` field, and this link was formalized with a foreign-key constraint. In practice this implies that each component in the `building_part` table must be explicitly connected to a legitimate parent object in the `building` table. The reconstructed building is therefore not just a set of polygons presented together in QGIS, but a structured database object consisting of related pieces.

This allows for both scalability and compatibility. This allows for interoperability, as the Building/BuildingPart relationship is explicitly expressed and may be queried or exported to formats such as GeoJSON and NGSI-LD-style JSON. It is scalable in the sense that the same relational structure might be replicated for other buildings, providing proper identifiers and grouping criteria are available. The relational structure of the rebuilt output stored in PostGIS is shown in Table 4.7. The parent building table is used to store the building information and the component-level `building_part` table is used to store the building part information.

Table	Purpose	Main fields	Relationship
building	Stores the parent building object.	<code>building_id</code> , <code>name</code> , <code>building_use</code> , <code>ngsi_entity</code>	Parent table.
building_part	Stores each reconstructed component.	<code>part_id</code> , <code>building_id</code> , <code>height_m</code> , <code>part_type</code> , <code>lod_potential</code> , <code>quality_flag</code> , <code>ngsi_entity</code> , <code>relationship</code> , <code>partOf</code> , <code>geom</code>	Linked to building through <code>building_id</code> .

TABLE 4-7 POSTGIS RELATIONAL STRUCTURE OF THE RECONSTRUCTED OUTPUT. SOURCE: AUTHOR'S ELABORATION.

The parent table was created as follows:

```
CREATE TABLE IF NOT EXISTS building (  
    building_id VARCHAR(50) PRIMARY KEY,  
    name VARCHAR(100),  
    building_use VARCHAR(100),  
    ngsi_entity VARCHAR(150)  
);
```

The parent object was inserted using the following SQL:

```
INSERT INTO building (  
    building_id, name, building_use, ngsi_entity  
)  
VALUES (  
    'Lavazza_B1',  
    'Lavazza Building',  
    'office / commercial',  
    'urn:ngsi-ld:Building:Lavazza_B1'  
)  
ON CONFLICT (building_id) DO NOTHING;
```

After importing the reconstructed QGIS layer as `building_part`, the relationship was implemented as a foreign key:

```
ALTER TABLE building_part  
ADD CONSTRAINT fk_building_part_building  
FOREIGN KEY (building_id)  
REFERENCES building(building_id);
```

This foreign key constraint is the evidence of the Building/BuildingPart logic in the main database. It guarantees that every `building_part` component has a valid parent building in the building table. Methodologically it transforms the reconstructed building from a visual cluster into a relational spatial representation.

4.4.3 SQL Validation of the Building/BuildingPart Relationship

A SQL join query was performed to fetch all components of the parent building. This query confirms that the reconstruction of the structure is saved as a relational model, and not simply as a visual layer.

```
SELECT
    b.building_id,
    b.name,
    p.part_id,
    p.height_m,
    p.part_type,
    p.lod_potential,
    p.ngsi_entity
FROM building b
JOIN building_part p
ON b.building_id = p.building_id
WHERE b.building_id = 'Lavazza_B1'
ORDER BY p.height_m DESC;
```

building_id	name	part_id	height_m	part_type	lod_potential	ngsi_entity
Lavazza_B1	Lavazza Building	LAV_7341	30.64	tower	LoD1-like	urn:ngsi-id:Building
Lavazza_B1	Lavazza Building	LAV_15145	14.63	main_body	LoD1-like	urn:ngsi-id:Building
Lavazza_B1	Lavazza Building	LAV_1082	12.74	block	LoD1-like	urn:ngsi-id:Building
Lavazza_B1	Lavazza Building	LAV_1081	9.39	block	LoD1-like	urn:ngsi-id:Building
Lavazza_B1	Lavazza Building	LAV_12854	5.79	block	LoD1-like	urn:ngsi-id:Building
Lavazza_B1	Lavazza Building	LAV_7342	5.2	block	LoD1-like	urn:ngsi-id:Building

TABLE 4-8 SQL QUERY RESULT SHOWING ALL BUILDINGPART COMPONENTS LINKED TO THE PARENT BUILDING OBJECT IN POSTGIS. SOURCE: AUTHOR'S ELABORATION.

Table 4.8 displays the SQL validation results used to evaluate the Building/BuildingPart connection in PostGIS. The table demonstrates that the rebuilt components are not saved as one-off geometries but are associated with one parent Building object by employing the common building_id field. This is direct

indication that the object-reconstruction logic has been effectively transferred from QGIS to a relational spatial database structure.

The result shows that the reconstructed structure works within the database. In QGIS, the building can be represented as a series of related volumetric components; in PostGIS the same logic becomes SQL queryable and verifiable. It stores the parent object to the building table and each component as a distinct record to the building_part table. The join query pulls out all components for the parent object, showing that the relationship is not only visual or descriptive, but actually implemented formally in the database.

This validation aids interoperability and scalability as well. The components can be identified, queried and exported as one structured object. The same relational logic can be used for additional buildings with proper grouping rules, identifiers or spatial criteria. Table 4.8 confirms the procedure creates a database-ready structure, not just a static visualization, compatible with GeoJSON export, NGSI-LD-style representation and UDT-oriented reuse in the future.

A second summary query was used to count components and summarize height values:

```
SELECT
    building_id,
    COUNT(*) AS number_of_parts,
    ROUND(AVG(height_m)::numeric, 2) AS average_height_m,
    ROUND(MAX(height_m)::numeric, 2) AS max_height_m,
    ROUND(MIN(height_m)::numeric, 2) AS min_height_m
FROM building_part
WHERE building_id = 'Lavazza_B1'
GROUP BY building_id;
```

The summary query contains a concise database-level description of the reconstructed object. In lieu of enumerating each component, it gathers the building_part records related to the parent building and outputs the total count of components and their height distribution. This supports that the reconstructed item could be queried as a coherent database entity and not merely as individual sections. The result indicates that the parent building contains six BuildingPart records with an average height of 13.07 m and a maximum height of 30.64 m.

building_id	number_of_parts	average_height_m	max_height_m
Lavazza_B1	6	13.07	30.64

TABLE 4-9 SUMMARY STATISTICS OF THE RECONSTRUCTED BUILDINGPART COMPONENTS IN POSTGIS. SOURCE: AUTHOR’S ELABORATION.

Consequently, Table 4-9 extends the SQL validation table given in the preceding section. As shown in Table 4-8, each BuildingPart is properly related to the parent Building object. Table 4-9 highlights the rebuilt object at the database level. This demonstrates that PostGIS is capable of supporting both aggregated object-level interpretation and granular component-level examination, which is crucial. The

table confirms the methodology that the reconstruction of Building/BuildingPart is visual, but also queryable, measurable and ready for future scalable reuse.

4.4.4 GeoJSON and NGSI-LD-style Outputs

GeoJSON and NGSI-LD style JSON outputs were produced using the PostGIS table. GeoJSON displays a web-ready spatial export, and NGSI-LD-style JSON shows future entity-property-relationship compatibility. These results are not a deployed FIWARE Context Broker but illustrate that the reconstructed database structure may be converted towards FIWARE compatible logic.

The geometry was changed to WGS84/EPSC:4326 for the GeoJSON output using ST_Transform(geom, 4326). This change was performed at the export step to ensure that the output was compatible with web-based GeoJSON usage while the analytical GIS and PostGIS workflow still used the source/project reference system. Then the altered geometry was converted to GeoJSON format using PostGIS ST_AsGeoJSON (PostGIS Project, 2026b).

GeoJSON FeatureCollection query:

```
SELECT jsonb_pretty(
  jsonb_build_object(
    'type', 'FeatureCollection',
    'features', jsonb_agg(
      jsonb_build_object(
        'type', 'Feature',
        'id', part_id,
        'geometry', ST_AsGeoJSON(ST_Transform(geom, 4326))::jsonb,
        'properties', jsonb_build_object(
          'building_id', building_id,
          'part_id', part_id,
          'height_m', height_m,
          'part_type', part_type,
          'lod_potential', lod_potential,
          'quality_flag', quality_flag,
          'ngsi_entity', ngsi_entity,
          'relationship', relationship,
          'partOf', "partOf"
```

```

        )
    )
)
) AS geojson
FROM building_part
WHERE building_id = 'Lavazza_B1';

```

The parent Building entity was generated using a JSON query that aggregates all component entity identifiers into a hasPart relationship:

```

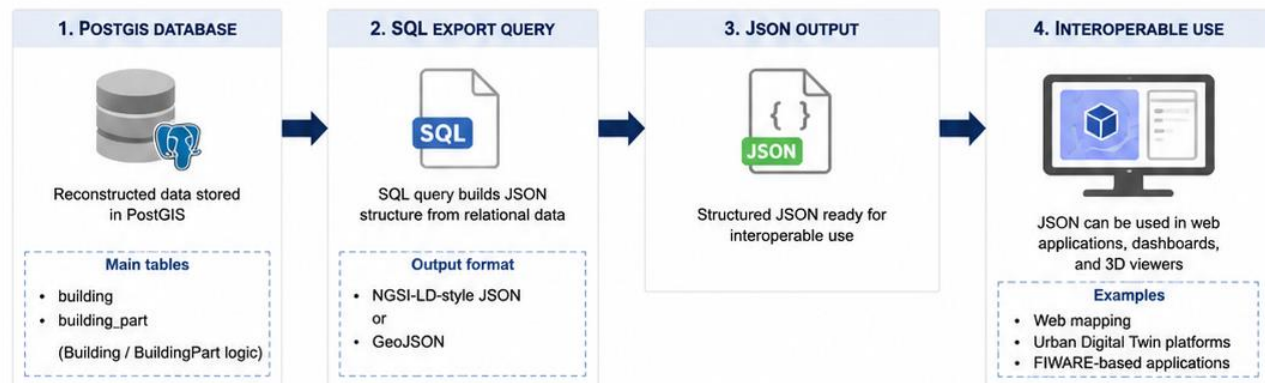
SELECT jsonb_pretty(
    jsonb_build_object(
        'id', b.ngsi_entity,
        'type', 'Building',
        'name', jsonb_build_object('type','Property','value',b.name),
        'buildingUse', jsonb_build_object('type','Property','value',b.building_use),
        'hasPart', jsonb_build_object(
            'type', 'Relationship',
            'object', jsonb_agg(p.ngsi_entity ORDER BY p.part_id)
        )
    )
) AS ngsi_building
FROM building b
JOIN building_part p
ON b.building_id = p.building_id
WHERE b.building_id = 'Lavazza_B1'
GROUP BY b.ngsi_entity, b.name, b.building_use;

```

Each BuildingPart entity was generated with its own identifier, properties, and relationship to the parent building:

```
SELECT jsonb_pretty(
    jsonb_build_object(
        'id', ngsi_entity,
        'type', 'BuildingPart',
        'partOfBuilding', jsonb_build_object('type','Relationship','object',"partOf"),
        'height', jsonb_build_object('type','Property','value',height_m),
        'partType', jsonb_build_object('type','Property','value',part_type),
        'lodPotential', jsonb_build_object('type','Property','value',lod_potential),
        'qualityFlag', jsonb_build_object('type','Property','value',quality_flag)
    )
) AS ngsi_building_part
FROM building_part
WHERE building_id = 'Lavazza_B1'
ORDER BY part_id;
```

A structured output that can be used for interoperable purposes can be generated from the rebuilt building_part data saved in PostGIS, as shown in Figure 4.3. The main workflow is displayed in the upper half of the figure: Reconstructed Building/BuildingPart data is saved in the PostGIS database, accessed using SQL, exported as JSON and then made available for web apps, dashboards, 3D viewers or future UDT platforms. The lower half shows two examples of this export logic. The NGSI-LD-style JSON output models each component as an entity with an id, properties and relationships while the GeoJSON output keeps the geographical geometry along with the required attributes. This graphic shows that the output is not only a visible 3D model, but also a structured and re-usable data representation that may be used for future interoperability.



A. EXAMPLE OF NGSI-LD-STYLE JSON OUTPUT



B. EXAMPLE OF GEOJSON OUTPUT



FIGURE 4.3 EXAMPLE OF GeoJSON OR NGSI-LD-STYLE JSON OUTPUT GENERATED FROM POSTGIS. SOURCE: AUTHOR'S ELABORATION.

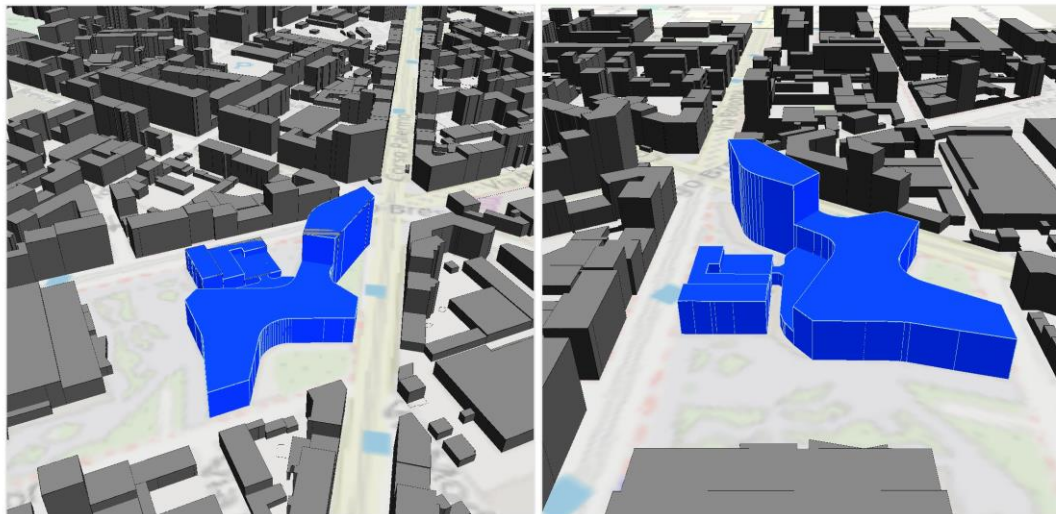
After validation using PostGIS and export to JSON, the `building_part` table was reloaded into QGIS through the PostGIS connection. The significance of this phase was that it evaluated the feasibility of the reconstructed data's transition from the database environment to a GIS visualization workflow without compromising its object structure or attributes. The layer was styled by `part_type` or `part_id`, and extruded by the standardized `height_m` field. Consequently, the building could be represented as a cohesive three-dimensional object while simultaneously preserving the unique characteristics of each component. In other words, the output does not merge the parts into one simpler block. Each `BuildingPart` is still an independent feature with its own geometry, height, categorization, quality information and identifiers.

This 2D and 3D reconstruction is shown in Map 4.3. The 2D view provides a view of the component structure of the reconstructed item, so that the spatial organization of the original volumetric units may be understood. The same components are extruded by `height_m` in the 3D view, illustrating the LoD1-like modelling capability of the dataset after preprocessing and restructuring. Together the two views indicate that the PostGIS `building_part` layer can be used for both planimetric inspection and volumetric analysis.

The same reconstructed layer was then exported as an interactive 3d web model using `Qgis2threejs`. You may then click on each one and see its stored properties like `part_id`, `height_m`, `part_type`, `lod_potential`, `quality_flag`, `ngsi_entity`, `relationship`, and `partOf`. This is significant as the interactive model links the spatial form of the building to the structured data reasoning behind it. The user can not only observe the 3D geometry, but can also get the attribute of information supporting the interpretation of the object and the future interoperability.

Final output is consequently provided in three complementary forms. First, the static 2D/3D representation of QGIS shows the spatial and volumetric reconstruction of the building from the PostGIS layer. Second, the validation tables of the SQL show that the same components are saved as database entries associated with one parent `Building` object. Third, the interactive `Qgis2threejs` model demonstrates that the reconstructed components are clickable, inspectable and communicative in a web-based context. Together, these outputs demonstrate the workflow is not only visible, but also relational, queryable and suited for future UDT-oriented reuse.

Lavazza Building: 2D Component Structure and 3D Reconstruction



MAP 4-3 QGIS-BASED 2D AND 3D RECONSTRUCTION OF THE LAVAZZA BUILDING FROM THE POSTGIS BUILDING_PART LAYER. THE 2D VIEW SHOWS THE COMPONENT STRUCTURE, WHILE THE 3D VIEW SHOWS THE SAME COMPONENTS EXTRUDED ACCORDING TO HEIGHT_M.

Figure 4.4 illustrates the final interactive 3D demonstrator built in the workflow of this thesis. The left image displays the interactive 3D model generated by Qgis2threejs, exporting from QGIS. The rebuilt elements of the Lavazza building are shown in the context of the surrounding urban environment. Each component is interactively inspectable, which provides access to its related attributes, such as height values, part identities, LoD-related information, NGSI-LD-like identifiers and parent-building relationships. The related Google Maps 3D view is presented in the right-hand image. The 3D model achieved by the CSI-based reconstruction was compared with the true morphology of the Lavazza complex, using the Google Maps 3D view as a visual reference. The two views together highlight the promise and constraints of converting authoritative 2D/2.5D building data to an interactive 3D representation for Urban Digital Twin applications.



FIGURE 4.4 INTERACTIVE CLICKABLE 3D MODEL EXPORTED WITH QGIS2THREEJS, SHOWING COMPONENT ATTRIBUTES AND NGSI-LD-STYLE IDENTIFIERS. SOURCE: AUTHOR'S ELABORATION.

4.5 Chapter Summary

The implementation described in this chapter was conducted in the four methodological steps on the selected case-study data. The workflow involved spatial delimitation and preprocessing, Building/BuildingPart reconstruction, PostGIS relational storage, SQL validation, output to GeoJSON and NGSI-LD style, and interactive 3D visualization. The following chapter describes the interpretation of these results with respect to the study topic, the assessment dimensions, the constraints of the workflow and its potential for future UDT-oriented reuse.

05

CHAPTER

Discussion and Conclusion

Interpreting the main findings, summarizing the research contribution, and outlining future directions for scalable Urban Digital Twin development.

5.1 Discussion of the Main Findings

The results demonstrate that the dataset has obvious potential for fundamental 3D city modeling, particularly in cases where valid geometries and usable height values are available. The 020101_UNITA_VOLUMETRICA layer is the most essential base for this potential, since it comprises volumetric geometries and height-related properties that potentially facilitate LoD1-like extrusion. However, this potential is not evenly distributed over the sample. Some features have reliable height information, while others are missing, zero or ambiguous. This backs up one of the main points of the thesis: data access does not always mean data readiness. The dataset is official, rich in spatial information but still needs to be evaluated and pre-processed before it can be successfully re-used for 3D modelling.

The results reveal that the product of the thesis is not only a 3D visualization. The workflow reassembles fragmented GIS geometries into BuildingPart components, ties them to a parent Building object, stores the structure in PostGIS, validates it with SQL queries, outputs it as GeoJSON and NGSI-LD-style JSON, and visualizes it through an interactive 3D model. This sequence shows that the rebuilt data may be understood not just visually, but also as a structured, queryable and exportable object-based representation.

The research also indicates that the major constraint is not merely geometric. The dataset contains semantic information but it is dispersed over the different layers and is not pre-organized as a coherent object-based model. Thus, the data may describe features of the built environment, but they do not directly yield the semantic hierarchy that is required for standard-conforming 3D city modelling. In particular, the link between a building in the real world and its components is not always apparent. Therefore, interoperability requires further interpretation through derived identities, object reconstruction and explicit parent-child connections.

The Building/BuildingPart logic in this case solves the problem of translating fragmented GIS features into a more structured object representation. The procedure does not dissolve the original components into one streamlined geometry, but keeps each component as a separate BuildingPart and binds it to one parent Building object. This method is significant because it preserves component-level information, while clarifying the object structure and making it more suitable for CityGML/CityJSON-oriented interpretation and future FIWARE/NGSI-LD-style interoperability.

The PostGIS prototype confirms the conclusion that the reconstructed structure can evolve beyond QGIS representation. The output may be queried, measured, exported and validated more easily, as the parent Building and its BuildingPart components are stored in associated spatial database tables. SQL queries prove that the components are connected to the parent object, and GeoJSON and NGSI-LD-style JSON outputs show that the same structure can be prepared for web-based viewing and future interoperable reuse. In this way, the thesis contributes not only a 3D visual representation but also a structured data pipeline.

Overall, the results indicate that the municipal GIS data can be a useful basis for 3D city modelling, but are not ready yet for full UDT integration. The CSI dataset offers important volumetric geometry and height associated features supporting LoD1-like modelling where values are valid. However, it does not immediately give a complete higher-LoD information, semantic object hierarchy, explicit database-ready relationships, or fully interoperable structure. Therefore, the dataset should be seen as a promising but incomplete basis: It is suitable as a basis for future 3D and UDT-oriented operations only after comprehensive cleaning, interpretation, restructuring and database-supported representation.

5.2 Answer to the Research Question

The dataset is partially ready for the transition to 3D city modeling and eventual UDT-based interoperability. If accurate footprints and height values are given, it can support LoD1-like modelling and offers useful semantic information to analyze the constructed environment. However, this information is not suitable for standard-oriented reuse straight away, as it needs to be cleaned, interpreted, restructured and to establish clear object relationships.

The results demonstrate the feasibility of a UDT-oriented reuse transition from a GIS-based representation through a defined sequence of methodological activities. These include height standardization, component selection, object reconstruction, derived field creation, relational database storage, SQL validation and structured export. These activities are not mandatory for the dataset to be used for conventional GIS analysis, but they are essential for a proper setup for standard-oriented 3D modelling and UDT-oriented workflows.

The thesis' contribution is to demonstrate how this shift can be operationalized. This procedure transforms fragmented GIS geometry into a Building/BuildingPart structure, checks the relationship in PostGIS, exports the reconstructed data as GeoJSON and NGSI-LD-style JSON and visualizes the results with static and interactive 3D outputs. Consequently, the thesis not only discusses the limits of the dataset, but also presents a practical means of translating municipal GIS data into a more structured, queryable and interoperable form.

The answer to the research question is thus conditional. The data set can facilitate the shift towards 3D city modelling and future UDT-oriented interoperability, but not automatically. Its readiness depends on a workflow on several scales, linking the territorial data context, the assessment at the district size, the reconstruction at the building/component level and the database/output representation. Hence, the proposed workflow should be considered as a verified prototype for the selected case study with possible transferability on other buildings where similar geometry, height features and grouping requirements are present.

5.3 Limitations of the Study

The thesis does not implement a full UDT platform. There are no live sensors, simulation engines, bidirectional feedback mechanisms or implemented FIWARE Context Broker. The NGSI-LD-style outputs are therefore prototypes that demonstrate future interoperability capabilities, rather than an operational context-broker implementation.

The thesis does not do a complete CityGML or CityJSON conversion either. These standards provide as conceptual and methodological benchmarks for the evaluation of object structure, Level of Detail and interoperability potential. For a full transformation, further schema validation, geometry correction and more comprehensive semantic modelling would be needed.

Finally, the PostGIS implementation is tested at the building level. It shows the relational storage, queryability and export potential, but extending the workflow to the complete district or city would require automated grouping rules, stable identifiers, stronger validation and additional data sources like LiDAR, photogrammetry, BIM or official building documentation.

5.4 Future Work

Future study should extend the Building/BuildingPart reconstruction to a larger number of buildings to apply the already established technology at a larger scale. This workflow, consisting of repetitive steps such as height normalization, feature recognition, secondary keys, relational storage in PostGIS and structured export, can be applied to other buildings with similar geometry, height properties and grouping requirements. The key future challenge is therefore not whether the reasoning is useable, but how to automate and validate it over a bigger district or city scale dataset.

The second objective is to incorporate additional data sources to increase height completeness and higher-LoD representation. LoD2 and LoD3 modelling can be enhanced with roof geometry, façade information, apertures or more detailed object features, by using LiDAR, photogrammetry, BIM, official building documentation or verified architectural sources.

A third direction is the establishment of a true FIWARE/NGSI-LD workflow. The JSON prototype developed in this thesis might be tested with a Context Broker in order to query, update building and component entities and connect to dynamic data sources. Such a method would be closer to an operating UDT backend.

One last direction is a public-facing dashboard that incorporates readiness indications, SQL/PostGIS outputs, GeoJSON export, and the interactive 3D model. Such a dashboard will increase the transparency of the process and facilitate communication to planners, public administrations and non-specialist stakeholders.

5.5 Conclusion

This thesis demonstrates how municipal GIS data can provide a useful base for 3D city modelling and future UDT-oriented procedures, although this transfer is not automatic. The essential issue is not whether there are geometry or height values but if the data are structured, interpretable and related in a manner that allows for reuse under the standard. The investigation reveals that official building databases include substantial geographical and semantic information but still require thorough review, cleansing, interpretation and restructuring before they can be used in more advanced digital urban workflows.

The proposed methodology explains how this change can be dealt with in a practical and repeatable approach. In the first step, GIS building geometries are checked and re-built as BuildingPart components in QGIS. Then, these components are linked to a parent Building object, saved in PostGIS as a relational spatial structure, checked by SQL queries, exported as GeoJSON and NGSI-LD-style JSON and finally visualized through an interactive 3D model. This sequence shows that the output is not merely a visual representation, but also a structured, queryable and interoperable data prototype.

The fundamental contribution of the thesis is thus the link between data-readiness evaluation and implementation. The methodology combines geometric completeness, semantic richness, interoperability and scalability to identify what the dataset already supports and what adjustments are required for future usage. The PostGIS and interactive 3D outputs also illustrate the applicability of the same rebuilt logic beyond a single static map, in support of future automation, dashboard integration and UDT-oriented development.

In conclusion, the thesis demonstrates that extant municipal building data should not be disregarded due to their limitations, nor should it be presumed that they are prepared for UDT implementation. Their usefulness comes in the possibility of being assessed, reorganized and linked to standard oriented operations. The suggested QGIS-PostGIS pipeline is a specific methodological pathway from institutional geodata to object-based 3D reconstruction, database representation, and future interoperable urban digital systems.

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Webography

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Appendix A – FIWARE-inspired Relational Schema

A.1 Example SQL-style Schema for the FIWARE-inspired Restructuring of the Lavazza Case Study

```
CREATE TABLE building (  
    building_id VARCHAR(50) PRIMARY KEY,  
    name VARCHAR(100),  
    building_use VARCHAR(100),  
    ngsi_entity VARCHAR(150)  
);  
  
CREATE TABLE building_part (  
    part_id VARCHAR(50) PRIMARY KEY,  
    building_id VARCHAR(50),  
    height_m NUMERIC,  
    num_floors INTEGER,  
    part_type VARCHAR(50),  
    lod_potential VARCHAR(50),  
    quality_flag VARCHAR(50),  
    ngsi_entity VARCHAR(150),  
    relationship VARCHAR(50),  
    partOf VARCHAR(150),  
    geom geometry(Polygon, 4326),  
    FOREIGN KEY (building_id) REFERENCES building(building_id)  
);
```

A.2 Example Population of the Relational Schema for the Lavazza Building

```
INSERT INTO building (building_id, name, building_use, ngsi_entity)  
VALUES ('Lavazza_B1', 'Lavazza Building', 'office / commercial', 'urn:ngsi-  
ld:Building:Lavazza_B1');  
  
INSERT INTO building_part (  
    part_id, building_id, height_m, part_type, lod_potential, quality_flag, ngsi_entity,  
    relationship, partOf  
)  
VALUES  
    ('LAV_1081', 'Lavazza_B1', 9.39, 'block', 'LoD1-like', 'complete_for_LoD1', 'urn:ngsi-  
ld:BuildingPart:LAV_1081', 'partOfBuilding', 'urn:ngsi-ld:Building:Lavazza_B1'),  
    ('LAV_1082', 'Lavazza_B1', 12.74, 'block', 'LoD1-like', 'complete_for_LoD1', 'urn:ngsi-  
ld:BuildingPart:LAV_1082', 'partOfBuilding', 'urn:ngsi-ld:Building:Lavazza_B1'),  
    ('LAV_7341', 'Lavazza_B1', 30.64, 'tower', 'LoD1-like', 'complete_for_LoD1', 'urn:ngsi-  
ld:BuildingPart:LAV_7341', 'partOfBuilding', 'urn:ngsi-ld:Building:Lavazza_B1'),  
    ('LAV_7342', 'Lavazza_B1', 5.20, 'low_block', 'LoD1-like', 'complete_for_LoD1',
```

```
'urn:ngsi-ld:BuildingPart:LAV_7342', 'partOfBuilding', 'urn:ngsi-ld:Building:Lavazza_B1'),  
  ('LAV_12854', 'Lavazza_B1', 5.79, 'connector', 'LoD1-like', 'complete_for_LoD1',  
'urn:ngsi-ld:BuildingPart:LAV_12854', 'partOfBuilding', 'urn:ngsi-ld:Building:Lavazza_B1'),  
  ('LAV_15145', 'Lavazza_B1', 14.63, 'main_body', 'LoD1-like', 'complete_for_LoD1',  
'urn:ngsi-ld:BuildingPart:LAV_15145', 'partOfBuilding', 'urn:ngsi-ld:Building:Lavazza_B1');
```

Appendix B - Interactive Dashboard

B.1 Dashboard Overview

The dashboard is intended to communicate the main outputs of the thesis in a web-based and portfolio-ready format. It can include dataset-readiness indicators, layer summaries, height availability charts, 2D maps, and the interactive 3D model. The dashboard does not replace the analytical results in the thesis; it acts as a communication output that makes the methodology easier to inspect and share.

Dashboard Access Link

Insert the final GitHub Pages or dashboard link here after publication. Suggested wording: The interactive dashboard and 3D model are available at: <https://niloofarjl78.github.io/Urban-Digital-Twin-Dashboard/>

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